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Soil Nutrient Dynamics under Horse Gram Intercropping in *Melia dubia*–Based Agroforestry in the Central Dry Zone of Karnataka

Syed Ali, L. Vasudev[1], Salma[2], Manoj Kumar Jhariya[3], Arnab Banerjee[4], Lalji Singh[2*], Sangram B. Chavan[5] and J.S. Singh[6]

College of Forestry (Sirsi), University of Agricultural Sciences, Dharwad-581 401, India
[1]Department of Farm Forestry, College of Horticulture, Hiriyur-577 598, India
[2]Department of Forestry, Indira Gandhi Krishi Vishwavidyalaya, Raipur-492 012, India
[3]Department of Farm Forestry, [4]Department of Environmental Science
Sant Gahira Guru Vishwavidyalaya, Sarguja, Ambikapur-497 001, India
[5]ICAR-National Institute of Abiotic Stress Management, Malegaon, Baramati-413 115, India
[6]Department of Botany, Banaras Hindu University, Varanasi-221 005, India
**E-mail: lalji.singh2@gmail.com*

Abstract: Agroforestry is a sustainable land-use system that integrates trees and crops, enhancing soil fertility and productivity, particularly in semi-arid regions. This study evaluated the impact of intercropping *Macrotyloma uniflorum* (horse gram) in *Melia dubia* (Malabar neem)-based agroforestry on soil nutrient status in the central dry zone of Karnataka. Soil samples were collected from five depths (0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm, and 80-100 cm) before and after harvesting, and analyzed for key soil parameters using a response index approach. The intercropping significantly reduce soil pH (from 7.2 to 6.8), with a response index of -4.8%, due to organic acid release from decomposed litter. Electrical conductivity (EC) decreased from 0.42 dS m^{-1} to 0.35 dS m^{-1}, with a response index of -16.6%, indicating improved soil structure. Soil organic carbon (SOC) increased from 0.48% to 0.62%, with a response index of +29.2%, attributed to organic matter accumulation. Available nitrogen (N) improved from 215 kg ha^{-1} to 265 kg ha^{-1}, showing a response index of +23.2%. Similarly, available phosphorus (P_2O_5) and potassium (K_2O) increased from 16.8 to 22.5 kg ha^{-1} and 240 to 280 kg ha^{-1}, with response indices of +33.9% and +16.7%, respectively, largely due to nutrient cycling and organic matter decomposition. Statistical analysis indicated improvements in soil fertility under intercropped conditions compared to sole cropping. These findings highlight that *M. dubia*-based agroforestry with horse gram enhances soil nutrient retention and fertility, offering a viable strategy for sustainable agriculture in resource-limited dryland agriculture

Keywords: Agroforestry, Soil fertility, Intercropping, Nutrient cycling, Sustainable agriculture

In present time agriculture across the globe in general and India in particular is going through severe crisis of land, water, food under the pressure of climate change (Pathak et al., 2014). It was observed that the yield component is being affected severely by practicing monoculture cropping in various regions (Larsen et al., 2025). Monoculture practices also lead to loss of gene pool, decrease in yield, productivity and quality along with land degradation through loss of soil fertility and health (Meena et al., 2025). In this connection, intercropping is a suitable measure which may be used to improve the quality and health of the soil through agroforestry practices that would also help in improving soil fertility (Kumari et al., 2025, Jinger et al., 2023). It would also provide a guideline for selecting suitable climate-resilient cropping system depending upon the existing climatic conditions (Kumar et al., 2024).

The growing demand for food, fodder, fuel, and timber, coupled with diminishing land resources, necessitates the adoption of sustainable land-use practices to enhance productivity per unit area (Shuite et al., 2025). This challenge is particularly significant in semi-arid regions like the central dry zone of Karnataka, where limited water availability and poor soil fertility constrain agricultural output. Traditional farming systems, reliant on rainfed conditions, often result in low yields and economic vulnerability. To address these challenges, agroforestry-an integrated land-use system combining trees with crops offers a promising solution by enhancing soil fertility, optimizing resource use, and improving farm resilience (Jinger et al., 2022, Prajapati et al., 2022).

Melia dubia (Malabar neem), a fast-growing, multipurpose tree species, has gained prominence in agroforestry due to its economic value and adaptability to diverse climatic conditions (Thakur et al., 2018, Jinger et al., 2024, Malek et al., 2024). It is widely cultivated for timber, plywood, and industrial applications, making it a viable option for integrating into farming systems (Ashok et al., 2017, Thakur et al., 2020, 2023, Jinger et al., 2025) with no allopathic effect on understorey crops (Kumar et al., 2017, Parmar et al., 2019). On the other hand, horse gram (*Macrotyloma uniflorum*), a hardy, drought-tolerant pulse crop, serves as an excellent intercrop in agroforestry systems (AFs) due to its ability to fix nitrogen (N), improve soil organic matter (SOM), and provide nutritional and economic benefits to farmers (Prasad and Singh 2015).

Intercropping horse gram with *M. dubia* has the potential to enhance soil nutrient status by increasing organic carbon (OC) content, N availability, and overall soil fertility through litter decomposition and nutrient cycling. Additionally, AFs mitigate soil degradation, reduce erosion, and enhance water retention, making them well-suited for semi-arid regions (Subba and Dhara, 2017, Dobhal et al., 2024). Despite the recognized benefits, limited research exists on the impact of intercropping horse gram in *M. dubia*-based AFs, particularly on soil nutrient dynamics.

It was hypothesized that the integration of horse gram in *M. dubia*–based AFs significantly enhances soil physico-chemical properties and overall fertility compared to monocropping systems. The objective of this study was carried out to evaluate the influence of horse gram cultivation within *M. dubia*–based agroforestry on key soil parameters, thereby generating evidence to support sustainable agriculture and agroforestry practices in dryland regions.

MATERIAL AND METHODS

Study sites: The experimental field was conducted at the Zonal Agricultural and Horticultural Research Station of Hiriyur, Chitradurga district of Karnataka lying between in 13°56'57" N and 76°37'13" E with an elevation of 600 above MSL. The climate of the area reflects a dry zone having an average annual rainfall of about 660 mm. The average temperature ranged between 17.7-31.5 °C with an average relative humidity of 72%.

Experimental details: Experiment was set up in the year 2018-19. At the time of cultivation the age of *M. dubia* was three years old which was intercropped with horse gram in randomized complete block design with five replications which includes the treatment combination as- T1 – 4 m × 1 m spacing with horse gram T2 – 4 m × 2 m spacing with horse gram T3 – 4 m × 3 m spacing with horse gram T4 - Sole horse gram crop

Soil sample collection and preparation: Soil samples were drawn from five depths: d1 (0-20 cm), d2 (20-40 cm), d3 (40-60 cm), d4 (60-80 cm), and d5 (80-100 cm) before and after harvesting from all the treatments. Collected soil samples were brought to the laboratory in polythene bags for further processing. The soil samples were dried under shade, ground with a pestle and mortar, and sieved through 2 mm sieve. The processed soil samples were analyzed for pH, EC, available N, phosphorus (P_2O_5), and potassium (K_2O). For OC analysis, the powdered soil samples were further ground in an agate mortar and passed through a 0.5 mm sieve. The treatments considered were different spacing between *M. dubia* trees: T1 (4 m × 1 m), T2 (4 m × 2 m), T3 (4 m × 3 m), and T4 (sole HG). The procedure for the analysis of various characteristics in initial and post-harvest soil samples was followed as per standard laboratory protocols.

Soil chemical analysis: The collected soil samples were analyzed for key chemical properties using standard laboratory procedures. Soil pH was measured using a digital pH meter in a 1:2.5 soil-water suspension (Jackson, 1973). Electrical conductivity (EC) (dSm^{-1}) was determined using a conductivity meter in a 1:2.5 soil-water suspension (Richards, 1954). % organic carbon (SOC) was estimated using the Walkley and Black (1934) wet oxidation method. Available N (kg ha^{-1}) was determined using the alkaline permanganate method (Subbiah and Asija 1956). Available phosphorus (kg ha^{-1}) was measured using the Olsen's method (Olsen et al., 1954). Available potassium (kg ha^{-1}) was estimated using neutral normal ammonium acetate extraction followed by flame photometry (Jackson 1973).

Statistical analysis: The data was analyzed with SPSS package. Correlation study between the soil attributes before and after harvesting of horse gram intercropping system was done in order to established the influence of soil attributes among themselves. The treatment means of the soil parameters of various treatments were done through Duncan's Multiple Range Test (DMRT) to evaluate the variation within the treatment means.

RESULTS AND DISCUSSION

The initial soil chemical analysis before intercropping horse gram revealed variations in pH, EC, SOC, and nutrient availability across different treatments and soil depths. Soil pH ranged from 8.22-8.81 (Table 1), with the highest measured in sole horse gram plots (8.81 at 60-100 cm depth) and the lowest in T1 (4m × 1m) (8.22-8.32). Electrical conductivity (EC) varied from 0.24 to 0.39 dS m^{-1} with the highest in sole crop (0.39 dS m^{-1} at 0-20 cm) and the lowest in T1 (0.28-0.25 dS m^{-1}). Nutrient analysis indicated that available N ranged from 98.00 to 186.20 kg ha^{-1} (Table 1), phosphorus from 8.30 to 28.40 kg ha^{-1} and potassium from 186.60 to 304.80 kg ha^{-1}, with the highest values observed in T3 (4m × 3m) at 0-20 cm. Similarly, SOC ranged from 0.19-0.46% (Table 2), with the highest value in T3 (0.46% at 0-20 cm) and the lowest in sole horse gram (0.19-0.23%). These findings suggest that wider tree spacing (T3) enhanced nutrient retention and OC accumulation, whereas sole cropping had higher pH and EC but lower SOC and nutrient availability. Post-harvest, significant variations in soil properties were observed across different treatments and soil depths (0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm, and 80-100 cm). The highest pH (8.11-8.82) was in sole horse gram plots (Table 3), while among *M. dubia* treatments, T3 consistently had the highest pH, followed by T2 (4m × 2m) and T1 (4m × 1m). EC followed a similar trend, with sole crop horse gram exhibiting the highest EC (0.33-0.38 dS m^{-1}), while T3 recorded the highest EC among *M. dubia* treatments across all depths (Table 4). The availability of N (161.80-197.40 kg ha^{-1}), phosphorus (14.20-33.60 kg ha^{-1}) (Table 5), potassium (284.60-310.70 kg ha^{-1}), and SOC (0.21-0.48%) was highest in T3. In contrast, sole crop horse gram had the lowest values for these nutrients. These results indicate that *M. dubia* spacing influenced soil properties, with wider spacing improving nutrient availability and OC accumulation more effectively than closer spacing (T1) or sole cropping.

The impact of *M. dubia* intercropping on soil chemical properties was further reflected in the response index, where soil pH and EC showed negative values across all treatments. Conversely, available N, phosphorus, potassium, and SOC exhibited positive response indices when horse gram was intercropped but negative under sole cropping. The response index ranged from -0.018 to -0.001

Table 1. Soil pH, EC and available nitrogen recorded before horse gram intercropping as influenced by different treatments

Treatment	pH					EC (dS m^{-1})					Available nitrogen (kg ha^{-1})				
	0-20 cm	20-40 cm	40-60 cm	60-80 cm	80-100 cm	0-20 cm	20-40 cm	40-60 cm	60-80 cm	80-100 cm	0-20 cm	20-40 cm	40-60 cm	60-80 cm	80-100 cm
T_1 (4 m × 1 m)	8.22	8.25	8.28	8.30	8.32	0.28	0.27	0.26	0.26	0.25	137.00	131.60	126.20	120.40	115.40
T_2 (4 m × 2 m)	8.28	8.30	8.31	8.33	8.34	0.29	0.28	0.27	0.25	0.24	162.40	156.00	149.60	143.80	138.20
T_3 (4 m × 3 m)	8.32	8.34	8.36	8.37	8.37	0.34	0.33	0.32	0.30	0.28	186.20	179.00	172.40	166.00	160.20
T_4 (Sole HG)	8.76	8.78	8.80	8.81	8.81	0.39	0.37	0.36	0.35	0.34	108.40	104.60	101.60	99.80	98.00
CD (p=0.05)	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	6.58	5.89	5.62	5.33	6.03

Table 2. Soil available phosphorous (P_2O_5), potassium (K_2O) and organic carbon recorded before horse gram intercropping as influenced by different treatments

Treatment	Available P_2O_5 (kg ha^{-1})			Soil available K_2O (kg ha^{-1})			Soil organic carbon (%)		
	0-20 cm	40-60 cm	80-100 cm	0-20 cm	40-60 cm	80-100 cm	0-20 cm	40-60 cm	80-100 cm
T_1(4 m × 1 m)	23.58	15.00	10.80	261.40	250.20	238.60	0.39	0.31	0.24
T_2(4 m × 2 m)	25.80	19.70	13.60	278.80	265.40	253.00	0.44	0.36	0.28
T_3(4 m × 3 m)	28.40	22.20	13.80	304.80	292.60	283.60	0.52	0.44	0.36
T_4(Sole HG)	18.40	11.60	8.30	202.60	191.20	182.20	0.29	0.23	0.20
CD (p=0.05)	1.26	0.84	0.85	5.20	5.68	5.01	0.01	0.02	0.02

Table 3. Soil pH, EC and available nitrogen recorded after harvest of horse gram as influenced by different treatments

Treatment	pH			Electric Conductivity (dS m^{-1})			Available nitrogen (kg ha^{-1})		
	0-20 cm	40-60 cm	80-100 cm	0-20 cm	40-60 cm	80-100 cm	0-20 cm	40-60 cm	80-100 cm
T_1 (4 m × 1 m)	8.11	8.28	8.32	0.24	0.23	0.22	141.60	130.80	117.40
T_2 (4 m × 2 m)	8.13	8.31	8.33	0.25	0.23	0.22	169.60	156.40	140.20
T_3 (4 m × 3 m)	8.17	8.35	8.37	0.27	0.24	0.23	197.40	179.80	161.80
T_4 (Sole HG)	8.76	8.80	8.82	0.38	0.35	0.33	106.40	100.20	96.40
CD (p=0.05)	0.03	0.02	0.02	0.02	0.01	0.01	6.74	5.88	5.80

Table 4. Soil available phosphorous (P_2O_5), potassium (K_2O) and organic carbon recorded after harvest of horse gram as influenced by different

Treatment	Available P_2O_5 (kg ha^{-1})			Available K_2O (kg ha^{-1})			Soil organic carbon (%)		
	0-20 cm	40-60 cm	80-100 cm	0-20 cm	40-60 cm	80-100 cm	0-20 cm	40-60 cm	80-100 cm
T_1 (4 m × 1 m)	25.40	16.20	11.20	263.70	251.42	239.10	0.41	0.32	0.25
T_2 (4 m × 2 m)	29.50	22.30	14.20	283.00	267.00	253.80	0.47	0.38	0.29
T_3 (4 m × 3 m)	33.60	25.70	12.50	310.70	295.30	284.60	0.56	0.46	0.37
T_4 (Sole HG)	17.00	10.74	7.90	201.20	189.60	181.40	0.28	0.22	0.19
CD (p=0.05)	1.18	0.73	4.50	4.64	5.64	5.23	0.01	0.02	0.02

for pH (Fig. 1), -0.006 to -0.233 for EC (Fig. 2), -0.012 to 0.060 for N (Fig. 3), -0.132 to 0.183 for phosphorus (Fig. 4), -0.008 to 0.019 for potassium (Fig. 5), and -0.061 to 0.096 for SOC (Fig. 6).

Higher level of variation was recorded between the treatment means of available N and potassium (Table 5). Lesser variation of the treatment means was observed for rest of the parameters. This therefore indicates that the soil attributes reflected significant variation in the available N and potassium level before horse gram intercropping. Further, the correlation matrix of the soil attributes before horse gram intercropping reflected positive correlation between pH and EC. Further, N, phosphorous, potassium and OC was positively and significantly correlated with each other (Fig. 7).

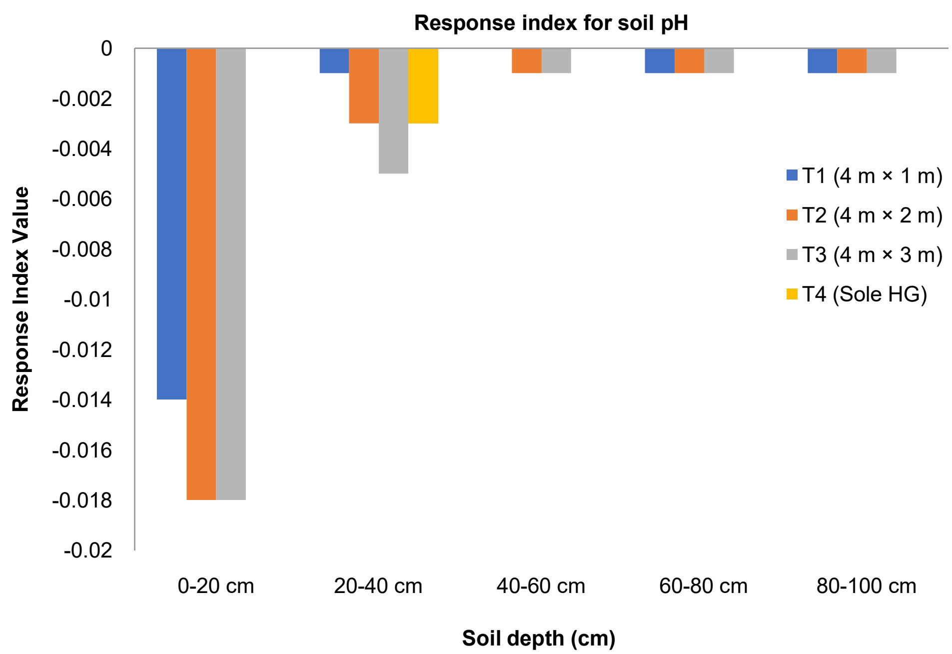

Fig. 1. Response index for pH as influenced by different treatments

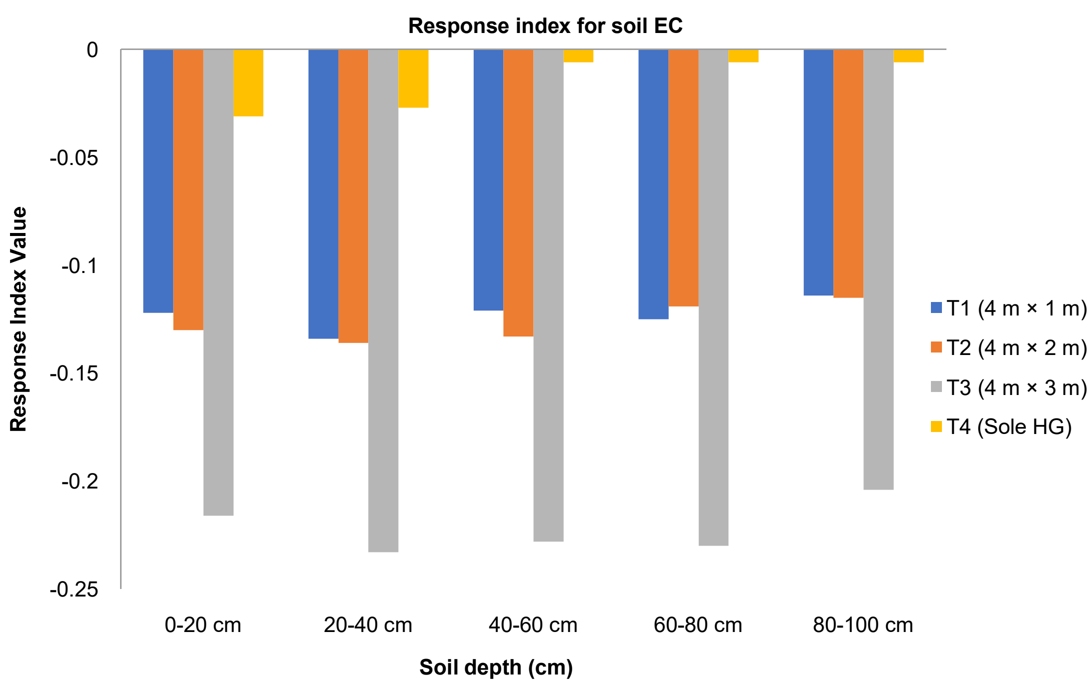

Fig. 2. Response index for EC as influenced by different treatments

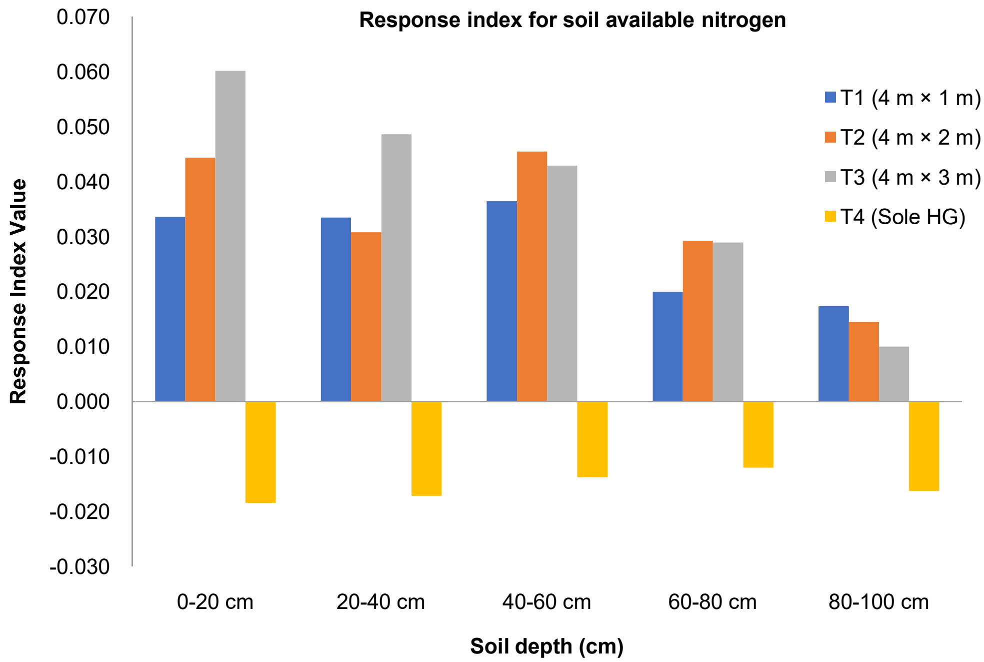

Fig. 3. Response index for available nitrogen as influenced by different treatments

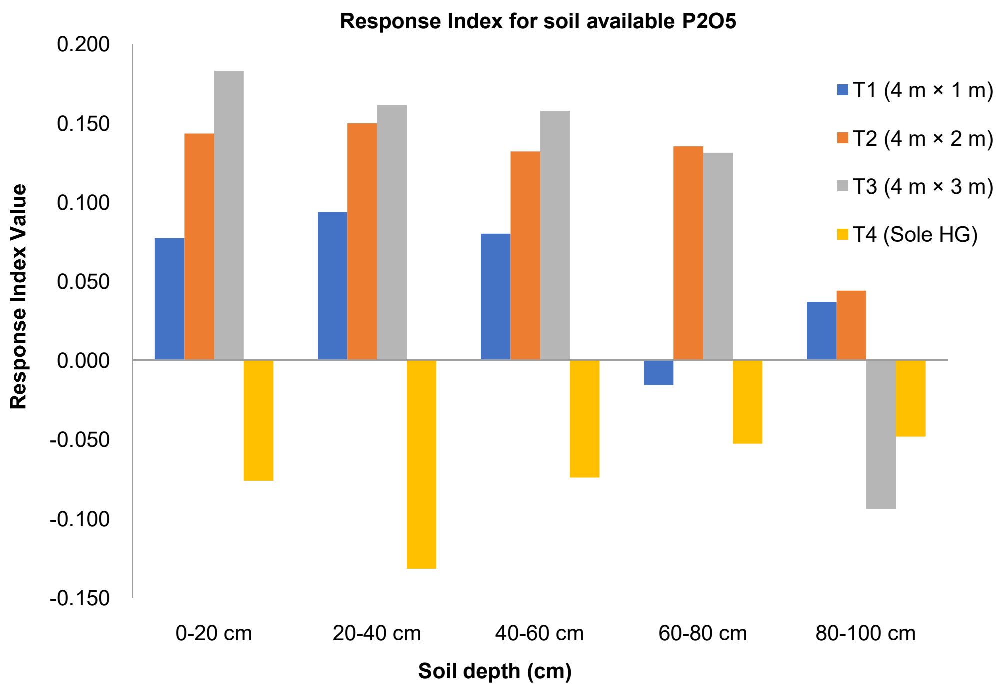

Fig. 4. Response index for available phosphorus as influenced by different treatments

Table 5. Variation of treatment means of soil attributes before horse gram intercropping

Treatment	pH	EC	Available N (kg ha^{-1})	Available P_2O_5 (kg ha^{-1})	Soil available K_2O (kg ha^{-1})	Soil organic carbon (%)
T_1 (4 m × 1 m)	8.274^{b}	0.264^{b}	126.12^{bc}	16.276^{a}	249.88^{b}	0.314^{ab}
T_2 (4 m × 2 m)	8.312^{b}	0.266^{b}	150.08^{ab}	19.76^{a}	265.72^{ab}	0.358^{ab}
T_3 (4 m × 3 m)	8.352^{b}	0.314^{ab}	172.76^{a}	21.62^{a}	293.44^{a}	0.44^{a}
T_4 (Sole HG)	8.792^{a}	0.362^{a}	102.48^{c}	12.52^{a}	191.84^{c}	0.238^{b}

Similar trend of higher level of variation was recorded between the treatment means of available N and potassium (Table 6). Lesser variation of the treatment means was observed for rest of the parameters. This indicates that the soil attributes reflected significant variation in the available N and potassium level after horse gram intercropping represents similar trend of correlation matrix as was observed before horse gram intercropping. pH was positively and significantly correlated with EC (Fig. 8). Available N, phosphorous, potassium and OC was be significantly and positively correlated among themselves.

The present study demonstrated that *M. dubia*-based AFs, particularly the tree-legume intercropping treatment (T3), significantly enhanced soil fertility indicators such as soil organic carbon (SOC), available nitrogen (N), phosphorus (P), and potassium (K), while reducing soil pH

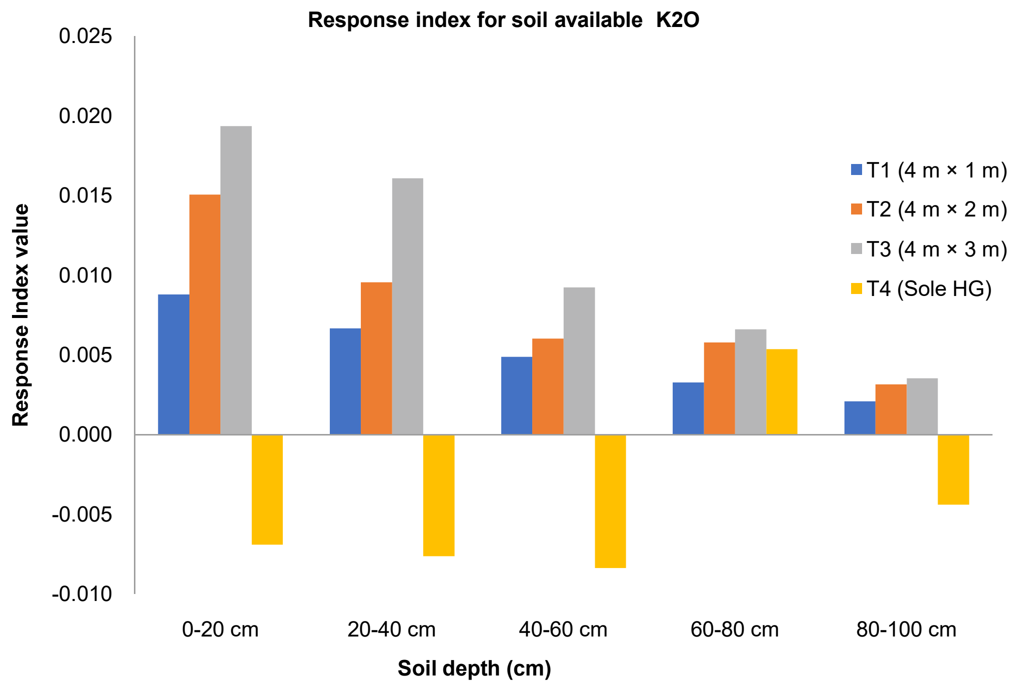

Fig. 5. Response index for available potassium as influenced by different treatments

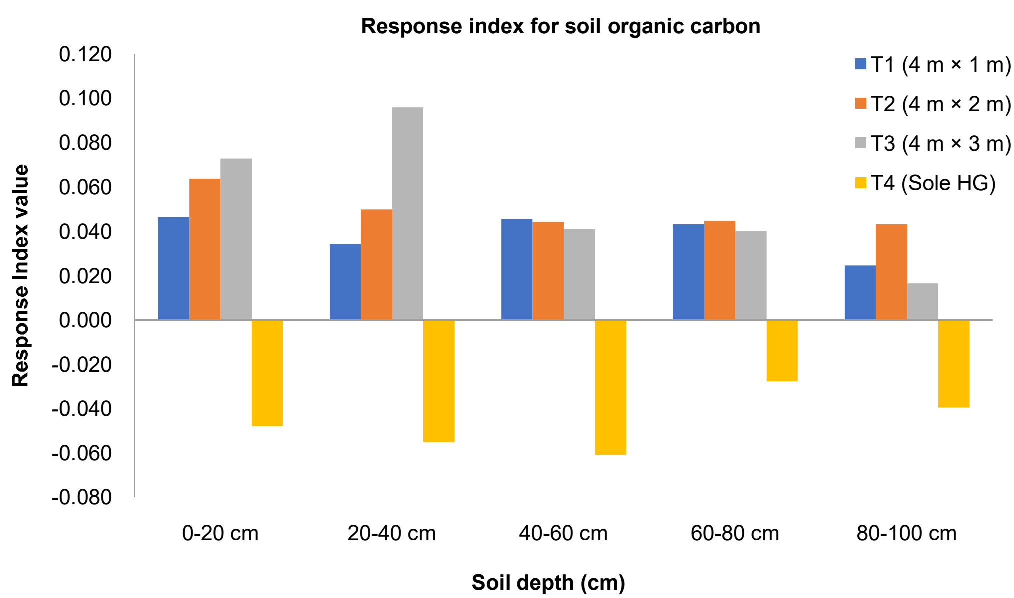

Fig. 6. Response index for soil organic carbon as influenced by different treatments

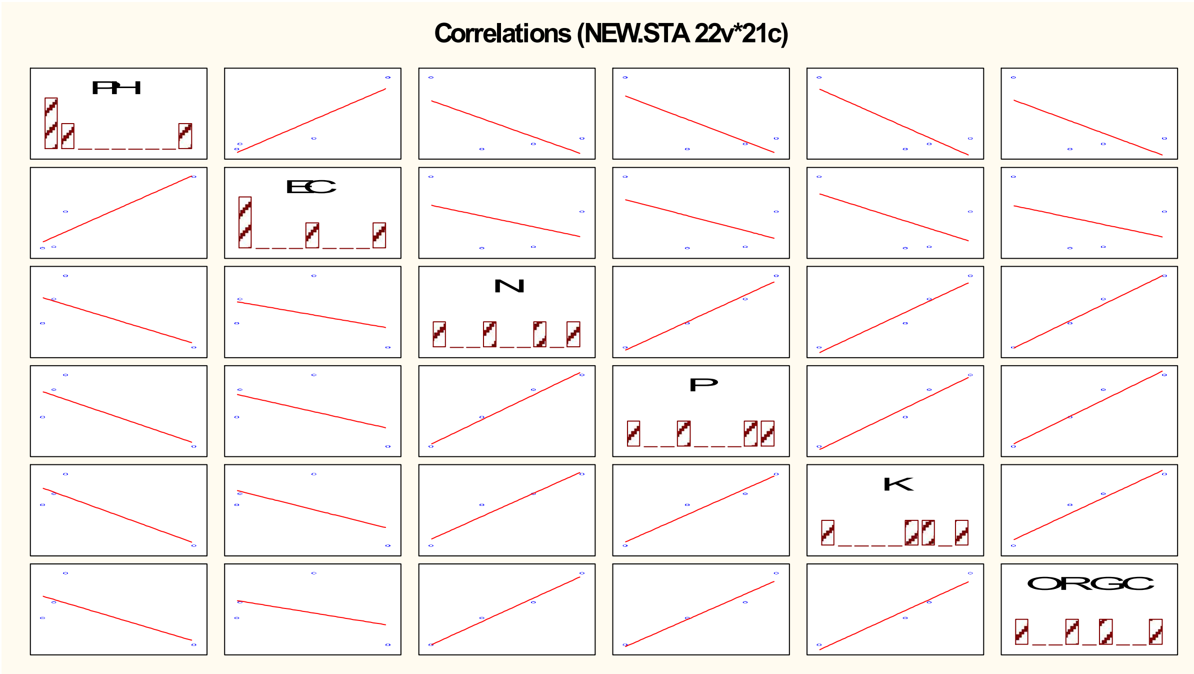

Fig. 7. Correlation matrix of soil attributes before horse gram intercropping

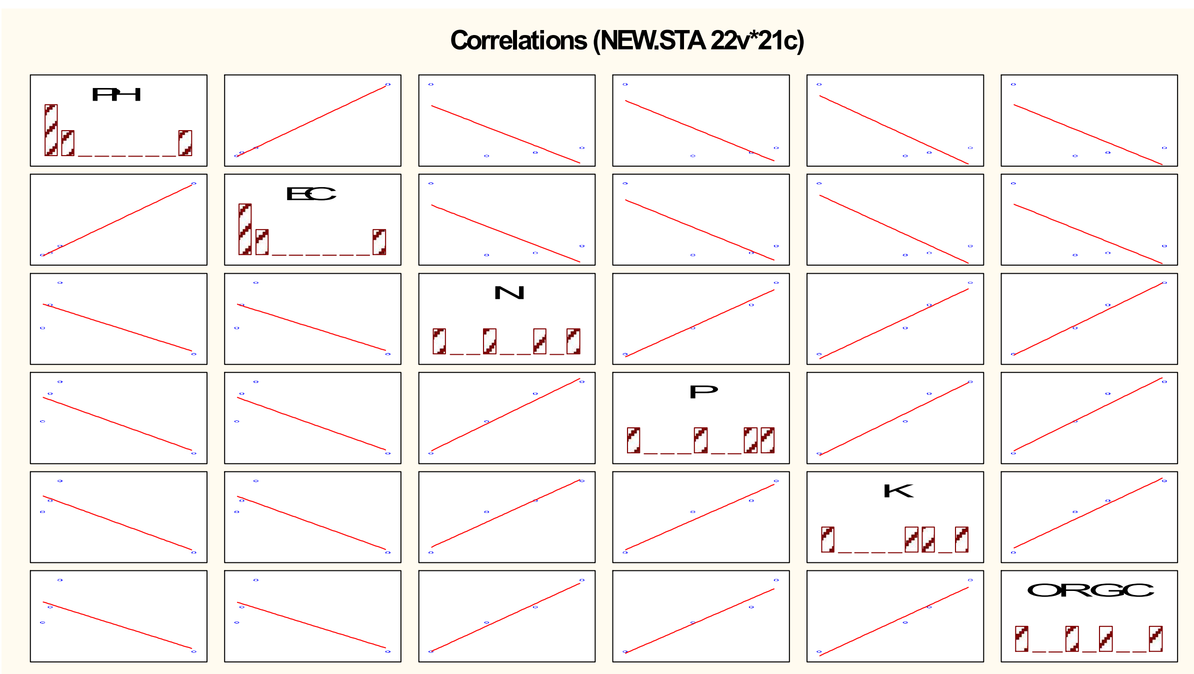

Fig. 8. Correlation matrix of soil attributes after horse gram intercropping

Table 6. Variation of treatment means of soil attributes after horse gram intercropping

Treatment	pH	EC	Available N (kg ha^{-1})	Available P_2O_5 (kg ha^{-1})	Soil available K_2O (kg ha^{-1})	Soil organic carbon (%)
T_1 (4 m × 1 m)	8.248^{b}	0.228^{b}	129.72^{bc}	17.28^{a}	251.224^{b}	0.326^{ab}
T_2 (4 m × 2 m)	8.274^{b}	0.232^{b}	155^{ab}	22.28^{a}	267.86^{b}	0.378^{ab}
T_3 (4 m × 3 m)	8.31^{b}	0.244^{b}	179.36^{a}	24.4^{a}	296.7^{a}	0.468^{a}
T_4 (Sole HG)	8.79^{a}	0.354^{a}	100.88^{c}	11.498^{a}	190.98^{c}	0.228^{b}

and electrical conductivity (EC).The reduction in soil pH under *M. dubia* aligns with Kumar et al., (2008), where similar acidification in tree-based systems due to organic acid release from litter decomposition in dry semi-arid conditions of central India. Nanda et al. (2021) observed similar trends in drylands of Rajasthan. Singh et al. (2018), also observed that legumes to raise soil pH through biological Nitrogen fixation and less acidic root exudates in arid regions. The decrease in EC, particularly in T3, can be attributed to better nutrient uptake and improved SOM mineralization, similar to observations by Ravi (2005) in southern India and Patel et al. (2018) in semi-arid Gujarat. SOC accumulation was highest in surface soils under *M. dubia*, supported by findings of Kar et al. (2019) where increased SOC in AFs in Odisha due to higher litter input and reduced oxidation from canopy cover. The decline in SOC with depth is also in line with Salve et al. (2018), due to reduced microbial activity and organic input in subsoil layers under agroforestry in Maharashtra. Enhanced N, P, and K availability in intercropped plots was driven by improved litter quality and microbial activity, which agrees with Bharadwaj et al. (2017) and Kaur et al., (2022), where higher phosphorus availability is linked with increased phosphatase activity in Haryana and Punjab respectively,. Uthappa et al. (2015) also reported enhanced nutrient cycling in semi-arid Karnataka. The superior performance of T3 further supports the compatibility of *M. dubia* with legumes, as observed by Thakur et al. (2019) in *M. dubia* + *Cymbopogon* systems in Chhattisgarh. Overallur findings confirm the sustainability potential of *M. dubia*-based AFs under dryland conditions, aligning with broader national and global evidence (Dhyani 2014, Jinger et al., 2022, 2023, 2024, Dobhal et al., 2024), which highlights agroforestry as a nature-based solution for improving soil health, enhancing nutrient cycling, and restoring productivity in degraded or low-input ecosystems.

CONCLUSION

The intercropping horse gram with *M. dubia* in dry zone significantly improved soil fertility by enhancing SOC, available N, P, and K through litter decomposition and nutrient cycling. The decline in soil pH under tree-based systems indicated improved microbial activity and SOM breakdown. Compared to sole cropping, wider tree spacing reflected higher nutrient retention and OC accumulation than sole cropping and hence can be recommended to be applied under field condition for improvement of soil fertility. Therefore, intercropping demonstrated better nutrient availability, highlighting AFs as a sustainable land-use strategy for semi-arid regions. This approach not only enhances soil health but also provides economic and ecological benefits, promoting resilience to climate variability and improving farm incomes.

AUTHOR'S CONTRIBUTIONS

Syed Ali, Salma Kabeer and Manoj Kumar Jhariya wrote the main manuscript. Syed Ali, Manoj Kumar Jhariya and, Arnab Banerjee prepared the figures, Vasudev L, Manoj Kumar Jhariya, Lalji Singh, Sangram B Chavan and J.S. Singh reviewed the manuscript.

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