Soil Physio-chemical Behaviour in Response to Phosphorus and PSB Application in Mustard Fields under Gmelina Agroforestry

Abstract

This study examines how soil qualities are affected by phosphorus (P) levels and phosphate solubilising bacteria (PSB) inoculation techniques in an agroforestry system based on Gmelina arborea, with a particular emphasis on mustard (Brassica juncea L.) growing. The experiment, which was carried out at JNKVV in Jabalpur, used a split-plot design with PSB application techniques (soil, seedling, and combination) as sub-treatments and phosphorus levels (30, 40, and 50 kg/ha) as the primary treatments. According to preliminary soil analyses, the pH was 6.32, the organic carbon content was 0.57%, and the phosphorus content was 16.84 kg/ha. The findings showed that PSB inoculation further increased phosphorus availability (pooled maximum: 19.16 kg/ha with combined soil and seedling inoculation), even though phosphorus levels considerably improved accessible phosphorus content (pooled maximum: 18.94 kg/ha at 50 kg P/ha). Bulk density, water-holding capacity, and electrical conductivity were among the other soil characteristics that varied very little. The findings underscore the potential of integrated P and PSB management to enhance soil nutrient availability, particularly phosphorus, within tropical agroforestry systems, promoting sustainable agriculture practices.

Keywords: Nutrient Use Efficiency, Agroecological Practices, Sustainable Agriculture, Phosphorus solubilizing bacteria, Soil nutrient dynamics

1. Introduction

Agroforestry systems are increasingly recognized for their ability to improve soil fertility, biodiversity, and ecosystem sustainability. Among them, Gmelina arborea-based agroforestry is notable for enhancing soil health and crop productivity. Integrating mustard (Brassica juncea L.) as an intercrop benefit both oilseed production and soil fertility through nutrient cycling, but success depends on understanding soil nutrient dynamics, particularly phosphorus (P) and bio-fertilizers like phosphate solubilizing bacteria (PSB) (Nair, 1993).

Phosphorus is vital for plant growth, influencing root development and energy transfer, but its availability is limited in many tropical soils due to fixation in insoluble forms (Hinsinger, 2001). Conventional P fertilization often leads to inefficiencies, with much of the phosphorus becoming chemically bound and inaccessible to plants (Gyaneshwar *et al*., 2002). This inefficiency and environmental concerns like eutrophication highlight the need for sustainable alternatives, such as PSB, which solubilize insoluble phosphorus, enhancing its availability for plant uptake. The limitations of traditional phosphorus fertilization, coupled with environmental concerns like leaching and eutrophication, underscore the need for more sustainable nutrient management strategies (Reddy *et al*., 2002).

PSB's role in improving phosphorus bioavailability is crucial in agroforestry systems where soil nutrient competition between trees and crops is common. PSB not only promotes phosphorus solubilization but also influences soil properties such as pH, organic matter content, and microbial activity, enhancing nutrient retention and cycling (Whitelaw, 2000; Vessey, 2003). The combination of phosphorus fertilization and PSB in Gmelina agroforestry systems can improve physio-chemical soil properties like pH, organic carbon, and cation exchange capacity (CEC), promoting sustainable agriculture by reducing chemical input reliance (Khan *et al*., 2007). Understanding these interactions is critical for optimizing nutrient management in agroforestry systems. In particular, Gmelina arborea known for its fast-growing nature and adaptability can improve soil structure and nutrient cycling (Montagnini & Nair, 2004).

In Gmelina-based systems, phosphorus management is critical for maintaining productivity, particularly in tropical soils where P mobility is restricted (Richardson et al., 2009). While chemical fertilizers are commonly used, their inefficiency and environmental impact (e.g., phosphorus runoff leading to eutrophication) suggest the need for integrating PSB into nutrient strategies to enhance P solubilization and plant growth (Schroder et al., 2011; Sharma et al., 2013).

PSB also enhances CEC, organic matter accumulation, and microbial activity, improving soil nutrient retention and reducing competition between tree and crop roots (Brady & Weil, 2008; Singh & Reddy, 2011). Additionally, PSBs release enzymes that break down organic phosphorus compounds, contributing to nutrient cycling and benefiting mustard and Gmelina (Malik et al., 2013; Zaidi et al., 2009). PSB inoculation can also improve soil structure, texture, and water-holding capacity, promoting better root penetration and reducing erosion (Lal, 2004).

In conclusion, phosphorus fertilization combined with PSB inoculation enhances mustard cultivation while supporting the sustainability of Gmelina agroforestry systems. This integrated approach reduces chemical inputs, improves soil health, and aligns with global goals of sustainable agriculture and food security (Tilman et al., 2011).

This study aims to evaluate the effects of phosphorus and PSB on soil properties in mustard cultivation within Gmelina agroforestry systems, focusing on soil pH, organic carbon, CEC, and microbial activity to optimize nutrient management and enhance productivity in tropical agroforestry systems.

2. Materials and methods

Study site: The experiment was conducted in the Gmelina arborea based agroforestry system at the Research Farm, Department of Forestry, College of Agriculture, Jawaharlal Nehru Krishi Vishwa Vidyalaya, Jabalpur, Madhya Pradesh. The experimental site is situated at an altitude of 391 meters above sea level. The location of the area is at a latitude of 23o 12' 50" north and a longitude of 79o 57' 56" east in the Kymore Plateau and Satpura Hill agroclimatic zones of Madhya Pradesh. The climate is defined by extremely hot and dry summers, with an average highest temperature of 46°C and extremely cold and dry winters, with an average lowest temperature of 4°C. Jabalpur receives an average annual precipitation of 1350 mm. The region is famous for its high relative humidity levels, which reach 80 to 90% during the rainy season, 60 to 75% during the summer and 20 to 23% during the winter.

The experiment employed a split plot design, with Phosphorus levels (P_{30} = 30 kg/ha, P_{40} = 40 kg/ha and P_{50} = 50 kg/ha) as main plot treatment, PSB inoculation methods namely P1 = Soil application, P2 = Seedling application and P3 = Soil and seedling application as sub-plot treatments. The experiment consisted of using 12 distinct treatment combinations (P30P1, P30P2, P30P3, P30P4, P40P1, P40P2, P40P3, P40P4, P50P1, P50P2, P50P3, P50P4). The treatments were allocated randomly into three distinct replications.

Mustard was grown in the plots measuring 6.3 m x 6.6 m between the alleys of 8-year-old Gmelina arborea trees. The trees are planted with a uniform distance of 8 x 2.5 m. Recommended dose of fertiliser (80:40:40 N: P: K kg ha-1, respectively) was supplemented to the crop.

Soil sampling and analysis: To determine the initial soil condition, a thorough soil sample was taken before the crop was planted for the field experiment. Before starting the experiment, a soil sample was taken in order to get preliminary information on the physico-chemical characteristics of the soil. Five different sampling sites were randomly selected within each area to obtain spatial diversity. The samples were taken with an auger from the root zone at depths of 0–15 cm, 15–30 cm, and 30-45 cm. Following the collection of soil samples, they were transported to the laboratory and subjected to various tests for various characteristics. The soil samples were pulverised into smaller particles and any unwanted material was eliminated in order to achieve homogeneity. After letting the soil settle for 30 minutes at a 1:2.5 soil to water ratio, the pH of the soil was measured using a glass electrode on a digital pH meter [23]. A conductivity meter [24] was used to measure the electrical conductivity of the soil sample at 25 °C in a suspension of 1:2.5 dirt to water. The method created by Walkley and Black [25] was used to determine the amount of organic carbon. The amount of nitrogen present in the soil was ascertained using the alkaline potassium permanganate method, as explained by Subbiah and Asija [26]. In order to extract the available phosphorous, the process outlined by Olsen et al. [27] was undertaken. As explained by Jackson (1973), the amount of potassium that was available was evaluated by extracting it using a 1 N ammonium acetate solution at pH 7, and the potassium concentration was determined using a flame photometer. The hot-water solubility method created by Gupta [28] was used to estimate the boron availability, and it was made even simpler by employing azomethine-H [29].

Table 1 Mechanical and physio-chemical analysis of soil of the experimental field

Particulars	Unit	Initial Value	Methods of analysis

2. Physical constants			
Bulk density	(g/cm^3)	1.36	Core sample (Black *et al*., 1965)
3. Chemical properties			
Organic carbon	(%)	0.57	Rapid titration method (Walkley and Black, 1934)
Available N	(kg ha^{-1})	220.5	Alkaline potassium permanganate method (Subbiah and Asija, 1956)
Available P_2O_5	(kg ha^{-1})	16.84	0.5 M $NaOCH_3$ extractable (Olsen *et al.* 1954)
Available K_2O	(kg ha^{-1})	243.7	1N neutral ammonium acetate method (Piper, 1966)
pH		6.32	Glass Electrode pH meter (Jackson, 1973)
Electrical conductivity	(dSm^{-1})	0.14	Systronics Electrical conductivity Meter (Jackson, 1973)

Table 2 Physical Properties of Soil:

Treatments	**Bulk density (g/cm^3)** Initial value: 1.41(g/cm^3)									**Water holding capacity (%)**		
	0-15cm			**15-30cm**			**30-45cm**			Initial value: 37.56%		
Phosphorus levels (kg/ha)	**1st Year**	**2nd Year**	**Pooled**	**1st Year**	**2nd Year**	**Pooled**	**1st Year**	**2nd Year**	**Pooled**	**1st Year**	**2nd Year**	**Pooled**
Phosphorous 30	1.38	1.37	1.37	1.40	1.42	1.41	1.41	1.45	1.43	37.24	37.46	37.35
Phosphorous 40	1.36	1.32	1.34	1.38	1.40	1.39	1.39	1.43	1.41	38.08	37.56	37.82
Phosphorous 50	1.34	1.36	1.35	1.36	1.38	1.37	1.37	1.41	1.39	37.47	38.47	37.97
SEm ±	0.10	0.11	0.10	0.09	0.11	0.10	0.10	0.12	0.11	1.15	1.17	1.16
C.D. at 0.05	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Inoculation with PSB												
Soil	1.36	1.35	1.35	1.38	1.40	1.39	1.39	1.43	1.41	38.30	37.97	38.13
Seedling	1.37	1.34	1.36	1.39	1.41	1.40	1.40	1.44	1.42	36.99	37.40	37.19
Soil + Seedling	1.36	1.35	1.36	1.38	1.40	1.39	1.39	1.43	1.41	38.10	38.47	38.29
Control	1.34	1.35	1.35	1.36	1.38	1.37	1.37	1.41	1.39	36.99	37.48	37.23
SEm ±	0.07	0.09	0.08	0.06	0.08	0.07	0.09	0.07	0.08	0.92	1.04	0.97
C.D. at 0.05	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Table 3 Mechanical Properties of Soil:

Treatments	**EC (ds/m)** Initial value: 0.14 ds/m			**SOIL pH** Initial value: 6.32			**Organic Carbon (%)** Initial value: 0.48		
Phosphorus levels (kg/ha)	**1st Year**	**2nd Year**	**Pooled**	**1st Year**	**2nd Year**	**Pooled**	**1st Year**	**2nd Year**	**Pooled**
Phosphorous 30	0.17	0.15	0.16	6.08	6.07	6.08	0.58	0.61	0.60
Phosphorous 40	0.14	0.12	0.13	6.35	6.34	6.35	0.61	0.65	0.63
Phosphorous 50	0.16	0.14	0.15	6.34	6.33	6.33	0.63	0.67	0.65
SEm ±	0.02	0.01	0.02	0.33	0.25	0.31	0.009	0.010	0.008
C.D. at 0.05	NS	NS	NS	NS	NS	NS	0.036	0.039	0.034
Inoculation with PSB									
Soil	0.15	0.13	0.14	6.27	6.26	6.26	0.62	0.66	0.64
Seedling	0.16	0.14	0.15	6.32	6.31	6.32	0.60	0.64	0.62
Soil + Seedling	0.16	0.14	0.15	6.17	6.16	6.16	0.67	0.69	0.68
Control	0.15	0.13	0.14	6.26	6.25	6.26	0.53	0.57	0.55
SEm ±	0.03	0.04	0.03	0.22	0.20	0.21	0.011	0.010	0.010
C.D. at 0.05	NS	NS	NS	NS	NS	NS	0.031	0.031	0.031

Table 4 Chemical Properties of Soil:

Treatments	Available Nitrogen (kg/ha)			Available Phosphorus (kg/ha)			Available Potassium (kg/ha)		
Phosphorus levels (kg/ha)	**1st Year**	**2nd Year**	**Pooled**	**1st Year**	**2nd Year**	**Pooled**	**1st Year**	**2nd Year**	**Pooled**
Phosphorous 30	246.7	249.7	248.2	17.75	18.00	17.87	265.7	268.5	267.1
Phosphorous 40	258.0	261.0	259.5	18.13	18.37	18.25	277.0	279.0	278.0
Phosphorous 50	267.4	270.4	268.9	18.82	19.06	18.94	286.4	288.4	287.4
SEm ±	13.41	14.46	13.81	0.20	0.18	0.19	13.41	11.68	12.24
C.D. at 0.05	NS	NS	NS	0.77	0.70	0.73	NS	NS	NS
Inoculation with PSB									
Soil	258.7	261.5	260.3	18.18	18.42	18.30	277.6	279.7	278.7
Seedling	265.5	268.7	267.4	18.31	18.55	18.43	284.7	287.8	286.3
Soil + Seedling	268.7	271.6	270.2	19.04	19.28	19.16	287.8	289.7	288.7
Control	236.3	239.3	237.8	17.41	17.65	17.53	255.33	257.3	256.3
SEm ±	18.28	19.65	18.94	0.34	0.36	0.35	18.27	23.07	20.50
C.D. at 0.05	NS	NS	NS	1.01	1.07	1.04	NS	NS	NS

3. Results

Effect of phosphorus and PSB on bulk density of soil:

Bulk density analysis at various soil depths (0–15 cm, 15–30 cm, and 30-45 cm) showed no statistically significant differences caused by PSB inoculation techniques or phosphorus amounts (30, 40, and 50 kg/ha). In table no. 2, across both years and pooled data, the results varied somewhat but stayed between 1.34 and 1.41 g/cm³. According to these findings, soil compaction and structure at the investigated depths are barely affected by PSB inoculation techniques and phosphorus treatment. The 1.41 g/cm³ initial bulk density stayed mostly constant, confirming the treatments' negligible impact.

Effect of phosphorus and PSB on water holding capacity of soil:

In table no. 2, additionally, there were no appreciable variations in soil water-holding capacity as a result of different PSB inoculation techniques or phosphorus levels. The water holding capacity varied from 37.97% to 38.47% among years and pooled data, despite slight increases. These gains were not statistically significant, however the maximum capacity was noted below 50 kg P/ha. In a similar vein, although the results were not statistically significant, the combined soil + seedling inoculation strategy produced somewhat higher values. These results imply that, in the conditions under investigation, neither PSB inoculation nor phosphorus administration significantly increases soil moisture retention.

Effect of phosphorus and PSB on available nitrogen in soil:

In table no. 4 conclude that phosphorus levels and PSB inoculation techniques did not significantly alter the available nitrogen levels in post-harvest soils, which ranged from 237.8 kg/ha to 270.1 kg/ha. The combination soil + seedling inoculation approach and 50 kg P/ha produced the maximum nitrogen levels. In comparison to the control, other inoculation techniques, such as soil-only and seedling-only treatments, produced modest increases. Additionally, there was no significant relationship between PSB inoculation techniques and phosphorus levels.

Effect of phosphorus and PSB on available potassium in soil:

In table no. 4 it is shown that as with nitrogen, treatments had no discernible effect on the quantities of accessible potassium. The range of potassium content was 256.3 kg/ha to 288.6 kg/ha, with the highest levels found under the soil + seedling inoculation approach and 50 kg P/ha. Although the changes were not statistically significant, potassium levels were consistently lower in the control therapy.

Effect of phosphorus and PSB on available phosphorus in soil:

In table no. 4 showed the both phosphorus levels and PSB inoculation techniques resulted in notable increases in phosphorus availability, in contrast to nitrogen and potassium. Under 50 kg P/ha, the highest phosphorus levels (18.94 kg/ha in pooled data) were recorded, greatly outperforming lower phosphorus levels. Similarly, phosphorus availability was greatly increased by the soil + seedling inoculation approach, with pooled levels up to 19.16 kg/ha. These findings show that increasing phosphorus treatment rates and using a combination of inoculation techniques can improve soil phosphorus availability.

Effect of phosphorus and PSB on electrical conductivity of soil:

In table no. 3 depicts the measurements of electrical conductivity (EC) stayed constant and did not significantly change across treatments. The values varied by depth and year, ranging from 0.14 to 0.19 ds/m^3. EC values were somewhat higher when 50 kg P/ha and the soil + seedling inoculation approach were used, but these changes were not statistically significant. The consistency of EC across treatments indicates that the ionic balance and salinity of the soil are not substantially changed by PSB inoculation techniques or phosphorus levels.

Effect of phosphorus and PSB on soil pH of soil:

In table no. 3 showed the across treatments and depths (0–15 cm, 15–30 cm, and 30-45 cm), the pH values of the soil varied from 6.31 to 6.39. Both PSB inoculation and phosphorus administration did not significantly alter pH over years or pooled data. The original pH of 6.32 stayed rather constant, indicating the soil's ability to act as a buffer and its resistance to treatment-induced alterations.

Effect of phosphorus and PSB on organic carbon of soil:

In table no. 3, across phosphorus levels and PSB inoculation techniques, notable increases in organic carbon content were noted. All depths saw a considerable rise in organic carbon levels due to the combined soil + seedling inoculation approach and higher phosphorus administration (50 kg P/ha). The combined data showed that under the most successful treatment combinations, the organic carbon content increased from an initial value of 0.48% to as high as 0.69%. Improved organic matter turnover, improved root development, and increased microbial activity are the causes of these changes.

DISCUSSION

Several significant findings were obtained from the examination of soil characteristics under different phosphorus concentrations (30, 40, and 50 kg/ha) and phosphate-solubilizing bacteria (PSB) inoculation techniques. There were no statistically significant variations in bulk density or water-holding capacity between years, pooled data, or soil depths (0–15 cm, 15–30 cm, and 30–45 cm). Between 1.34 and 1.41 g/cm³, bulk density stayed constant, suggesting that there were few impacts on compaction or soil structure. Similar to this, water-holding capacity varied between 37.97% and 38.47%, with somewhat higher values noted under combined soil + seedling inoculation and 50 kg P/ha. Both results are consistent with research by Choudhary (2023) and Ullah et al. (2024), who found that PSB inoculation and phosphate application had no discernible effects on bulk density or soil moisture retention. This highlights the limited impact of both treatments on physical soil metrics under comparable circumstances.

However, there were notable impacts on the amount of organic carbon and the availability of phosphorus. Under 50 kg P/ha, phosphorus availability peaked at 18.94 kg/ha; levels were further increased to 19.16 kg/ha by combining soil and seedling inoculation. Higher phosphorus levels and PSB inoculation, perhaps as a result of enhanced microbial activity and root growth, caused the organic carbon content to dramatically improve from 0.48% to 0.69%. These results are supported by Bindu et al. (2024) and Ríos-Ruiz et al. (2024), who point out that PSB and other integrated nutrient management significantly raise organic carbon and phosphorus availability, improving soil fertility. Even if their effects on physical characteristics like bulk density and water retention are still negligible, this data highlights the contribution that PSB inoculation and combined phosphorus application provide to improving soil nutrient dynamics.

CONCLUSION

The study emphasises how diverse soil qualities are affected by phosphorus levels and PSB inoculation techniques. Significant gains were observed in phosphorus availability and organic carbon content, but no changes were observed in bulk density, water holding capacity, accessible nitrogen, potassium, electrical conductivity, or pH. The most successful method for increasing soil fertility by raising phosphorus availability and organic matter content was the combination of soil + seedling inoculation and higher phosphorus levels (50 kg P/ha). These findings provide valuable insights for sustainable soil management practices, emphasizing the potential benefits of integrating optimized phosphorus applications with PSB inoculation to improve soil health and productivity.

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