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Effects of agromineral and biostimulant applications on nutrient uptake in corn (*Zea mays* L.)

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ABSTRACT

Sufficient nutrient availability is crucial for plant growth and reflects the ecological functions of soil. In modern agriculture, which emphasizes efficiency and sustainability, the interactions among soil, minerals, organic matter, and microorganisms play a key role in enhancing nutrient uptake by plants, including corn, which relies heavily on potassium, phosphor, and magnesium. Wet tropical soils are generally nutrient-poor due to leaching, necessitating approaches that integrate soil amendments with biological agents. Pyroclastic material, as a local source rich in primary minerals, has the potential to improve soil fertility depending on its weathering rate. The weathering process is accelerated by root exudates and soil microbial activity. Among functional microbes, potassium-solubilizing bacteria (PSB) play a crucial role by releasing the potassium from insoluble minerals through biochemical mechanisms, thereby enhancing nutrient use efficiency in corn. In addition, humic substances contribute to improving soil structure, increasing cation exchange capacity, and facilitating the release of micronutrients. This study aimed to evaluate nutrient uptake in corn plants following the application of pyroclastic material, humic substances, and potassium-solubilizing bacteria. The study was conducted in the greenhouse of DITSL, Faculty of Agriculture, IPB University, using a completely randomized design (CRD) with 24 treatment combinations. Pyroclastic material was applied at varying doses, while humic substances and PSB were applied at a constant base dose. The parameters observed included plant height, leaf number, stem diameter, plant biomass, and nutrient uptake. The results showed that the combination of a pyroclastic material (450 g) with humic substances and PSB produced the highest plant growth compared to other treatments. However, no significant differences were observed in leaf number and stem diameter. Nutrient concentration significantly affected the uptake of calcium, potassium, and magnesium.

Keywords: agromineral, biostimulant, nutrient uptake, corn, pyroclastic, humic substances, potassium-solubilizing bacteria.

INTRODUCTION

The availability of adequate nutrients in the soil is not only a key determinant of plant growth, but also reflects the ecological function of soil as an active biological system. In modern agriculture, which emphasizes input efficiency and sustainability, nutrient absorption by plants is closely linked to the complex interactions among soil, minerals, organic matter, and microorganisms. Corn (*Zea mays* L.), with its physiologically aggressive and efficient root system for nutrient uptake, is highly dependent on the availability of nutrients in forms accessible to the roots (Marschner, 2012). Under the soil conditions characterized by low mineral reactivity or limited nutrient storage capacity, the integrated approaches that combine soil amendments with biological agents are becoming increasingly important.

Wet tropical soils generally undergo intensive weathering due to high rainfall, which results in limited nutrient availability. To address this limitation, the use of mineral-rich local resources such as pyroclastic materials has been explored as an alternative for enhancing soil nutrient content. These materials contain amorphous minerals as well as primary minerals, such as feldspar and pyroxene, which are rich in alkaline elements (Fiantis et al., 2009). However, the agronomic potential of pyroclastic materials largely depends on their weathering processes in the soil. This weathering is influenced not only by physical and chemical factors, but also by soil microbial activity and plant root exudates, which can accelerate mineral dissolution (Uroz et al., 2009).

In the rhizosphere, plant roots release exudates, such as organic acids and phenolic compounds that enhance the mobilization of nutrients from soil minerals and organic matter. This process can be further supported by functional microorganisms, such as potassium-solubilizing bacteria (PSB). PSB act synergistically with plant roots to release potassium from insoluble minerals, such as feldspar and mica, through microacidification mechanisms involving the production of organic acids and the secretion of enzymes (Etesami et al., 2017). The application of PSB in the root zone has been shown to improve potassium use efficiency, reduce the dependence on conventional chemical fertilizers, and promote the formation of a more stable soil microstructure. This effect is particularly important for crops such as corn, which are highly sensitive to potassium availability, especially during the early vegetative stage and cob formation (Fageria, 2001).

Humic substances serve as a bridge between the chemical system of the soil and the plant's biological system. They improve soil structure and act as complexing agents that enhance mineral solubility and the availability of micronutrients (Tan, 2014). Studies have shown that the application of humic substances can also trigger physiological changes in plants, such as increased antioxidant enzyme activity and greater root hair density, which ultimately expand the absorption zone and improve nutrient uptake efficiency (Nardi et al., 2002). The combination of humic substances with microorganisms, such as PSB, exhibits additive and synergistic effects in enhancing nutrient bioavailability, particularly when applied alongside reactive mineral sources such as pyroclastic material.

The research on the effects of humic substances in stimulating plant growth has been carried out for a long time. In the early 19th century, humus was regarded as the primary soil fraction responsible for supplying nutrients to plants. Tan (2003) reported that humic substances enhance plant growth by accelerating respiration, increasing cell membrane permeability, and improving water and nutrient uptake. Consequently, humic substances are widely recognized for their potential use as fertilizers, soil conditioners, and plant growth stimulants. Hermawan (2012) stated that the application of humic substances can reduce the recommended fertilizer dosage. Humic substances are able to bind cations, thereby facilitating their absorption by plant roots and enhancing the exchange of micronutrients within the plant's vascular system. Although the exact transfer mechanism is not yet fully understood, soil experts suggest that as plants absorb water, humic substances carrying micronutrients move toward the root zone, where they can be taken up by plants (Konova, 1966).

The effects of the application of humic substances on plant growth and yield have been widely reported. Salman et al., (2005) reported that the application of humic substances enhanced both yield and fruit quality in watermelon. Humic substances are recognized as soil ameliorants that participate in complex reactions and influence soil fertility by modifying its physical, chemical, and biological properties. In soils, humic substances improve structure, stabilize aggregates, as well as enhance aeration and water retention. Chemically, they interact with metal ions through chelation, while biologically, they stimulate microbial activity, thereby promoting soil fertility. Hence, the application of humic substances is considered a potential alternative to conventional organic amendments.

Meanwhile, PSB are considered beneficial soil microorganisms because of their ability to solubilize potassium-bearing minerals through decomposition, mineralization, as well as nutrient storage and release mechanisms (Parmar and Sindhu, 2013). Potassium solubilization by PSB occurs through several mechanisms, including the production of organic acids and polysaccharides, the formation of ionic complexes, and ion exchange reactions in the soil (Etesami et al., 2015). These bacteria are commonly found in the rhizosphere of plants, under both aerobic and anaerobic conditions (Meena et al., 2016a). Verma et al., (2017) successfully isolated seven PSB strains from different regions in India, three of which were shown to enhance legume crop yields.

Several PSB have been successfully identified, including *Bacillus mucilaginosus*, *Bacillus edaphicus*, and *Bacillus circulans* (Parmar and Sindhu, 2013; Meena et al., 2016a). In addition, a wide range of other bacterial species have been reported to possess potassium-solubilizing capabilities, such as *Burkholderia cepacia*, *Delftia acidovorans*, *Paenibacillus macerans*, *Pantoea agglomerans*, and several members of the *Pseudomonas* genus, including *P. aureofaciens*, *P. chlororaphis*, *P. fluorescens*, *P. solanacearum*, and *P. syringae*. The genus *Bacillus* also encompasses other species with similar traits, such as *B. pumilus*, *B. subtilis*, *B. amyloliquefaciens*, *B. fimus*, *B. licheniformis*, and *B. megaterium*. Furthermore, additional PSB include *Agrobacterium radiobacter*, *Azospirillum brasilense*, *A. lipoferum*, *Azotobacter chroococcum*, *Serratia entomophilia*, and members of the genus *Streptomyces*, such as *S. griseoviridis* and *S. lydicus* (Glick, 2012).

An agronomic approach that integrates local resources (pyroclastic material), active organic matter (humic substances), and nutrient-solubilizing microbes (PSB) offers new opportunities to increase corn productivity without adding to the environmental burden of synthetic inputs. However, there is still a lack of systematic studies evaluating the combined effects of these three inputs on actual nutrient uptake in corn, particularly in relation to the nutrient dynamics within the rhizosphere. Therefore, this study was conducted to comprehensively assess how the interactions among pyroclastic material, humic substances, and PSB influence nutrient accumulation in corn tissues. The findings are expected to provide a scientific basis for designing adaptive fertilization systems tailored to local agroecosystems, thereby supporting more efficient and sustainable agricultural practices.

The interaction among pyroclastic material, humic substances, and PSB represents an important research focus, as these three inputs have synergistic potential to improve soil quality and support plant growth. Pyroclastic material supplies essential minerals, humic substances enhance nutrient use efficiency, and PSB increase potassium availability. The combination of these inputs is expected to provide an integrated solution for improving crop productivity, particularly on marginal lands. Therefore, the objective of this study was to investigate the interactions among the pyroclastic material, humic substances, and PSB in relation to plant growth. The findings are expected to contribute to the development of sustainable agricultural technologies that enhance crop productivity while preserving the environment.

MATERIAL AND METHODS

This research was conducted from May to November 2024. The pyroclastic material was collected from Mount Merapi, Yogyakarta, at sampling points located at 7°32′5″ S and 110°26′5″ E. Soil samples were collected from Mamunyu Village, Mamuju District, Mamuju Regency, West Sulawesi, at sampling points located at 2°42′03″ S and 118°55′28.1″ E. The incubation and cultivation of corn were carried out in the Greenhouse of the Department of Soil Science and Land Resources, Faculty of Agriculture, IPB University. The nutrient uptake analysis was conducted in the Laboratory of the Department of Soil Science and Land Resources, Faculty of Agriculture, IPB University.

The tools used in this study included pots, measuring tapes, calipers, rulers, buckets, dippers, writing instruments, documentation equipment, and other supporting tools. The materials used consisted of soil, pyroclastic material, humic substances, potassium-solubilizing bacteria, hybrid corn seeds, NPK fertilizer as base fertilizer, and other supporting materials.

Experimental procedures and stages

1. Soil sampling was carried out by collecting topsoil at a depth of 0–30 cm. The soil was then air-dried, crushed, and sieved through a 2 mm mesh to obtain a uniform particle size.
2. Pyroclastic sand samples were collected from the top layer at a depth of 0–10 cm. The samples were then air-dried and ground to a fine texture that passed through a 0.5 mm sieve.
3. The greenhouse experiment began with a three-month incubation period, followed by the planting of corn.
4. This study consisted of 24 treatment combinations with pyroclastic doses of 0 (control), 4, 8, 16, 30, and 60 tons per hectare, which were equivalent to 0, 28.125 g, 56.25 g, 112.5 g, 225 g, and 450 g per 4.5 kg pot, respectively. Each treatment was replicated three times,

resulting in a total of 72 experimental units, as presented in Table 1. The reference dose of humic substances was 80 L/ha with a humic content of 36%; therefore, for a humic content of 20%, it was equivalent to 0.325 g/4.5 kg of soil sample. The dose of potassium-solubilizing bacteria was 3.6 mL/sample based on previous research (Mutmainnah, 2018). The potassium solubilizing bacteria used was Bacillus mucilaginosus, obtained from the Soil Biology Laboratory collection of Jember University, with isolate code PSB 05, at a rate of 1.2 mL per sample.

5. The experiment was arranged in a completely randomized design (CRD).
6. The parameters observed included plant height, stem diameter, and number of leaves, which were measured regularly until the plants were 1.5 months old (6 WAP). After harvest, the biomass of the corn plants was analyzed.
7. The plant tissue analysis was carried out to determine the level of nutrient uptake. The analysis was performed using the wet digestion method with HNO_3 and $HClO_4$. Silicon (Si) was specifically analyzed using the gravimetric method.
8. The effects of the pyroclastic material, humic substances, and PSB on corn growth and nutrient uptake were analyzed using one-way analysis of variance (ANOVA). Significant differences among treatments were further evaluated using Tukey's honestly significant difference (HSD) test.

RESULTS AND DISCUSSION

Calcium nutrient uptake concentration

Calcium (Ca) is one of the macronutrients essential for plant growth and development. Its role has been widely studied, particularly regarding its function as a critical nutrient for plants. Calcium is required to support physiological processes, especially in leafy vegetables (Aryandhita and Kastono, 2021; Abror et al., 2023). In plants, calcium regulates cell permeability, maintains the stability and function of membranes, as well as controls ion transport and exchange (Abror et al., 2023). It also promotes meristematic cell division, facilitates nitrate assimilation, and regulates enzymatic activity, all of which positively influence plant growth. However, calcium deficiency often arises due to its uneven distribution, as calcium is immobile and cannot be translocated from older to younger tissues (Yuwono, 2009). Such deficiencies can reduce crop quality and economic value, leading to disrupted shoot development, stunted growth, and the occurrence of tip burn symptoms, which are commonly observed in many crops.

The results showed that the addition of pyroclastic material, either alone or in combination with humic substances and PSB, significantly increased the calcium (Ca) uptake by plants (Figure 1a). The application of a pyroclastic material (S+P) led to a dose-dependent increase in Ca uptake, with the highest value observed at 450 g, reaching approximately 0.65% ppm, compared to the control (soil only), which was around 0.25%. This indicates that the pyroclastic material provides a readily available source of Ca through mineral weathering. Pyroclastic deposits are known to be rich in silicate minerals such as plagioclase and pyroxene, which contain Ca and are easily weathered, particularly under humid and warm tropical conditions (Fiantis et al., 2010). The release of base cations such as Ca through pyroclastic weathering has been reported as one of the key factors determining the productivity of young volcanic soils (Shoji and Takahashi, 2002; Shoji et al., 1993).

The addition of humic substances to pyroclastic treatment (S+H+P) did not always result in a linear increase in Ca uptake. The highest value was observed at a dose of 150 g (0.25%), followed by a decrease at 450 g (Figure 1b). Humic substances are known to chelate nutrients, such as Ca^{2+}, thereby enhancing solubility but also forming organic complexes that are slow to mobilize (Stevenson, 1994; Tan, 2014; Gerke, 2018).

The combination treatment of the pyroclastic material with potassium-solubilizing bacteria (S+PSB+P) resulted in a significant and consistent increase in Ca uptake with increasing doses of the pyroclastic material. The highest uptake was recorded at a dose of 450 g (0.60%) (Figure 1c), which was comparable to the maximum value obtained with the pyroclastic material alone. Potassium-solubilizing bacteria play a key role in dissolving silicate minerals through the exudation of organic acids such as citric and gluconic acids, which accelerate the weathering of primary minerals and release Ca bound within the crystal structure (Sheng and He, 2006). In addition, the presence of potassium-solubilizing bacteria

Table 1. Treatments applied to corn plants in the greenhouse experiment

Code	Description
P1	Soil
P2	Soil + Pyroclastic 28.125 g
P3	Soil + Pyroclastic 56.25 g
P4	Soil + Pyroclastic 112.5 g
P5	Soil + Pyroclastic 225 g
P6	Soil + Pyroclastic 450 g
P7	Soil + Humic substences
P8	Soil + PSB
P9	Soil + Humic substences + pyroclastic 28.125 g
P10	Soil + Humic substences + pyroclastic 56.25 g
P11	Soil + Humic substences + pyroclastic 112.5 g
P12	Soil + Humic substences + pyroclastic 225 g
P13	Soil + Humic substences + pyroclastic 450 g
P14	Soil + PSB + pyroclastic 28.125 g
P15	Soil + PSB + pyroclastic 56.25 g
P16	Soil + PSB + pyroclastic 112.5 g
P17	Soil + PSB + pyroclastic 225 g
P18	Soil + PSB + pyroclastic 450 g
P19	Soil + Humic substences + PSB
P20	Soil + Humic substences + PSB + pyroclastic 28.125 g
P21	Soil + Humic substences + PSB + pyroclastic 56.25 g
P22	Soil + Humic substences + PSB + pyroclastic 112.5 g
P23	Soil + Humic substences + PSB + pyroclastic 225 g
P24	Soil + Humic substences + PSB + pyroclastic 450 g

Note: PSB – potassium solubilizing bacteria.

enhances soil microbiological activity, further supporting nutrient mobilization.

The complete combination treatment (S+H+PSB+P) did not show better results compared to the combination without humic substances. The highest Ca uptake was only around 0.52% (Figure 1d). This may be attributed to the interaction between humic substances and microbial activity, which could lead to the formation of complex compounds that reduce the effectiveness of PSB in mineral dissolution or, conversely, inhibit Ca bioavailability. Canellas and Olivares (2014) reported that humic substances can exert ambiguous effects on soil microorganisms, depending on its concentration and environmental conditions. At high doses or under specific conditions, humic substances may inhibit microbial respiration and decrease mineral dissolution activity.

When comparing treatments, it was evident that the single pyroclastic treatment (S+P) and the pyroclastic + PSB treatment (S+PSB+P) produced the highest Ca uptake. In contrast, treatments with the addition of humic substances, either alone (S+H+P) or in combination with PSB (S+H+PSB+P), resulted in lower and more variable values. These findings indicate that the pyroclastic material derived from volcanic eruptions has considerable potential as a natural calcium source for soil management. The integration of the pyroclastic material with PSB provided optimal outcomes by accelerating mineral weathering and enhancing the release of calcium in plant-available forms. However, the application of humic substances requires careful dose management, as its effect on nutrient uptake is influenced by complex interactions between organic matter and the soil biological system. Overall, the combination of a pyroclastic material and PSB can be recommended as an ecological strategy to improve soil fertility, particularly in acidic and nutrient-poor volcanic soils.

Potassium nutrient uptake concentration

Potassium plays a crucial role in sugar and starch formation, sugar translocation, enzyme activation, and stomatal regulation. In sweet corn, potassium application has been shown to increase cob weight and enhance sweetness. As an essential macronutrient, potassium also stimulates the translocation of carbohydrates from leaves to other plant organs. According to Mengel and Kirkby (2001), the movement of photosynthates to tomato fruits is significantly influenced by potassium availability. Furthermore, potassium enhances the transport of photosynthetic products from leaves to roots, thereby increasing the energy supply required for root growth as well as for the development of fruit size and quality.

The addition of the pyroclastic material to the soil (S+P) increased potassium uptake, with the highest value observed at a dose of 28.125 g (0.24%) compared to the soil control (0.18%) (Figure 2a). However, increasing the dose beyond 28.125 g resulted in a decline in potassium uptake, with values decreasing to around 0.19% at a dose of 450 g. This finding suggests that while the pyroclastic material contains available potassium, higher application rates may lead to nutrient antagonism, competition with other cations (e.g., Ca^{2+}, Mg^{2+}), or binding to soil particles that

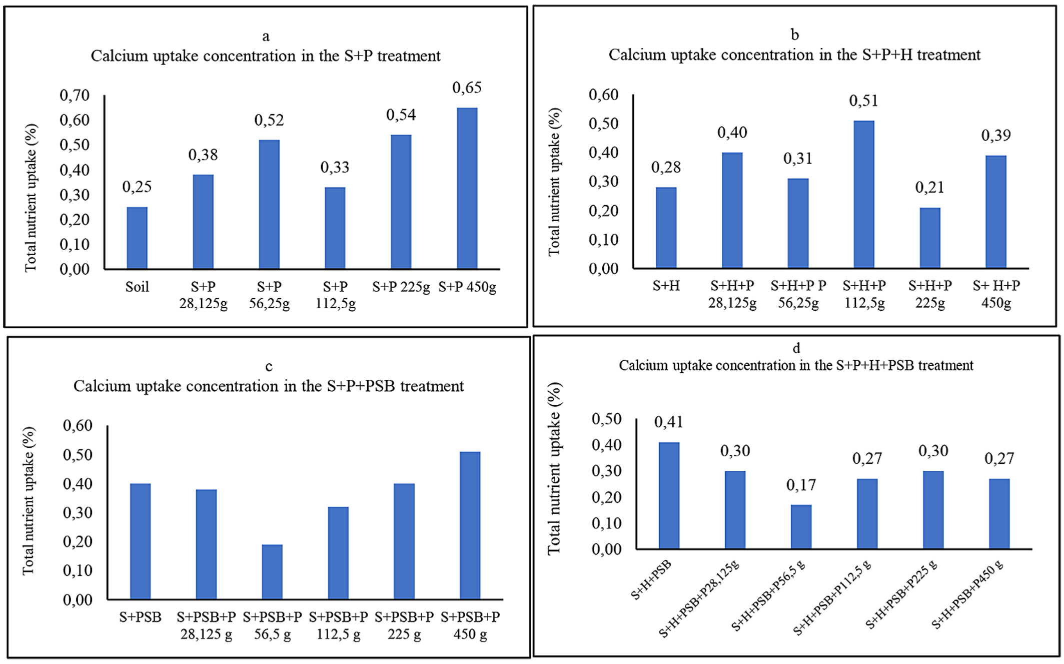

Figure 1. Total calcium uptake in corn plants across different treatment groups: S – soil; P – pyroclastic; H – humic substances; PSB – potassium solubilizing bacteria

reduce potassium solubility. According to Sparks (2003), potassium availability can be limited by retention on the surfaces of soil minerals, particularly secondary minerals, where it may become trapped within amorphous mineral structures.

The S+H+P treatment resulted in a more stable increase in potassium uptake compared to the treatment without humic substances (Figure 2b). The highest value was obtained at a dose of 450 g (0.25%), which was greater than all other doses. This indicates that the addition of humic substances can enhance potassium solubility and mobility through the formation of organic complexes and by increasing the cation exchange capacity of soil. Humic substances act as binding agents that improve soil biological activity while preventing potassium fixation by soil particles (Tan, 2014). In addition, organic matter improves soil moisture retention and provides additional cation exchange sites, thereby supporting potassium uptake by plant roots (Canellas and Olivares, 2014).

The combined treatment of the pyroclastic material and potassium-solubilizing bacteria (S+PSB+P) showed a different pattern compared to the previous treatments (Figure 2c). The highest potassium uptake occurred at a low dose (28.125 g) but declined sharply at the highest dose (450 g), reaching only 0.10%, suggesting a possible inhibitory effect. This indicates that under certain combinations, PSB activity may be disrupted by the accumulation of ions from high pyroclastic doses or by unfavorable environmental conditions, such as increased salinity or changes in pH. At higher doses, insoluble potassium accumulation that cannot be mobilized by microbes or potassium fixation by soil particles may also occur. PSB mobilizes potassium by producing organic acids (e.g., citric and gluconic acids) that dissolve potassium from silicate minerals (Sheng and He, 2006); however, this activity can be inhibited in ion-saturated environments or when the carbon-to-nutrient ratio is imbalanced.

The complete combined treatment (S+H+PSB+P) showed a stable upward trend, with the highest potassium uptake observed at a dose of 450 g (0.12%) (Figure 2d). Although this value was lower than the treatment without PSB, it demonstrates that the synergy between humic substances and PSB can help maintain stable potassium uptake across different pyroclastic doses. Humic substances support microbial growth and sustains the bioactivity of PSB, thereby enabling continuous potassium dissolution even under the high ionic conditions associated with pyroclastic material. According to Nardi et al., (2002), compounds of humic substances can enhance the expression of microbial genes involved in phosphate and potassium solubilization.

The S+H+P treatment provided the highest potassium uptake, indicating that the synergy between

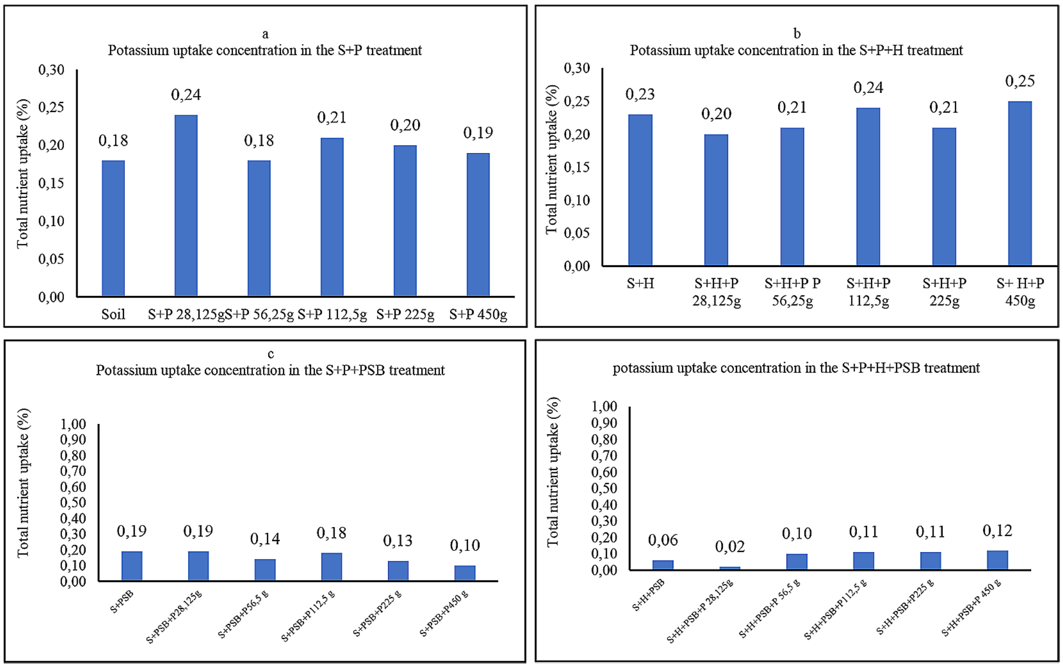

Figure 2. Total potassium uptake in corn plants across different treatment groups: S – soil; P – pyroclastic; H – humic substances; PSB – potassium solubilizing bacteria

humic substances and pyroclastic material was the most effective in enhancing potassium absorption. In contrast, the combination of high pyroclastic doses with PSB alone is not recommended, as it drastically reduced potassium uptake. The pyroclastic material can serve as an alternative natural source of potassium, particularly in tropical soils that are inherently potassium deficient. However, its application must be carefully adjusted to the optimal dose, since excessive amounts may reduce its effectiveness. Integration with humic substances has been shown to improve the effectiveness of the pyroclastic material as a potassium source by enhancing soil structure and nutrient availability. Conversely, combining pyroclastic material with PSB alone requires careful management, as high ionic conditions may inhibit the activity of potassium solubilizing microbes. The most effective strategy for optimizing potassium uptake is the combination of the pyroclastic material with humic substances, while the use of PSB should be tailored to soil conditions and applied at pyroclastic doses that are not excessively high.

The findings imply that volcanic materials, such as pyroclastic rock, can be sustainably utilized to improve the fertility of tropical acidic soils, particularly when combined with organic amendments such as humic substances and biological agents like potassium-solubilizing bacteria. This integrated approach supports sustainable agriculture by reducing dependence on inorganic fertilizers. Although it may not completely replace their use, it can substantially minimize the reliance on synthetic inputs.

Magnesium nutrient uptake concentration

Magnesium (Mg) is a secondary macronutrient essential for plants, serving as the central atom in chlorophyll and acting as a co-factor in numerous enzymatic processes, including photosynthesis, cell and protein formation, starch synthesis, energy transfer, and the regulation of carbohydrate partitioning throughout plant tissues. According to Quideau et al., (1999), soil Mg enhances the uptake of nutrients from both organic matter and added fertilizers, maintains the availability of micronutrients, as well as improves soil porosity, structure, and aeration, thereby benefiting soil microbiology and chemistry. These improvements create a friable soil environment that facilitates root growth and nutrient absorption. In this study, the pyroclastic treatment without additional amendments significantly increased Mg uptake compared to the control soil (Figure 3a). Uptake consistently increased with the application rate, reaching its highest value at 450 g, indicating that pyroclastic material provides Mg in plant-available forms. Volcanic pyroclastics are rich in primary minerals such as olivine, pyroxene, and plagioclase, which gradually weather and release Mg into the soil (Fiantis et al., 2010; Shoji et al., 1993).

The addition of humic substances produced variable effects depending on the pyroclastic dose (Figure 3b). The highest Mg uptake was observed at the lowest dose (T+H+P 28.125 g) and again at the highest dose (450 g), whereas intermediate doses (75 g and 150 g) resulted in reduced uptake. This pattern suggests that humic substances contributes to Mg mobilization, but its effectiveness is strongly influenced by the interaction between organic and mineral components. Humic substances enhance soil structure and increases the cation exchange capacity (CEC), thereby improving Mg availability. However, at intermediate pyroclastic doses, the formation of organo-mineral complexes may immobilize Mg and limit its uptake (Stevenson, 1994).

The combination of pyroclastic material and PSB showed considerable variation in Mg uptake (Figure 3c). The highest uptake was recorded in the treatment without pyroclastic addition (S+PSB) and at the moderate dose of 112.5 g (S+PSB+P), whereas a sharp decline occurred at the highest dose of 450 g. This suggests that the nutrient-releasing activity of PSB through organic acid exudates is impaired under high ionic conditions associated with large additions of the pyroclastic material. Moreover, potassium-solubilizing bacteria do not directly solubilize Mg, making their effectiveness on Mg availability lower than that of humic substances. According to Sheng and He (2006), the release of Mg from silicate minerals is more effectively facilitated by specific microorganisms such as Penicillium or Aspergillus, rather than by PSB.

The combined treatment of the three components (S+H+PSB+P, 450 g) resulted in the highest Mg uptake, surpassing all other treatments (Figure 3d). This finding suggests a synergistic interaction among the three components under high pyroclastic doses. Humic substances enhances cation exchange capacity and improves Mg solubility, while PSB contributes to maintaining favorable soil microbiological conditions that facilitate pyroclastic mineral weathering, even though it does not directly solubilize Mg. At high doses, pyroclastic material provides an abundant source of Mg, which, in combination with humic substances and microbial activity, optimizes its availability for plant uptake.

A pyroclastic material is a potential source of Mg, and its release can be optimized by the addition of humic substances and mineral-solubilizing microbes. The use of humic substances is particularly important in enhancing the efficiency of pyroclastic material through their role in mobilizing

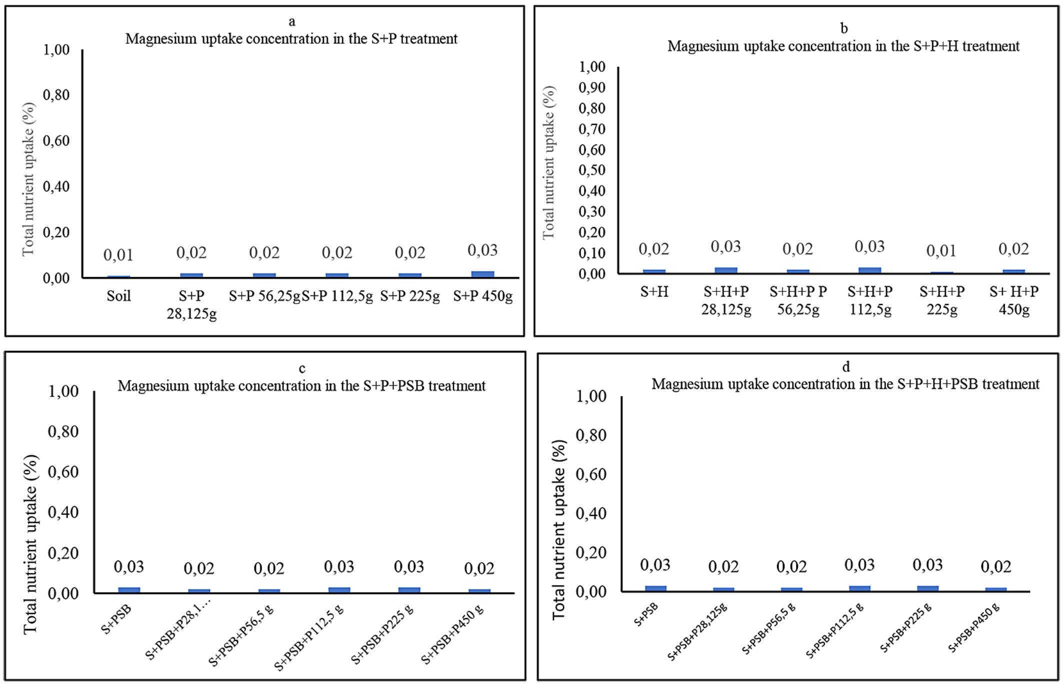

Figure 3. Total magnesium uptake in corn plants across different treatment groups: S – soil; P – pyroclastic; H – humic substances; PSB – potassium solubilizing bacteria

nutrient ions. Although potassium-solubilizing bacteria are not sufficiently effective in solubilizing Mg, they can facilitate the release of other nutrients (e.g., potassium), making their synergy with humic substances and the pyroclastic material beneficial. However, excessively high doses of the pyroclastic material may disrupt microbial activity; therefore, dose optimization is essential to ensure sustainable land productivity.

Plant biomass of corn

Figure 4 shows that the average weight of corn plants increased in all treatments with ameliorants compared to the control (untreated soil). Corn plants grown in untreated soil had an average weight of only 12.86 g, whereas the other treatments ranged from 14.78 g to 15.86 g.

A significant increase in plant weight was first observed in the pyroclastic treatment, with an average weight of 15.22 g, representing an 18.35% increase compared to the control. This finding indicates that the addition of the pyroclastic material can enhance the physical and chemical properties of the soil. The pyroclastic material contains primary and amorphous minerals that are rich in nutrients such as potassium, calcium, magnesium, and several microelements. The presence of amorphous minerals, such as volcanic glass, also accelerates weathering and the release of essential nutrients (Parfitt et al., 1983; Wada, 1990; Shoji and Takahashi, 2002; Kuznetsova and Motenko, 2014). Moreover, the porous structure of pyroclastic material improves soil aeration and water-holding capacity, further supporting plant growth.

Furthermore, the addition of humic substances material to pyroclastic increased plant weight to 15.72 g. Humic substances function as natural chelating agents that enhance the availability of micronutrients and improve soil aggregate structure (Muscolo et al., 2013). In addition, humic substances can increase soil microbial activity and stimulate root growth, leading to improved nutrient absorption (Canellas et al., 2002; Canellas and Olivares, 2014). Thus, the combination of pyroclastic material and humic substances creates a synergistic effect between soil chemical improvement and biological activity

The treatment with the pyroclastic material and PSO resulted in the highest plant weight, reaching 15.86 g, which represents a 23.25% increase compared to the control. This finding confirms that KSOs play a crucial role in enhancing potassium availability through the dissolution of potassium-bearing silicate minerals, both amorphous and crystalline. Strains such as *Bacillus mucilaginosus* and *Paenibacillus* sp. are capable of producing organic acids, including citric, oxalic, and gluconic acids, which lower the microenvironmental pH and facilitate the release of potassium from minerals (Lian et al., 2008; Parmar and Sindhu, 2013). Potassium is essential for osmotic regulation, stomatal function, and the translocation of photosynthetic products, all of which contribute directly to increased plant biomass.

However, the combination of pyroclastic material, humic substances, and PSB resulted in a

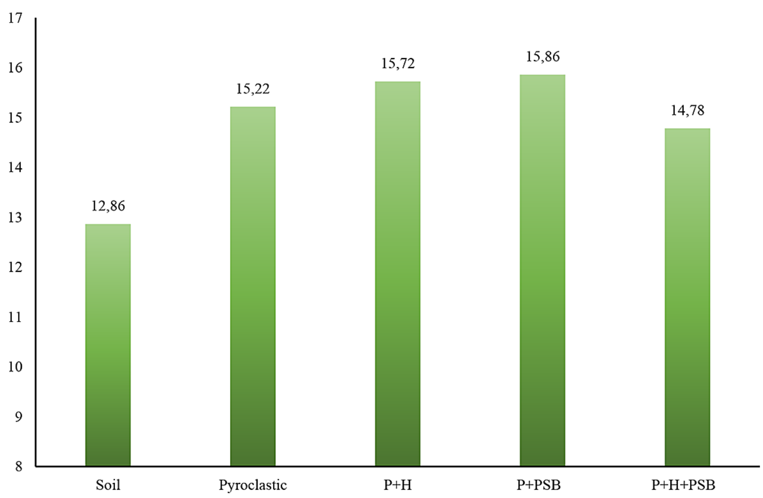

Figure 4. Average weight of corn plants under each treatment: S – soil; P – pyroclastic; H – humic substances; PSB – potassium solubilizing bacteria

lower plant weight (14.78 g) compared to the two-component treatments (pyroclastic + humic substances or pyroclastic + PSB). This outcome may be attributed to antagonistic interactions between humic substances compounds and microbial activity. Complex organic molecules in humic substances can alter pH balance or bind metal ions in forms unavailable to microbes, thereby reducing the effectiveness of PSB (Arancon et al., 2006). Furthermore, excessively high concentrations of humic substances may become phytotoxic or inhibit microbial colonization in the rhizosphere (Canellas et al., 2015)

Overall, these results suggest that volcanic materials (pyroclastic) combined with biological agents such as PSB can serve as an effective strategy to enhance plant productivity in suboptimal soils. However, interactions among ameliorants must be carefully considered, as competition or antagonism within the soil–rhizosphere system may reduce their effectiveness.

CONCLUSIONS

On the basis of the results and discussion regarding the nutrient uptake in corn plants, the following conclusions can be drawn:

1. A pyroclastic material effectively increases nutrient uptake concentrations (calcium, potassium, magnesium), particularly when combined with humic substances acid and PSB. However, its effectiveness depends on the type of nutrient, dosage, and the interactions among the components.
2. The highest Ca uptake was recorded in the 450 g T+P treatment (0.65%), the highest Potassium uptake in the 450 g T+H+P treatment (0.26%), and the highest Mg uptake in the 450 g T+P treatment.

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