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Enhancing Fruit Crop Performance: The Role of Phosphate-Solubilizing Bacteria in Growth, Yield and Quality Improvement

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

Phosphorus is a crucial macronutrient in plant development, playing a vital role in metabolic activities and growth. Due to its poor availability in soil, phosphorus (P) is essential for healthy plant growth, particularly in tropical regions. P is present in nucleic acids, catalysts, coenzymes, nucleotides, and phospholipids. Optimal phosphorus availability is essential for plant reproductive structure formation during early development. Soil phosphorus content is around 0.05%, but due to insoluble phosphates, soluble forms are not readily available for plants. Chemical P fertilizers are used to increase available P levels, but these are costly and have negative environmental impacts. The limited P-source and high-quality rock P deposits may be exhausted within the next century,

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leading to the search for environmentally friendly alternatives. Biofertilizers with P-solubilizing properties are an environmentally friendly alternative to chemical-based Phosphorus fertilizers. PSB, beneficial microorganisms, hydrolyse insoluble phosphorus compounds into soluble P, facilitating plant uptake. This eco-friendly and economically sound approach overcomes P scarcity. Throughout the review, these PSBs are discussed in terms of how they have been applied and used to improve fruit crop growth, yield, and quality, providing promising evidence that these PSBs can be used as a viable alternative to inorganic phosphate fertilizers in the future for sustainable agriculture.

Keywords: Soil phosphorous; phosphorous solubilizing bacteria; PSB; biofertilizer; fruits.

1. INTRODUCTION

"Phosphorus is a significant macronutrient that plays a crucial role in plant metabolic activities and development, second only to nitrogen" [1]. "Due to its poor availability in the soil, phosphorus (P) is one of the main macronutrients that limits plant development and is necessary for healthy plant growth, especially in tropical regions" [2]. It represents somewhere in the range of 0.2 and 0.8% of the dry load of plants [3], and it is held inside nucleic acids, catalysts, coenzymes, nucleotides, and phospholipids. P is fundamental in each part of plant development and improvement, from the atomic level to numerous physiological and biochemical plant activities including photosynthesis [3], improvement of roots, fortifying the shoots and stems, development of blossoms and seeds, crop development and nature of yield, energy creation, storing and transfer reactions, root development, cell division and augmentation, Nitrogen obsession in vegetables, obstruction to establish sicknesses [4], nitrogen fixation in legumes [5], change of sugar to starch, furthermore, moving of the hereditary attributes [6]. "Optimal phosphorus availability is essential for the formation of plant reproductive structures during early plant development" [6]. "Lack of phosphorus results in stunted growth and dark green colouration due to the enhancement of anthocyanin formation" [7].

"The soil has a phosphorus content of around 0.05%. Due to their fixation as insoluble phosphates of iron, aluminium, and calcium in the soil, soluble forms of P are not as readily available for plants" [8]. Because of this, soil P becomes fixed, and, in most agricultural soils, available P levels must be increased by adding chemical P fertilisers. These fertilisers not only constitute a significant expense of agricultural

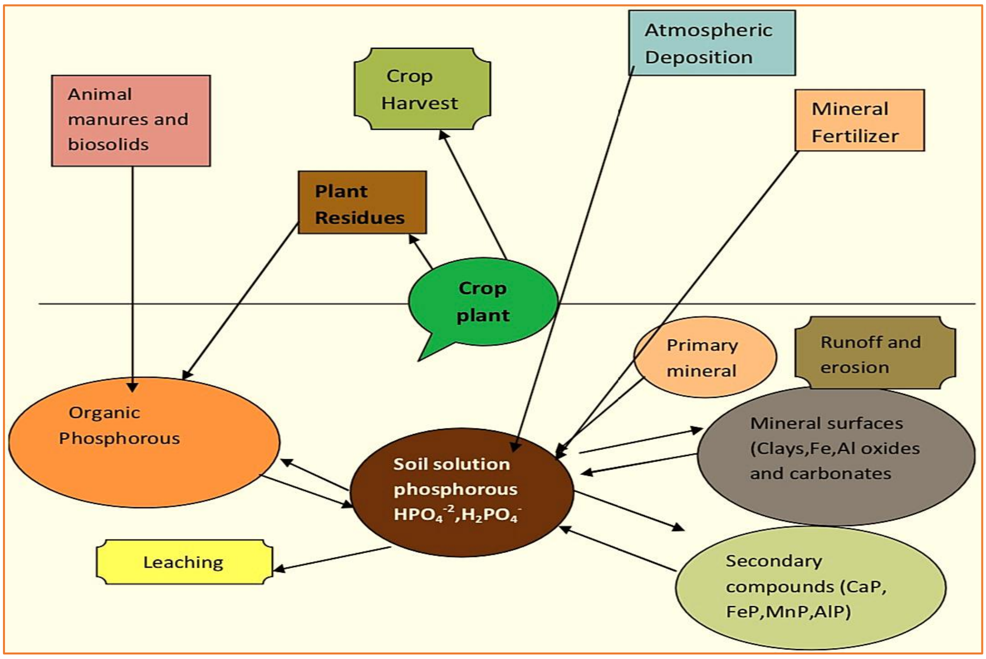

Fig. 1. Phosphorous cycle in nature [70]

production but also have a negative environmental impact on the health of the soil as a whole and degrade freshwater, marine, and terrestrial resources. Accordingly, elevated P levels are a primary cause of surface water eutrophication, which can result in algal blooms [8]. The frequent and careless use of chemical P fertilisers reduces crop output by upsetting microbial diversity, which in turn causes soil fertility to be lost [9]. The P-source in the world is limited and the world's high-quality rock P deposits may be exhausted within the next century due to its limited nature and current pace of consumption [10]. Beyond a certain point, producing P-based fertilisers would need processing lower-grade rock, which will be more expensive [11]. The recognition of all the potential challenges related to chemical P fertilisers, combined with the enormous expenditures involved in their production, has prompted the search for environmentally friendly and economic alternatives to enhance crop production on poor and phosphorous-deficient soils [12]. Using microbial inoculants (biofertilizers) with P solubilizing properties in agricultural soils is an environmentally benign alternative to chemical-based P fertilisers.

2. PHOSPHORUS SOLUBILISING BACTERIA (PSB)

"A few bacterial animal categories can change the insoluble type of phosphorous into a dissolvable one and are known as phosphate-solubilising microorganisms (PSBs)" [13]. "They are otherwise called plant development-advancing rhizobacteria (PGPR) because they colonize the plant roots and advance plant development. PSB has been utilized for crop creation starting around 1903. Phosphobacterin is the bacterial compost containing cells of Bacillus megatherium var. phosphaticum arranged primarily by USSR researchers. These microorganisms assume a critical part in providing phosphate to plants, in a climate cordial and manageable way" [14]. "Joined application of arbuscular mycorrhiza and phosphate solubilizing microbes upgraded the take-up of both local P from soil and P coming from the phosphatic rock" [15,16]. "Among the entire microbial populace in soil P, solubilizing bacteria contain 1–50% and P solubilizing fungi 0.1 to 0.5% of the entire individual populace" [17]. "PSBs are concentrated in the rhizosphere since this is the metabolically most active area" [18]. The mode of action of these PSBs includes increasing the surface area of the plant roots, increasing the availability of nutrients in the soil to the plants, and assisting nitrogen fixation. *Pseudomonas fluorescens, Bacillus megatherium var. phosphaticum, Acrobacter acrogens, Nitrobacter spp*., *Serratia spp*., *Escherichia coli*, *Pseudomonas striata*, *Bacillus polymyxa* are some of the microbes that have phosphate solubilising capacity.

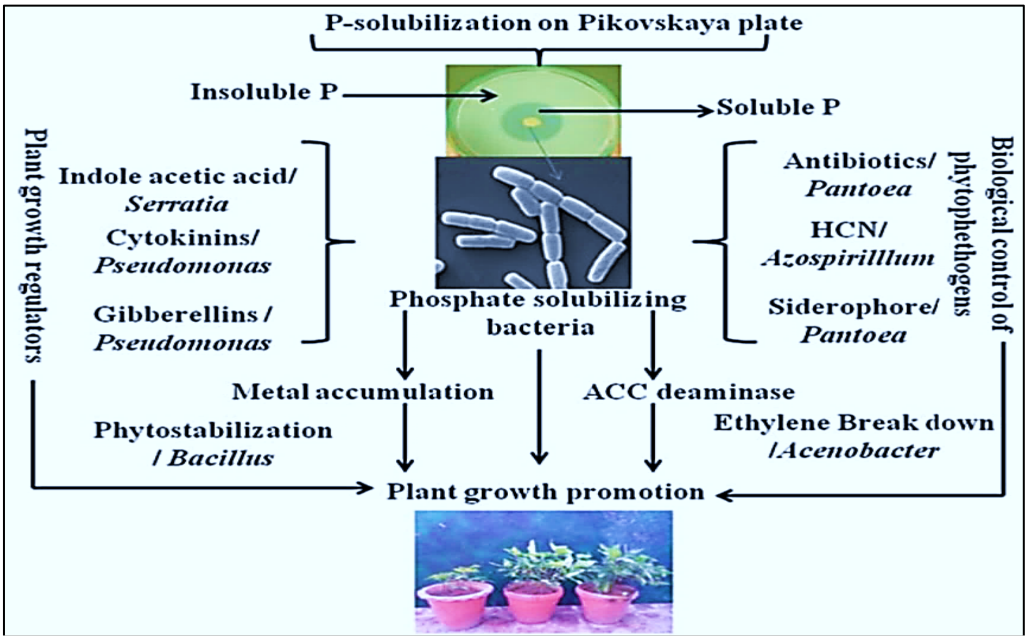

Fig. 2. Functional diversity of PSB [71]

3. MECHANISM OF PHOSPHORUS SOLUBILIZATION

3.1 Production of Organic Acids

"Microbial secretion of low-molecular-weight organic acids is a crucial mechanism for the mineralization of phosphorus in soil. By producing organic acids, the phosphate solubilizing bacteria (PSB) can lower the surrounding pH" [19]. "These natural acids can either break up phosphates because of anion trade or can chelate Ca, Fe or Al particles related to the phosphates" [9]. Nonetheless, soil microorganisms shift significantly in their capacity to discharge natural acids and, consequently, solubilize mineral phosphates at various degrees.

3.2 Production of Acid Phosphatase

The mineralization of phosphorus compounds is completed by the activity of a few phosphates (likewise called phosphor hydrolase), which are available in a wide assortment of soil microorganisms and assume a critical part in the osmosis of phosphate from natural mixtures by plants and microorganisms [20]. It includes the hydrolysis of phosphoester or phosphor anhydride bonds.

4. EFFECT OF PSB ON CROPS

- The biofertilizer PSB has a positive effect on siderophores' secretion, which is used to chelate and absorb iron from the environment. Iron take-up is vital for compounds like Nitrogenase and hydrogenase nitrogen obsession.
- They can create various kinds of chemicals like auxins, abscisic corrosive (ABA), gibberellic corrosive and cytokinins [21].
- PSB can combine 1-amino cyclopropane-1-carboxylate (ACC) deaminase catalyst which switches ACC over completely to smelling salts and forestalls the inhibitory impact of ethylene in roots as ACC is a quick forerunner of ethylene and consequently expanding root length and development [22].
- They upgrade the organic nitrogen obsession in plants [23].
- Siderophores, molecules that bind metals, are produced by them [24], β-1,3 glucanase, fluorescent shades, chitinases, anti-infection agents and cyanides to safeguard plants against microorganisms [25].
- They give protection from dry spells, saltiness, water-logging and oxidative pressure [26] and help in the solubilisation and mineralization of supplements [27].
- They produce water-solvent nutrients like niacin, thiamine, riboflavin and biotin for plant development [28,29].
- They advance free-living nitrogen-fixing microbes and improve nitrogen obsession and the stock of supplements like phosphorous, sulfur, iron and copper [30,31].

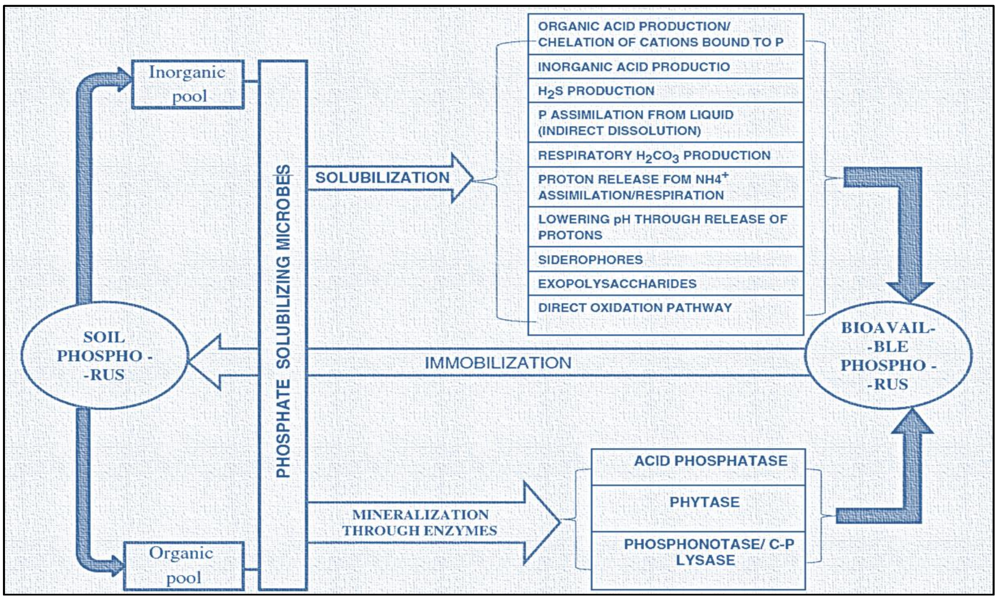

Fig. 3. Soil phosphorous mobilization and immobilization by bacteria [3]

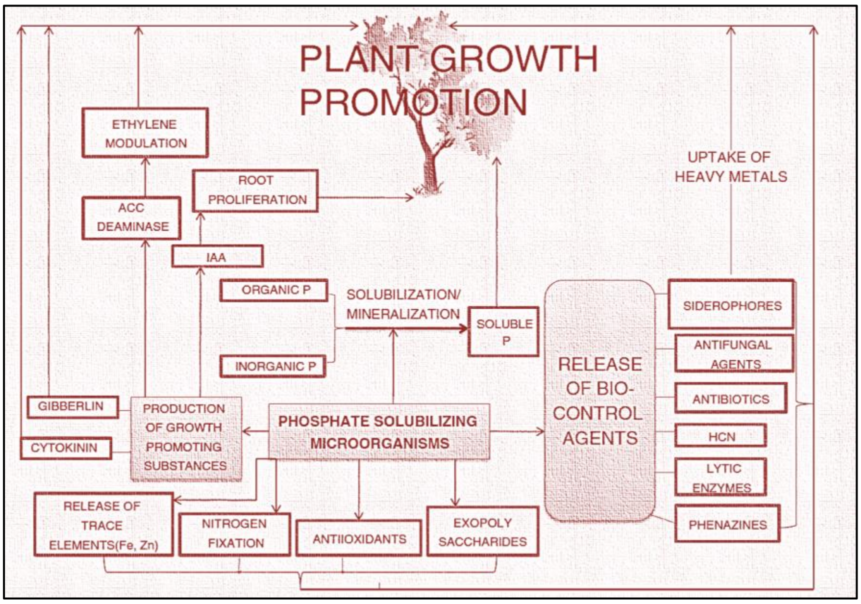

Fig. 4. Mechanism of plant growth promotion by phosphorous solubilizing microorganism [3]

5. EFFECT OF PSB ON FRUIT MORPHOLOGICAL CHARACTERISTICS

5.1 Canopy Volume

A study effect of PSB application in Nanasaheb Purple grapes got the most noteworthy shoot length (92.06 cm), shoot measurement (8.43 mm), total chlorophyll (1.31mg/g) and leaf area (178 cm2) which were treated by PSB of 2.5ml/plant treatment [32]. A positive relationship between's PSB focus, and the development of the plant was noted. This may be because of the creation of auxin by PSB and the expanded stock of phosphorus by PSB [33]. Likewise, the expansion in development characters may be because of the stimulative impact of PSB on P solubilisation prompting higher P accessibility and take-up by plants [34,35]. A *per cent* expansion in plant level (8.93%), number of shoots/plant (69.23%), and number of nodes per plant (52.90%) in guava cv. L – 49 was reported when treated with vermicompost 7.5kg + PSB 50g [36]. Its very well results may be because of improved take-up of supplements under consolidated use of 7.5 kg Vermicompost + 50 g PSB per plant which could expand the accessible N, P, and K status of the soil. The consortium of Vermicompost + PSB presumably improved the soil by natural nitrogen obsession and maybe went about as a wellspring of energy (carbon) for its development and advancement and could added to upgraded auxin combination especially IAA in effectively isolating meristematic district in adolescents in guava plants. Research on the INM effect on strawberry cv. Sweet Charlie had evidenced that application of PSB along with azotobacter, vermicompost (5 tons), and poultry manure(2.5tons) resulted in maximum plant height(16.19cm), plant spread (24.68cm), and (77.26cm^2) [37].

5.2 Stem Girth

The greatest rate expansion in rootstock circumference (11.69%) and scion size (12.67%) during 2018 was in the mango cv. Dashehari plants were treated with Azotobacter 50 g + PSB 50 g + 3 kg Vermicompost, during a different biofertilizers treatment study [39]. This may be added to better nitrogen obsession in soil, the creation of phytohormone substances, and expanded take-up of supplements especially nitrogen and phosphorus given bio-natural manure application. The most extreme expansion in stem circumference (4.16cm) of Sweet Orange was assessed under the treatment of 80ml Azotobacter + 80ml PSB + 50kg FYM + RDF (800:400:400g NPK), though the base increment was seen in charge (RDF 800:400:400g NPK + 50kg FYM) [48]. The use of 50g Azotobacter + 50g PSB + 250g VAM + FYM + half RDF (200:160:200 NPK) gives the greatest stem girth (81.34cm) in banana [40]. The treatment containing Azotobacter 50 g + VAM 20 g + PSB 50 g + half N through vermicompost + half RDF expands the scion and rootstock circumference of Custard Apple as against different treatments and controls [49].

Table 1. Effect of PSB on canopy volume

Crop	Dosages of Phosphorus Solubilizing Bacteria	Results	References
Mango cv. Himsagar	75% RDF + Azospirillum and Azotobacter @250g +PSB @ 250g+ K-mobilizers@250g	High leaf supplement status (1.98-2.12% nitrogen, 0.17-0.18% phosphorus and 1.15-1.20% potassium)	[38]
Mango plants cv. Dashehari	Azotobacter 50g per plant + PSB 50g per plant	High-rate expansion in plant height (10.78%), number of shoots per plant (68.98 %), and the number of nodes per shoot (41.65 %)	[39]
Banana cv. Ardhapuri (Musa AAA)	half RDF + FYM + Azotobacter (50 g/plant) + PSB (50 g/plant) + VAM G. fasciculatum (250 g/plant)	Maximum plant height (190.84 cm), higher number of leaves (32.30) per plant and leaf area (17.93 m^2) and the minimum number of days (211.03) for shooting after planting and the number of days for harvest in the wake of shooting (117.46)	[40]
Strawberry cv. Chandler	vermicompost(250g/plant) and PSB(2g/plant)	More increased plant height(23.59cm), leaves per plant (12.67), primary branches per plant (10.50), auxiliary branches per plant (27.35)	[41]
Sapota (*Manilkara achras* (Mill.) Forseberg). cv. Kalipatti	100% RDF + Azospirillum 200g + PSB 200g	Increase in plant growth concerning days expected for growing of new shoots (24.30), length of the shoot (12.64 cm), No. of leaves per shoots (9.67), leaf area (19.48 cm2)	[42]
Strawberry cv. Chandler	Azotobacter + PSB + vermicompost + 50 % recommended NPK	More elevated plant height, plant spread, and leaf area per plant	[43]
Strawberry	vermicompost + Azotobacter + PSB +Arbuscular mycorrhiza	Greatest plant height (20.26 cm), plant spread (25.64 cm), number of leaves (54.30), and leaf area (97.87 cm 2)/plant	[44]
Mango	Bio-compost PSM @ 100 g/plant + Azotobacter @ 150g/plant + half RDF	Maximum plant height (6.72 m)	[45]
Aha lemon	Azospirillum 25g/tree + Azotobacter 25g/tree + 75% NPK/tree + *Bacillus circulans* 25g/tree + 27.5kg FYM/year	Increase in leaf area and shoot length	[46]
Valencia orange	180 N units/feddan + 120 K units/feddan + *B. circulans*	Maximum increase of shoot length (43.51cm)	[47]
sweet Orange	80ml Azotobacter + 80ml PSB + RDF 800:400:400g NPK + 50kg FYM	The maximum expansion in tree height (0.47m)	[48]
Custard Apple	Azotobacter 50 g + VAM 20 g + PSB 50 g + half N through vermicompost + half RDF	The most extreme plant height	[49]
Papaya	Azotobacter + PSB + 100% NPK + FYM	Increase in Plant height (201.95 cm)	[50]
Guava	PSB 100 g/tree + Azospirillum 100 g/tree + cowdung slurry @ 10 liter/tree + 75%RDF	Increase in plant height (4.91 m)	[51]

Crop	Dosages of Phosphorus Solubilizing Bacteria	Results	References
Guava	Azotobacter + PSB + FYM + RDF 100%	maximum plant height (3.43 m)	[52]
Mango	Azotobacter 100g + VAM 100g + *Trichoderma viridae* 100g + PSB 100g + 25 kg vermicompost + Oil cake 2.5 kg + 520: 160: 450 NPK g/plant	Increase in the crown height (78.3cm)	[53]
Papaya	PSB 2.5 g/m2 + Azotobacter 50 g/plant + half RDF-NPK 100g:100g:125g/plant	Increase in plant height at the blossoming and harvest stage	[54]

Table 2. Effect of PSB on stem girth

Crops	Dosages of Phosphorus Solubilizing Bacteria	Results	References
Sapota	100 percent RDF-1000: 500: 500 g NPK + 200g Azospirillum+200g PSB/Plant	The most extreme size of the shoot (2.06 cm) among the treatments	[42]
Banana	Azospirillium + PSB 20 g/plant	the most noteworthy stem girth development (63.00 cm)	[55]
Mango	Azotobacter 150g/plant + PSM 100 g/plant + half Inorganic manure	Most extreme stem circumference (79.32 cm)	[45]
Guava	Vermicompost 7.5 kg + PSB 50 g	Maximum and large rate expansion in rootstock size (7.67%) and scion circumference (7.88%)	[36]

6. EFFECT OF PSB ON FRUIT REPRODUCTIVE CHARACTERISTICS

6.1 Flowering

Research finding revealed that the greatest blooming shoot initiation (46.1%) in 10-year-old mango cv. Himsagar crops treated with 50% NPK + Azospirillum @ 250g + PSB @ 250g + K-mobilizers @ 250g. The superior outcome as far as blossoming by applying higher dosages of inorganic and biofertilizer mixes is because the plants get the necessary measure of significant supplements like nitrogen, phosphorus, and potassium [38]. Research concentrated on the effect of INM on the plant development and yield boundaries of strawberry cv. Chandler showed that, the treatment mix of Azotobacter + PSB + vermicompost + 50 % suggested portion of NPK recorded earliest in blossoming and largest number of blossoms per plant and blooming span [43]. Indian gooseberry displayed early blooming inception when treated with 3/fourth portion of NPK/tree + 100 kg FYM + Azotobacter @100g + Azospirillum @ 100g + PSB @ 100g. Be that as it may, a higher sex proportion was seen in the control (250.22 and 251.09) trailed by (a three-fourths portion of NPK/tree + 100 kg FYM) and (a half portion of NPK/tree + 100 kg FYM) [56].

6.2 Fruit Set and Development

Research on the effect of INM on strawberry cv. Chandler evidenced that, the treatment blend of Azotobacter + PSB + vermicompost + 50 % suggested portion of NPK was recorded earliest in fruit development [43]. Research on the effect of biofertilizer in Indian gooseberry detailed high fruit set (44.55% & 50.16%), fruit retention *per cent* (35.55% & 43.17%) was reported in Indian gooseberry with the treatment of biofertilizers (azotobacter, azospirillum, PSB @ 100g/tree each) alongside 75% RDF [56]. Research on nutrient management in sapota (*Manilkara achras*) cv. Kalipatti plants treated with 100% RDF + Azospirillum 200g + PSB 200g showed the biggest number of fruits per shoot (4.24) and number of fruits per tree (635.67) [42]. Research on INM effect on strawberry cv. Sweet Charlie found that application of PSB along with azotobacter, vermicompost (5 tons), and poultry manure(2.5 tons) noted the maximum number of fruits per plant (11.78) [37].

7. EFFECT OF PSB ON FRUIT SIZE AND WEIGHT

The most elevated typical fruit weight (663.67 g), and 50 berry weight (458.0 g) in Nanasaheb purple grapes are accounted for when treated with PSB @ 2.5ml/plant. An expansion in normal bundle weight and 50 berry weight was seen as the centralization of PSB application/plant (0.5, 1.0, 1.5, 2.0, and 2.5 ml/plant) expanded. A positive connection was seen between the PSB fixation and yield boundaries [32]. The biofertilizer application in mango cv. Himsagar got a higher fruit weight (267.2g), fruit length (9.62cm), and fruit diameter(7.74cm), in plants treated with 75% NPK + Azotobacter 250 g + PSB @ 250 g + K-mobilizer @ 250g. The superior outcome as far as fruit weight and size by applying higher portions of inorganic and biofertilizer mixes is because the plants get the expected measure of significant supplements like nitrogen, phosphorus, and potassium [38]. The most extreme load of the fruit in banana cv. Giant Cavendish was created with Azospirillium + PSB 20g per plant followed by Azotobacter + PSB 20g per plant while the lesser yield was recorded with

Table 3. Effect of PSB on fruit size and weight

Crops	Dosages of Phosphorus Solubilizing Bacteria	Results	References
Sapota	250 g PSB + 250 g Azotobacter per plant	Most extreme fruit weight (125.87 g)	[57]
Strawberry cv. Kurdistan.	Fertilizer + Azotobacter +wood debris + phosphorus solubilizing microorganisms + oil cake	Increased fruit size (3.11cm), length (3.95 cm), volume (20.397cm3), weight (11.11g) of fruits.	[58]
Strawberry cv. Chandler	Azotobacter + PSB + vermicompost + 50 % RDF of NPK	The extreme fruit weight in plants among the plants.	[43]
Mango	Bio-compost (Azotobacter 150g/plant + PSM 100 g/plant) + half RDF	Increment of fruit weight (285.15 g)	[45]
Nagpur mandarin	VAM 500 gm/plant + Azospirillum 100 gm/plant + 100% RDF + PSB 100 gm/plant	Increase in the fruit weight (149.98 g/fruit)	[59]
Mango cv. "Himsagar"	250 g Azospirillum + 250 g PSB + 850:425:1000 NPK + 100 gm borax + 100 gm $ZnSO_4$ (Zinc Sulfate)/tree/year + Vermicompost	Most extreme weight (i.e., 273.20gm)	[60]
Guava	PSB 100 gm/tree + Azospirillum 100 gm/tree + cow manure slurry @ 10 liters/tree + 75%RDF	The fruit breadth (7.46 cm) was increased among the treatments.	[51]
Guava	RDF 100% + FYM + Azotobactor + PSB	Greatest fruit weight (135.9g) among the treatments.	[52]
Papaya	PSB 2.5 g/m^2 + Azotobacter 50 g/plant + half RDF-NPK-100g:100g:125g/plant	the most noteworthy fruit weight (1670g) all among the treatments.	[54]
Guava	250g Azotobacter + 50kg FYM + 487.5g + 243.75g + 281.25g NPK + 250g PSB/plant	Greater fruit weight and size	[61]
Papaya	Azotobacter + PSB + 100 percent NPK + FYM	Maximum Fruit weight (0.952 kg) among the treatment.	[50]
Guava	Azospirillum + PSB + 10 kg Vermicompost + 100 percent N + 100 percent P_2O_5	Most elevated fruit width (7.91 cm), and pulp weight (211.61 g)	[62]

control because organic nitrogen obsession relies on the accessible type of phosphorus [55]. Research in the utilization of PSB to Nanasaheb grape plants showed an expansion in berry length from 19.33 to 22.67 mm while the berry width was expanded from 18.33 to 23.33 mm with the expansion in the convergence of PSB from 0.5 to 2.5 ml/plant separately [32]. Impact study of INM on strawberry cv. Sweet Charlie found that application of PSB along with azotobacter, vermicompost (5 tons), and poultry manure(2.5tons) yielded the maximum fruit weight (12.26g), fruit diameter (2.99cm) and fruit length (5.25cm) among the treatments [37].

8. EFFECT OF PSB ON YIELD

The best return (17.38kg) in grapes is accounted for when treated with PSB @ 2.5ml/plant. Expansions in yield were seen as the grouping of PSB application/plant (0.5, 1.0, 1.5, 2.0, and 2.5 ml/plant) expanded. A positive connection was seen between the PSB fixation and yield boundaries [32]. The expansion in fruit yield with immunization of P solubilizing microorganisms may be because of an expansion in P accessibility through the solubilization of insoluble inorganic phosphate by natural corrosive, deterioration of phosphate-rich natural mixtures and creation of plant development advancing substances [63]. Research on INM effect on *strawberry cv*. Sweet crops treated with PSB along with azotobacter, vermicompost (5 tons), and poultry manure (2.5 tons) resulted in the maximum yield per plant (112.63g) [37]. Research on the effect of biofertilizer concentrated on Indian gooseberry detailed that a high return for every tree (159.6 kg & 161.68 kg/tree) when treated with biofertilizers (Azotobacter, Azospirillum, PSB @100g/tree each) alongside 75% RDF [56]. In sapota (*Manilkara achras*). cv. Kalipatti, the plants treated with 100% RDF + Azospirillum 200g + PSB 200g showed the best yield per tree (53.33 kg). The most increased fruit yield regarding the number of fruits/plant (1569.33) and fruit yield per plant (197.53 kg/plant) were reported in sapota which were treated with 1125:750:375 g NPK + 15 kg vermicompost + 250 g Azotobacter + 250 g PSB/plant [57].

Table 4. Effect of PSB on yield

Crops	Dosages of Phosphorus Solubilizing Bacteria	Results	References
Mango cv. Himsagar	75% NPK + Azotobacter 250g + PSB @ 250g + K-mobilizer @ 250g	greatest fruit yield (60.4 kg/plant), and number of fruits/plants (225.7) among the treatments	[38]
Strawberry cv. Kurdistan	compost + Azotobacter + wood ash + phosphorus solubilizing microorganisms + oil cake	Increase in the fruit yield (238.95 g/plant)	[58]
Strawberry cv. Chandler	Azotobacter + PSB + vermicompost + 50 % suggested portion of NPK	the most extreme number of fruits per plant, yield per plant (181.84 g), marketable yield per plant (145.47 g) and yield per hectare (101.02 q).	[43]
Strawberry	vermicompost + Azotobacter + PSB +Arbuscular mycorrhiza	the most extreme yield (311.26 g) / plant	[44]
Aha lemon	Azospirillum 25g/tree + Azotobacter 25g/tree + 75% NPK/tree + *Bacillus circulans* 25g/tree + 27.5kg FYM/year	Greater fruit yield among the treatment	[46]
Nagpur mandarin	VAM 500 gm/plant + 100 percent suggested portion of compost + Azospirillum 100 gm/plant + PSB 100 gm/plant	The most extreme yield i.e., 112.75 kg/tree	[59]
Sweet Oranges	80ml Azotobacter + 80ml PSB + 50kg FYM + RDF (800:400:400g NPK)	The most noteworthy fruit yield (107.36kg) and marketable yield (105.46kg)	[40]
Guava	250g Azotobacter + 250g PSB+	Higher fruit yield	[61]

Crops	Dosages of Phosphorus Solubilizing Bacteria	Results	References
	50kg FYM + (487.5g + 243.75g + 281.25g NPK)/plant		
Guava	PSB 100 gm for each tree + Azospirillum 100 gm for every tree + cow dung slurry @ 10 liter for every tree + 75% RDF	Obtained the maximum yield (48.23 kg/tree)	[51]
Guava	treatment of RDF 100 % + Vermicompost + Azotobacter + PSB	Recorded the most extreme fruit yield (21.74kg/tree)	[52]
Mango	75% RDF + Azotobacter 250 g + 20 kg Vermicompost + 250 g PSB/plant	Most extreme fruit yield/tree (23.36 kg)	[44]
Papaya	PSB 2.5 g/m^2 + Azotobacter 50 g/plant + half RDF-NPK 100g:100g: 125g/plant	the most highest fruit yield/ha (259.97 ton) and marketable fruit yield/plot (299 kg)	[54]
Mango cv. Langra	Azotobacter (250g) + PSB (250g) + Vermicompost (30kg) + GA_3 (40ppm)	Resulted the best yield among the treatment	[64]
Mango	Bio-manure (PSM 100 g/plant + Azotobacter 150g/plant) + half NPK by RDF	Noted the most extreme fruit yield (57.20 kg/plant) and fruit weight (285.15 g)	[45]
Banana	Azospirillium + PSB 20g per plant	Highest number of fingers	[55]
Strawberry	FYM and Bio-composts (oil cake + wood debris + Poultry fertilizer + PSB + Azotobacter)	The highest noted yield (132.75q/ha.)	[65]
Guava	PSB 100gm/tree + FYM 26kg/tree/year + potash mobilizers100 gm/tree + Azotobacter100 gm/tree	Maximum fruit yield (i.e.114 kg/plant)	[66]
Plum	12.5% nitrogen acquired by FYM + 12.5% nitrogen from Vermicompost + 75% of N + PSB + Azotobacter	The best yield (52.14 kg/tree)	[67]

Table 5. Effect of PSB on fruit quality

Crops	Dosages of Phosphorus Solubilizing Bacteria	Results	References
Sapota	1125:750:375 g NPK+15 kg vermicompost +250 g Azotobacter + 250 g PSB/plant	Maximum fruit weight (125.87 g), fruit length (4.36 cm), fruit width (5.26 cm) and fruit volume (117.20cc), maximum pulp weight (101.66 g), greate (23.16ºB), and total sugar (18.03%) with least acidity (0.050%)	[42]
Strawberry	vermicompost + Azotobacter + Azospirillum + PSB	Higher TSS and total sugar with lower acidity (0.481%)	[69]
Nanasaheb purple grape	1ml PSB/plant	Most noteworthy TSS (18.67ºB) and least acidity (5.50 g/lit.)	[32]
Sapota	1125:750:375 g NPK + 15kg vermicompost + 250 g Azotobacter + 250 g PSB/plants	Most extreme total soluble solids (23.16 ºB), total sugar (18.03%) with least acidity (0.050%)	[57]

9. EFFECT OF PSB ON FRUIT QUALITY

A study on INM effect on strawberry cv. Sweet Charlie showed that application of PSB along with azotobacter, vermicompost (5 tons), and poultry manure (2.5 tons) increased the specific gravity of fruits (1.84) [37]. Papaya cv. Surya showed an elevated degree of carotenoids, lycopene, and a low degree of ascorbic acids in treatment with 50% RDF and Azospirillum + PSB+ mycorrhiza + vermicompost at 50g/plant [68]. Consolidated use of fertilizer + Azotobacter +wood ash + phosphorus solubilizing microorganisms + oil cake improved fruit complete sugars (7.95%), all out dissolvable solids (9.01°B), corrosiveness (0.857), TSS: acridity proportion (11.12) in strawberry cv. Kurdistan [58].

10. EFFECT OF PSB ON SOIL HEALTH

The prime role of PSB application is to improve the soil quality as well as promoting the plant growth and development while sustaining natural resources [72,73]. The plant growth is most obvious characteristic for evaluation the effect of PSB. Application of PSB 50g + vermicompost 7.5kg treatment in the guava cv. L-49 orchard soils revealed that there was a significant decrease in the pH, electrical conductivity, and organic carbon (%) as well as the available N, P, K status was significantly increased [36,74,75]. Soil application of PSB along with azotobacter + Vermicompost (5tons/ha) + Poultry manure(2.5tons/ha) significantly increased the soil residual available N, P, K, and organic carbon and decrease in the soil pH, and electrical conductivity was observed [37]. An examination on the impact of biofertilizers and inorganic composts on *Mango cv*. Himsagar, obtained soil's greatest accessible phosphorous (25.91kg/ha) and natural carbon (1.19%) in their treatment was 75% NPK + Azotobacter @ 250g + PSB @ 250g + K-mobilizer @ 250g. The higher soil supplement status is because of the use of joined medicines (inorganic composts + biofertilizers) [38]. The effect of INM on strawberry cv. Chandler and the use of Azotobacter + PSB + vermicompost + half RDF was viewed as more compelling in diminishing the electrical conductivity (0.02 dSm^{-1}) and pH (6.27) of soil. The natural carbon (1.95%), accessible nitrogen (314.64 kg ha^{-1}), phosphorous (17.56 kg ha^{-1}), and potassium (306.33 kg ha^{-1}) were recorded altogether higher in the soil after gathering of the harvest in treatment getting Azotobacter + PSB + vermicompost + half RDF [43]. Use of PSB (2.5ml PSB/plant and 2ml PSB/plant) treatment showed the microbial count 0.3 CFU/gm soil to 3.5 CFU/gm soil from the 30th, 45th, and 60th after application to harvest stage [32].

11. CONCLUSION

Phosphorus nutrition limits global agricultural productivity. To address the issue of phosphorus unavailability in agricultural soil, phosphatic fertilizers are routinely administered in an imbalanced way, degrading soil and crop health. Phosphoric fertilizer effectiveness is limited owing to fixation in both acidic and alkaline soils. Soil microorganisms have a role in P transformation, affecting the availability of phosphate to plant roots through several mechanisms. Microorganisms may solubilize and mineralize P from both organic and inorganic sources in soil. Inoculating PSB in soil effectively converts insoluble P compounds to plant-available form, leading to increased plant growth, crop output, soil quality, and sustainable agriculture. PSB promotes plant development by supplying readily absorbed P and producing plant growth hormones including IAA and GA. Additionally, PSB promotes plant development by producing siderophores and improving nitrogen fixation. In addition, PSB functions as a biocontrol against plant infections by producing antibiotics. Thus, PSBs provide possible replacements for inorganic phosphate fertilizers in meeting plant P needs and enhancing output in sustainable agriculture. Their application is both environmentally and economically sound. Further research is needed to investigate effective biofertilizers-PSB with numerous growth-stimulating properties in the field experiment.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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