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# Enhancing Phosphorus Release in Acidic Soils using Biochar Enriched with PSB : A Review

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**Abstract**

Phosphorus (P) is an essential nutrient for plant growth, but its availability is often limited in acidic soils due to P fixation and immobilization. Biochar, a carbon-rich material derived from biomass has been gained significant attention as a soil amendment to improve soil fertility and phosphorus availability. In recent years, the combination of biochar with phosphorus-solubilizing bacteria (PSB) has gained attention as a promising approach to enhance phosphorus release in acidic soils. Enriching biochar with PSB offers a synergistic strategy for phosphorus management. Biochar protects PSB from harsh soil conditions, while PSB enhance biochar's P adsorption capacity and unlock its bound P content. Studies have shown that PSB-enriched biochar can significantly increase plant-available phosphorus compared to biochar or PSB alone. This review summarizes the current understanding of biochar enriched with PSB and its impact on phosphorus dynamics in acidic soils. It discusses the mechanisms involved, factors influencing effectiveness and potential applications of this novel approach.

*Keywords* : Biochar, Phosphorus-solubilizing bacteria, Acidic soils, Phosphorus release, Soil fertility, Sustainable agriculture

Phosphorus (P) is an essential nutrient for all living organisms, playing crucial roles in various biological processes, including energy transfer, nucleic acid synthesis and cell signalling. In agricultural contexts, phosphorus is particularly important for plant growth and development, as it is a constituent of key molecules such as ATP (adenosine triphosphate) and DNA (deoxyribonucleic acid). Phosphorus is also involved in processes such as photosynthesis, root development & flower and fruit formation. Phosphorus availability is often a limiting factor for plant productivity, especially in acidic soils where P tends to become fixed or immobilized by interactions with soil minerals such as iron (Fe), aluminium (Al) and calcium (Ca) (Chintala *et al.,* 2014). These interactions render phosphorus less soluble and therefore, less accessible to plants. As a result, agricultural practices often involve the application of phosphorus fertilizers to ensure optimal plant growth and yield. However, excessive use of phosphorus fertilizers can lead to environmental issues such as nutrient runoff and eutrophication of water bodies (Yang *et al*., 2017 and Koch *et al*., 2018). Therefore, there is a need for sustainable approaches to manage phosphorus in agricultural systems. This has led to research into alternative strategies to enhance phosphorus availability in soils (Ohno and Amirbahman, 2010), such as the use of phosphorus-solubilizing bacteria (PSB) (Alori *et al*., 2017) and phosphorus-enriched soil amendments like biochar (Fei *et al*., 2019).

PSB are microorganisms capable of solubilizing phosphorus in soil through various mechanisms, including the secretion of organic acids, enzymes and siderophores (Khan *et al*., 2014). These bacteria can

**Table 1**

**Physical and chemical properties of Biochars produced from fast pyrolysis of corn stover, ponderosa pine wood and switch grass residue at 650°C with standard errors (Chintala *et al.*, 2014)**

| Properties | Corn stover biochar | Pine wood biochar | Switch grass biochar |
|---|---|---|---|
| Specific surface area ($m^2$ $g^{-1}$) | 43.4 ± 2.5 | 52.1 ± 4.1 | 48.0 ± 2.6 |
| pH | 11.4 ± 0.10 | 5.82 ± 0.05 | 10.4 ± 0.12 |
| EC (µS $cm^{-1}$) | 3000 ± 60.6 | 200 ± 22.1 | 890 ± 20.5 |
| $CaCO_3$ content (g $kg^{-1}$) | 2.51 ± 0.05 | 0.30 ± 0.02 | 2.00 ± 0.05 |
| CEC (Cmol $kg^{-1}$) | 60.1 ± 4.6 | 34.2 ± 2.3 | 50.6 ± 2.1 |
| PZNC | 2.35 ± 0.64 | 1.92 ± 0.05 | 2.03 ± 0.88 |
| VOC (%) | 15.2 ± 1.1 | 10.33 ± 0.83 | 12.16 ± 1.82 |
| Ca (g $kg^{-1}$) | 7.51 ± 0.31 | 2.57 ± 0.03 | 7.12 ± 0.22 |
| Mg (g $kg^{-1}$) | 5.34 ± 0.72 | 0.62 ± 0.31 | 5.25 ± 0.11 |
| K (g $kg^{-1}$) | 21.4 ± 1.3 | 1.96 ± 0.04 | 2.70 ± 0.10 |
| Na (g $kg^{-1}$) | 0.69 ± 0.01 | 0.62 ± 0.03 | 0.67 ± 0.01 |
| Bicarbonate extractable P (mg $kg^{-1}$) | 10.2 ± 0.96 | 4.15 ± 0.11 | 6.41 ± 0.55 |
| Total P (g $kg^{-1}$) | 2.0 ± 0.14 | 0.36 ± 0.03 | 1.89 ± 0.05 |
| Total N (g $kg^{-1}$) | 12.3 ± 1.0 | 3.53 ± 0.63 | 16.4 ± 1.7 |
| Total C (g $kg^{-1}$) | 740 ± 23.4 | 833 ± 29.7 | 780 ± 19.5 |

convert insoluble forms of phosphorus into plant-available forms, thus improving phosphorus uptake by plants (Richardson and Simpson, 2011). By inoculating soils with PSB or using PSB-enriched amendments, such as biochar, farmers can potentially reduce their reliance on chemical phosphorus fertilizers while enhancing soil fertility and promoting sustainable agricultural practices. Phosphorus is a vital nutrient for plant growth and agricultural productivity, but its availability in soil can be limited, especially in acidic soils. Sustainable approaches to managing phosphorus, such as the use of phosphorus-solubilizing bacteria and phosphorus-enriched soil amendments like biochar, offer promising solutions to enhance phosphorus availability, improve crop yields and mitigate environmental impacts associated with conventional phosphorus fertilization practices (Bramarambika *et al.,* 2021).

Furthermore, increasing interest in enhancing phosphorus in acidic soils and the provision of ecosystem services, such as carbon sequestration in soil, has provided an attractive land management option for reducing the fixation of phosphorus using materials rich in carbon. Biochar, a carbonaceous solid derived from the pyrolysis (thermal decomposition of organic compounds at a relatively lower temperature (<700°C) under limited supply of oxygen) of agricultural and forest residual biomass, has gained significant importance in recent days as a soil amendment because of its potential benefits in carbon sequestration in soil (Lehmann, 2007). Biochar can be produced from various feed stock materials or waste, such as agricultural residues, manures, industrial wastes etc. providing an alternative option for waste management (Rohitha *et al.,* 2021).

### Biochar as a Soil Amendment

Biochar is a carbonaceous material produced through the pyrolysis of biomass under controlled conditions. Novak *et al.* (2009) studied on physical and chemical properties of different forms of biochar from peanut hulls, peacan shells, poultry litter and switch grass. They found higher pyrolysis temperatures resulted in lower biochar mass recovery, greater surface areas, elevated pH and higher ash contents. Bramarambika *et al.* (2021) also reviewed that biochar can potentially be used to reduce the bioavailability and leachability of heavy metals in soil. It has a large surface area, high capacity to adsorb heavy metals and is typically an alkaline material which can increase soil pH and contributes to stabilization of heavy metals in soil. Biochar application raises SOC, pH, EC, CEC and exchangeable bases (Nandini and Prakasha, 2022) and reduces exchangeable acidity and aluminum (Qian *et al*., 2013).

It is characterized by a high surface area, porosity, and stability in soil (Fasiha and Devakumar, 2022). Biochar has been widely studied as a soil amendment for improving soil fertility, enhancing nutrient retention and mitigating greenhouse gas emissions (Table 2). Vecstaudza *et al*. (2018) observed that incorporating biochar resulted in a substantial rise in $Ca^{2+}$ and $Mg^{2+}$ concentrations, as well as a decrease in $Al^{3+}$ concentrations, independent of the scale of the biochar particles and the existence. Across the presence of low (< 2 mm) biochar particle size, plant growth was stimulated. The peculiar characteristics of stable C rich biochar such as high surface area, lower charge per unit region, the frequency of specific functional surface groups and ash content have a beneficial impact on the chemical properties of soil.

When applied to acidic soils, biochar can modify soil pH, increase cation exchange capacity and alleviate aluminium and iron toxicity, thereby creating a more favourable environment for plant growth (Niranjan, 2018). Rodriguez *et al*. (2009) noted that, in a maize trial in Colombia, the biochar produced from sugarcane bagasse increased soil pH from 4.0-4.5 to 6.0-6.5. Biochar is found predominantly in soil organic matter (SOM) fractions that reside in small clusters of soil particles or soil aggregates, rather than as free organic matter. The application of biochar to soil has shown significant improvements in the supply of major cations and phosphorus as well as in overall amounts of nitrogen. Topoliantz *et al*. (2006) recorded increase of CEC up to 40 per cent of the original CEC and pH in one pH unit, respectively. Gunamantha and Widana (2018) showed that the organic carbon, usable P, ash and fixed carbon content of pig-manure biochar is higher than the biochar produced from cow manure, while total N, accessible K, CEC and volatile matter is lower. On its ash composition, the biochar derived from pig manure is dominated by $SiO_2$, $Al_2O_3$, $Fe_2O_3$, $P_2O_5$ and CaO whereas, the biochar derived from cow manure is dominated by $SiO_2$, CaO, $Al_2O_3$, $K_2O$ and $P_2O_5$. All biochar, though show potential for enhancing the soil quality and rising livestock manure carbon emissions. Additionally, biochar has the potential to adsorb and retain phosphorus (P), reducing its leaching and runoff. While biochar shows great promise as a soil amendment, it's important to note that more

**TABLE 2**

**Effect of Biochar on different soil properties (Bhinda *et al.*, 2022)**

| Parameter | Findings | Reference |
|---|---|---|
| Cation exchange capacity | 50% increase | Glaser *et al*., 2002 |
| Fertilizer use efficiency | 10-30% increase | Gaunt and Cowie, 2009 |
| Liming agent | 1 unit pH increase | Lehman and Rondon, 2006 |
| Biological nitrogen fixation | 50-72% increase | Lehman and Rondon, 2006 |
| Soil moisture retention | Up to 18% increase | Srinivasarao *et al*., 2012 |
| Bulk density | Soil dependent | Laird, 2008 |
| Methane emission | 100% decrease | Rondon *et al*., 2005 |
| Nitrous oxide emissions | 50% decrease | Yanai *et al*., 2007 |
| Mycorrhizal fungi | 40% increase | Warnock *et al*., 2007 |

research is needed to fully understand its long-term effects on different soil types and crops. It's also important to use biochar that is produced from sustainable sources.

**Phosphorus-Solubilizing Bacteria (PSB)**

Phosphorus-solubilizing bacteria (PSB) are microorganisms capable of solubilizing inorganic P in soil through various mechanisms, including the production of organic acids, enzymes and siderophores. By converting insoluble forms of P into plant-available forms, PSB play a crucial role in enhancing P uptake by plants and improving soil fertility. Several genera of bacteria, such as *Bacillus, Pseudomonas* and *Rhizobium* have been identified as effective PSB.

Phosphate solubilizing bacteria (PSB) are the main contributors of plant nutrition in agriculture and could play a pivotal role in making soluble phosphorus

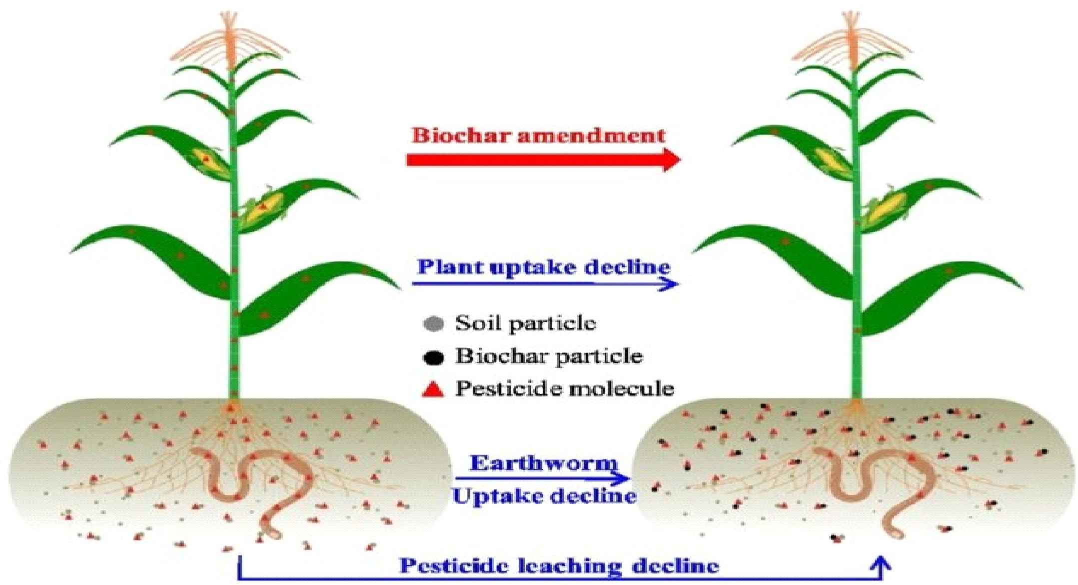


Fig. 1 : A schematic diagram of biochar amendment effects on the environmental behaviour of pesticides (*e.g.,* herbicides) in soil. *Source* : Khorram *et al*. (2016)

TABLE 3
**Production of organic acids by various phosphate solubilizers (Krishnamurthy, 1989 )**

| Organism | Predominant acids produced |
|---|---|
| *Escherichia freundii* | Lactic |
| *Aspergillus niger Pencillium* sp. | Citric, glycolic, succinic, gluconic, oxalic, lactic. |
| *Bacillus megaterium Pseudomonas* sp. *Bacillus subtilis* | Lactic, malic |
| *Bacillus megaterium* E. *freundii* | Citric, gluconic |
| *Arthrobacter* sp. *Bacillus* sp. *Bacillus firmus* B-7650 | Lactic, citric |
| *Aspergillus fumigatus Aspergillus candidus* | Oxalic, tartaric, citric, oxalic |
| *Pseudomonas aeruginosa* | Gluconic |
| *Pseudomonas striata* | Tartaric, citric |

available to plants (Khan *et al*., 2010). The principal mechanism in soil for solubilization of P is lowering of soil pH by microbial production of organic acids or the release of protons and mineralization by producing acid phosphatases (Tarafdar and Claasen, 1988) ultimately resulting in P availability in soil (Mohammadi and Sohrabi, 2012). The 2-keto-gluconic acid produced from direct oxidation of glucose by PSB play an important role in weathering and solubilization of phosphates in soil.

**Impact of Biochar on P Dynamics**

Biochar itself can influence P dynamics in several ways. Its porous structure acts as a reservoir for P, reducing leaching and keeping it available for plants. Biochar can also modify soil pH, potentially increasing the availability of bound P forms. However, the impact can vary depending on biochar properties like feedstock and pyrolysis temperature. Applying biochar along with chemical fertiliser treatment (BCF) greatly raised the soil's total and accessible P content. Additionally, when compared to CF treatment, BCF treatment dramatically reduced Fe/Al-Pi and residual P while increasing resin P, $NaHCO_3$-extracted P, Fe/Al-Po and HCl-extracted P. It was unexpected that the BCF treatment outperformed the CF treatment in terms of soil P sorption and release capacities. According to these findings, a two-year continuous application of biochar in the field may adsorb P through physical sorption as opposed to chemical reaction, improving P availability in the soil. (Wang *et al.,* 2021).

The transformation of P fractions can be influenced by some factors such as soil properties, type of P sources and rhizosphere processes (Negassa and Leinweber, 2009). The results of some studies showed that biochar application significantly changed P fractions in soil. Fe/Al-Pi is more labile than Ca-Pi but less available than resin-P for plants uptake (Hedley *et al*., 1994). Similar findings were also observed by Wang *et al*. (2021) who showed that biochar application can decrease the Fe/Al-Pi. This can be explained by two possible mechanisms: first, biochar particles in soil were enclosed by mineral fractions and the Fe3+ and Al3+ may be adsorbed by mineral fraction, which resulted in the presence of Fe and Al oxides and the trapped P was released (Chien *et al*., 2011); secondly, the Fe3+ and Al3+ in soil may be precipitated by the higher soil pH after biochar application (Murphy and Stevens, 2010).

**PSB: Unlocking Bound Phosphorus**

PSB are a group of beneficial soil bacteria that enhance P availability by secreting organic acids and

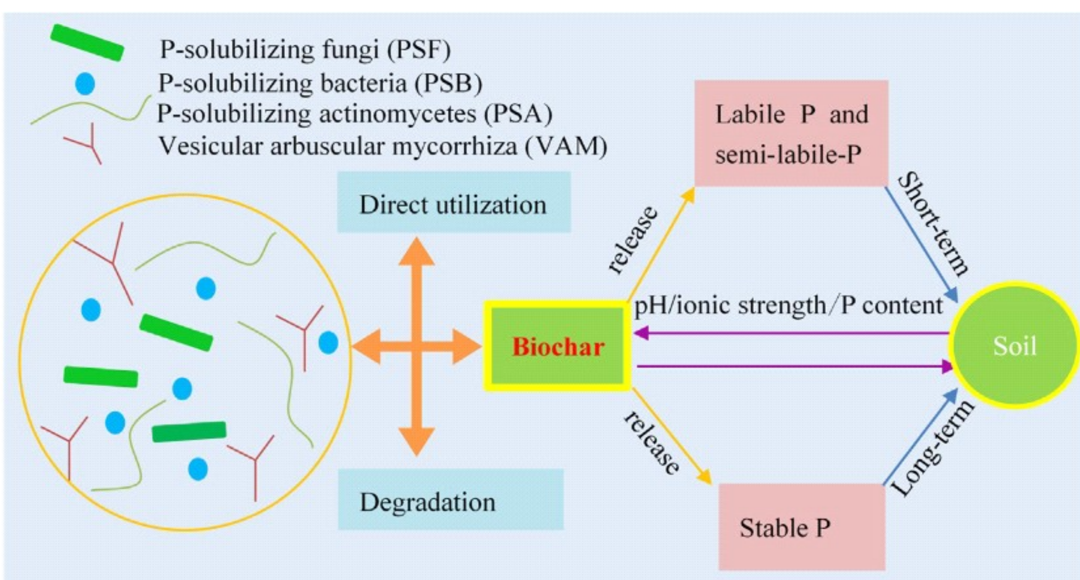


Fig. 2 : Processes of P release from biochar in soils and the fate of biochar P. (Li *et al.,* 2019)

TABLE 4

**Mechanisms at action in order to release phosphorus in acidic soils by PSB**

| | |
|---|---|
| Organic acid production | PSB produce organic acids (e.g., citric, malic, and gluconic acids) that can chelate soil minerals and solubilize bound P. |
| Enzymatic activity | PSB secrete phosphatases and phytases that hydrolyze organic P compounds, releasing inorganic P for plant uptake. |
| Siderophore production | PSB produce siderophores, which are iron-chelating compounds that can facilitate P solubilization by competing with soil minerals for iron. |

phosphatases. These enzymes convert insoluble P forms into plant-usable ones. Biochar provides a favourable habitat for PSB colonization and activity due to its high surface area and nutrient content. Phosphate-solubilizing bacteria, having the potential for phosphatase catalysis, can solubilize phosphate and serve as prospective supplier of soluble phosphorous for mangrove plants (Sundararaj *et al*., 1974).

The mechanism of mineral phosphate solubilization by PSB is associated with the secretion of organic acids such as gluconic, citric, acetic, malic, succinic and oxalic acid (Patel *et al.,* 2008 and Vyas & Gulati, 2009). These organic acids chelate the cations of Ca, Fe and Al bound to phosphates through their hydroxyl and carboxyl groups and convert the bound P into soluble forms. The efficacy of PSB for solubilizing phosphate depends on the amount and type of organic acids produced (Khan *et al.,* 2014). However, it is unknown whether production of one or multiple organic acids is a bacterial species-specific character or is regulated by the substrate availability. To release phosphate, the concentration of organic acids ranging from 10 to 100 mM was required in alkaline soils and citric acid was the most effective (Srivastava *et al.,* 2007). Gram negative PSB usually utilize a direct oxidation pathway to produce gluconic acid. This provides the acidification necessary to dissolve poorly soluble calcium phosphates such as tricalcium phosphate or hydroxyapatite (Sashidhar and Podile, 2010). Besides possessing P-solubilizing activity, PSB has greater potential to produce phytohormones, for example, indoleacetic acid and enzymes like phosphatase and phytases. The continuous supply of soluble P to soil P pool and phytohormones in the root environment have resulted in the increased P uptake and consequently improved the growth of crops (Othman and Panhwar, 2014). The bacterial phosphate solubilization process is mainly triggered by the secretions of organic acids, siderophores, exopolysaccharides and enzyme (phytase-phosphatase) activities. The bacterial metabolites either solubilize the inorganic forms of phosphorus or mobilize the organic sources of phosphorus through enhanced enzyme activities (Kishore *et al.,* 2015).

Different bacterial genera have been reported to have P-solubilizing capacity including strains from bacterial genera, *Acetobacter diazotrophic* (Maheshkumar *et al.,* 1999) and *Gluconacetobacter* sp. (Chung *et al.,* 2005). The ability to solubilize insoluble inorganic phosphate compounds by *G. diazotrophicus* was studied by Crespo *et al*. (2011), using different culture approaches. Qualitative plate assays using tricalcium phosphate as the sole P-source showed that *G. diazotrophicus* produced solubilization only when aldoses were used as the carbon source. Extracellular aldose oxidation *via.,* a pyrroloquinoline quinone-linked glucose dehydro genase (PQQ-GDH) is the main pathway for glucose metabolism in *G. diazotrophicus*.

Previously, Silva *et al*. (2007) have reported that strain 39PCAac1 as *Gluconobacter oxydans* sub sp. *oxydans* isolated from in red wine (Portugal) shows high ability to solubilize phosphate. Thermotolerant acetic acid producing *Acetobacter* and *Gluconobacter* have the direct oxidation pathway with thermotolerant glucose dehydrogenase (GDH) and solubilize mineral phosphate. The *Gluconobacter oxydans* sub sp. *industrius* strains have been shown to liberate phosphate from insoluble calcium phosphate by the produced gluconic acid (Paradh, 2015).

**PSB-Enriched Biochar: A Synergistic Approach**

The combination of biochar with PSB offers a synergistic approach to enhance P availability in acidic soils. PSB can colonize the porous structure of biochar and utilize its carbon substrate for growth and activity. In return, PSB enhance the solubilization of P within the biochar matrix, making it more accessible to plants. Moreover, biochar provides a stable habitat for PSB, protecting them from environmental stresses and extending their longevity in soil. Rafique *et al.* (2017) revealed that PSB inoculation, biochar incorporation and their combinations have positive effects on maize plant height and nutrient concentration on D45 and D65. In particular, plants treated with sawdust biochar + *Lysinibacillus fusiformis* strain inoculation increased N (32.8%), P (72.5%) and K (42.1%) against control. Application of PSB enriched biochar enhanced N (23.1%) and P (61.5%) than control which shows the significant interaction of PSB and biochar in nutrient uptake. PSB and biochar have the potential to be used as a promising amendment in improving plant growth and nutrient absorption besides the conventional approaches.

Biochar protects PSB from harsh soil conditions, while PSB enhance biochar's P adsorption capacity and unlock its bound P content. Studies have shown that PSB-enriched biochar can significantly increase plant-available P compared to biochar or PSB alone. Mousavi *et al.* (2022) reported that application of PSB enriched biochar altered the distribution and amount of inorganic P forms. PSB enriched biochar applied treatment increased the amount of $Ca_2$-P fraction in soil by 10 times. However, the amounts of $Ca_8$-P, Al-P and $Ca_{10}$-P fractions reduced significantly. Olsen P positively and significantly correlated with $Ca_2$-P, Fe-P and $Ca_{10}$-P fractions and suggesting that in the extraction of Olsen-P, phosphorus is released from these mineral fractions. The results showed that the use Enriched Biochar by PSB can provide long-term P supply to plants and had a better effect on increasing the availability of P in saline conditions.

**TABLE 5**

**Potential Applications of PSB enriched biochar**

| | |
|---|---|
| Improved Phosphorus Availability | Biochar, a carbon-rich material, benefits PSB and other helpful bacteria. This combo unlocks more plant-available phosphorus in soil. PSB thrive on biochar's high surface area, dissolving phosphorus through processes like acid production. The result: healthier plants with increased yields. |
| Enhanced Nutrient Use Efficiency | PSB-enriched biochar has the potential to improve plant nutrient uptake, especially phosphorus. This reduces reliance on chemical fertilizers, saving costs for farmers and protecting the environment from excess phosphorus pollution. |
| Soil Health Improvement | PSB in biochar boosts soil health by promoting beneficial microbes, nutrient cycling, and fighting pathogens. This leads to improved soil fertility, structure, and resilience. |
| Biofertilizer Production | Biochar can carry beneficial bacteria in fertilizers, improving their survival and boosting plant-available phosphorus. This offers a sustainable alternative to chemical fertilizers. |
| Remediation of Contaminated Soils | PSB-enriched biochar tackles two soil problems at once: nutrients and pollution. Biochar absorbs contaminants, making them less harmful, while PSB bacteria break them down or lock them in place. This double attack improves soil health. |

The combination of biochar with phosphorus-solubilizing bacteria (PSB) represents a promising approach to enhance phosphorus availability in acidic soils. PSB enriched biochar can improve soil fertility, promote plant growth and mitigate environmental concerns associated with conventional P fertilization practices. PSB-enriched biochar offers a sustainable solution for optimizing P dynamics in soil. This innovative technique combines the benefits of biochar and PSB to enhance plant-available phosphorus while minimizing environmental impact. Further research and development are essential to fully realize its potential for sustainable agriculture. Further, research is needed to optimize the formulation and application of PSB enriched biochar for specific soil and crop systems, as well as to assess its long-term effects on soil health and ecosystem sustainability.

**Future Directions**

Field-scale trials to validate laboratory findings. Developing application protocols for diverse soil and crop types and understanding the long-term interactions between PSB, biochar and soil biogeochemical processes and implication of biochar application on neutral/high pH soils are the issue for future.

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