

Fruit and Pulse Synergy: Evaluating Vigna mungo performance in Himalayan wild pomegranate based agroforestry systems

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Abstract

The integration of fruit-based agroforestry models with pulse cultivation, supported by integrated nutrient management practices, presents a sustainable approach for developing nations aiming to enhance productivity while maintaining soil and human health. This study evaluated the impact of planting conditions and integrated nutrient management on the growth, yield, and soil attributes of *Vigna mungo* (mash) under a wild pomegranate-based agroforestry system. The experiment was designed using a randomized block design factorial approach with twelve treatments involving organic and inorganic manures (T₁: RDF (Recommended dose of Fertilizer), T₂: FYM (100% N equivalent basis), T₃: Vermicompost (100% N equivalent basis), T₄: Goat manure (100% N equivalent basis), T₅: Jeevamrut @ 500 l/ha, T₆: 50% RDF + 50% FYM, T₇: 50% RDF + 50% VC, T₈: 50% RDF + 50% GM, T₉: 50% RDF + 50% Jeevamrut, T₁₀: 50% RDF + 25% FYM + 25% VC, T₁₁: 50% RDF + 25% GM + 25% Jeevamrut and T₁₂: Control) and two planting conditions (under wild pomegranate canopy and open conditions), each replicated thrice. The results indicated that *Vigna mungo* exhibited better growth and yield parameters in open conditions compared to the wild pomegranate canopy. Among the nutrient treatments, T₆ (50% RDF + 50% FYM) demonstrated superior growth and yield. Post-harvest soil analysis revealed improved physical and chemical properties under the agroforestry system with 100% FYM application (T₂). Economically, the wild pomegranate + *Vigna mungo* system yielded the highest net returns (US\$ 1094.09 ha⁻¹) and benefit-cost ratio (2.26) compared to sole cropping of *Vigna mungo*. This study accentuates the potential of integrating fruit trees with pulse crops under appropriate nutrient management to achieve sustainable agricultural practices, improved farmer incomes, and better soil and human health.

Introduction

Agriculture is confronted with the formidable task of nourishing a worldwide population of 9.7 billion by the year 2050, while concurrently addressing the adverse environmental and societal consequences (FAO et al. 2021). India is witnessing a remarkable surge in population each year, while the amount of arable land is rapidly shrinking. This population increase not only drives up global food demand and productivity (FAO 2018), but also significantly impacts land use. Fertile land is increasingly being repurposed for residential, transportation, and industrial development, leading to a reduction in agricultural space (Burgess et al. 2022; Tiwari 2003). Forests are vital for the livelihoods of many in developing countries, with 1.09 to 1.74 billion people relying on them for daily needs, and about 200 million indigenous people depending almost entirely on forest resources (Langat et al. 2016). This dependence has led to a decline in forest biodiversity and increased greenhouse gas emissions globally (Khan et al. 2020). The growing population's demand for forest products is outpacing current production levels, straining forest reserves (Henttonen et al. 2017; Kauppi et al. 2018).

Given the increasing population and decreasing areas under agriculture and forests, various approaches have been adopted to address this issue, such as expanding cultivated land or improving the utilization of existing agricultural land. However, monocultures that focus solely on either agricultural or forestry and forage crops often prove to be resource-inefficient (Townsend et al. 2008) and fail to optimize production to meet the growing demands for food, fuelwood, fodder, and more. Consequently, there is a need to shift towards nature-based solutions like agroforestry to meet these needs while also generating positive social, ecological, and economic impacts. Additionally, increasing temperatures, fluctuating weather patterns, and extreme events are anticipated to potentially reduce the edible food production of major crops by up to 1% in several developing nations (Ray et al. 2019). Climate-smart agriculture aims to achieve sustainable enhancements in agricultural productivity, improve resilience to climate change, minimize greenhouse gas emissions, and promote carbon sequestration (FAO 2013). As a result, the global recognition of the multitier system known as 'agroforestry' has gained prominence in the pursuit of optimizing productivity.

Agroforestry offers a promising solution to tackle these challenges by simultaneously catering to the needs of a rapidly growing global population while promoting sustainability and biodiversity conservation (Kloppenburg 1991; Patel and Moore 2017). As an environmentally responsible land use approach, agroforestry systems present an alternative to traditional subsistence farming practices, focusing on resource preservation and socioeconomic upliftment (Moreno et al. 2018, Dagar et al. 2020). Agroforestry has the potential to enhance soil productivity while providing various environmental benefits and risk mitigation through diversity

(Bisht et al. 2017). It represents an ecologically-based, dynamic natural resource management system that diversifies and sustains production, leading to increased economic, social, and environmental advantages for land users.

Poverty poses a substantial challenge for South Asian countries, including India, with rural areas experiencing particularly high levels that necessitate effective poverty reduction strategies (Thapa 2004). Agroforestry plays a significant role in improving rural livelihoods and alleviating poverty (FAO 2004). Major international organizations such as the World Bank, FAO, ICRAF, and other donors are consistently formulating strategies worldwide, incorporating agroforestry options to address the needs of impoverished populations. These strategies aim to enhance livelihoods, ensure food security, and improve environmental services (Dixon et al. 2001; Garrity 2004). In the context of India, the key objectives of the agroforestry policy involve building socio-economic resilience among marginalized smallholder farmers, meeting the growing demand for various agroforestry products such as timber, food, fuel, fodder, and fiber, as well as safeguarding the environment from extreme climatic events (NAP 2014).

Agroforestry stands out as a highly effective land-use strategy, addressing the dual objectives of enhancing food security and mitigating environmental degradation. This approach not only provides an economically viable option but also supports large-scale agricultural diversification, offering ecological benefits for environmental improvement. (Chaturvedi and Krishnan 2009). One of its most recognized advantages is the improved land use efficiency, driven by the synergistic yields and positive interactions between trees and crops (Zhang et al. 2007). However, for maximum economic benefits, the selection of tree-crop combinations is crucial and should primarily be guided by the local edapho-climatic conditions, farmer needs and traditions, and resource availability (Saroj and Dadhwal 1997). To achieve higher returns per unit area and realize the government's objective of doubling farmers' income, it is essential to integrate economically valuable trees and other profitable understory crops, which when contrasted with monocropping, demonstrates superiority owing to its economic and environmental advantages, along with its diminished susceptibility to external influences (Anshiso et al. 2017).

The wild pomegranate, scientifically known as *Punica granatum* L. and commonly referred to as 'Daru,' is a fruit plant belonging to the Punicaceae family. This ancient and esteemed fruit species is renowned for its abundance of bioactive compounds with medicinal properties. Daru can thrive in a variety of agro-climatic zones worldwide, ranging from tropical to temperate regions, although its primary cultivation is concentrated in tropical and sub-tropical areas. In India, it is naturally found in drier barren and sub-marginal lands of the mid-hill region of the outer Himalaya, specifically in Jammu and Kashmir, Himachal Pradesh, and Uttarakhand, at an elevations ranging from 900 to 1800 meters above mean sea level (Mushtaq and Gangoo 2017). The species is extensively distributed in Himachal Pradesh, especially in the districts of Mandi, Solan, Sirmour, Kullu, Chamba, and Shimla. It holds significant value for farmers due to its drought-resistant nature and minimal post-planting care requirements, substantially contributing to their livelihoods (Thakur et al. 2011). The wild pomegranate fruits closely resemble with cultivated pomegranates but are notably higher in acidity. This distinctive fruit boasts a unique flavor and color, attributed to its rich content of organic acids and anthocyanins. The sun-dried seeds with pulp are utilized in the production of 'anardana,' a condiment widely used as an acidifier in curries, chutneys, and various culinary dishes, enhancing the overall taste and aiding digestion. Locally, the anardana prepared in Himachal Pradesh, Jammu and Kashmir, and Uttarakhand is sold annually in local markets, fetching good prices ranging from Rs. 200 to 600 per kg, along with generating substantial by-products like flavedo. The pomegranate peel is rich in polyphenolic compounds such as ellagitannins and ellagic acid, while the arils contain anthocyanins (delphinidin3-glucoside, cyanidin, etc.), responsible for antioxidant, antimutagenic, anti-cancer, anti-inflammatory, and anti-diabetic effects (Masci et al. 2016 and Al-Rawahi et al. 2013). This has led to an increasing demand for value-added products derived from wild pomegranate in recent years (Sharma and Thakur 2018). Anthocyanins, in particular, contribute to the formation of an appealing pink-reddish hue in its arils. With its diverse pigments, phenolic compounds, acids, and vitamins, wild pomegranate offers various medicinal benefits for human health.

Black gram or Mash (*Vigna Mungo* L.), is one of the important pulse crop grown throughout the country. India currently is the largest producer of black gram accounting for more than 70% of the global production (1.5 million tonnes of seeds per annum), followed by Myanmar and Pakistan. As per the 4th advance estimates of food grain production for the 2021-22, the nationwide production estimate for Black gram reached 2.84 million tonnes, compared to 2.23 million tonnes in the previous year (2020-21). The crop is known for its resilience to adverse climatic conditions and its capacity to enhance soil fertility through the fixation of

atmospheric nitrogen. With a nutrient-rich composition, black gram contains 24 percent protein, 1.4 percent fat, and 59.6 percent carbohydrates. Besides, it serves as a valuable nutritive fodder for animals.

Organic and inorganic manures have a significant impact over the growth of plants. Improper application of inorganic fertilizers, devoid of organic supplements, has adversely impacted soil properties across physical, chemical, and biological dimensions, leading to environmental pollution (Kumar 2023; Albiach et al. 2000). While both chemical fertilizers and organic manures are acknowledged for their role in promoting crop growth, the consistent use of high doses of chemical fertilizers poses risks to soil health and the environment. In contrast, organic manures are gaining prominence as essential components of environmentally sustainable agriculture, with the goal of optimizing crop productivity (Sheikh and Dwivedi 2007). Organic manures and biofertilizers play a critical role in revitalizing the soil by converting unavailable soil nutrients into accessible forms through processes such as mineralization and solubilization (Singh et al. 2023). The utilization of organic manures contributes to enhancing soil quality, encompassing improvements in physical, chemical, and biological properties, as well as an increase in water-holding capacity. Consequently, this leads to elevated crop productivity and the preservation of crop quality. Organic manures like vermicompost, farmyard manure, and goat manure hold particular significance as they provide a means to reduce dependence on expensive chemical fertilizers, which can have detrimental long-term effects on soil health (Sharma 2005). Especially, enzyme activity, considered an indicator of microbial activity, is augmented by the addition of organic manures such as farmyard manure, vermicompost, goat manure, and other liquid fertilizers (Hebbal et al. 2018). In response to these concerns, the Himachal Pradesh government has implemented various initiatives, such as the Prakritik Kheti Khushal Kisan Yojana under Zero Budget Natural Farming, aimed at reducing cultivation costs and discouraging the use of chemical fertilizers and pesticides. Hence, the key approach to mitigate soil deterioration and restore long-term soil health is through the integration of organic, bio, and chemical fertilizers, known as integrated nutrient management.

The underlying biological principle of agroforestry is the utilization of fruit trees, which are woody perennials, minimize nutrient loss from the system and positively impact the growth of field crops. Therefore, diversifying agricultural practices by incorporating trees and other profitable understory crops is essential to boost returns per unit area and align with the government's objective of doubling farmers' income. Thus, keeping in view the economic importance of wild pomegranate along with black gram, the present study was carried out in order to evaluate the effect of planting conditions and integrated nutrient management on the growth and yield of black gram along with soil properties and economics of the system.

Material and Methods

Experimental Location and Climate

The experimental was conducted during the years 2022–2023 in two year old wild pomegranate orchard established at Experimental farm at Pandah of Department of Silviculture and Agroforestry, Dr. YS Parmar University of Horticulture and Forestry, Nauni-Solan (Himachal Pradesh). The experimental site was located at 30°51'06.42"N latitude, 77°09'48.57"E longitude and 1179 m elevation above the mean sea level (Fig. 1). The study area falls under the sub tropical belt of mid-hills sub humid agro-climatic zone of Himachal Pradesh, India. There is a considerable variation in the seasonal and diurnal temperature of the experimental site. Generally, May and June are the hottest months, whereas December and January the coldest ones. The annual rainfall ranges from 1100–1200 mm, major of which is received from the month of June to September i.e. monsoon period. The mean annual minimum temperatures for the year 2021, 2022 and 2023 were recorded as 13.68°C, 11.74°C and 12.68°C whereas, the mean annual maximum temperatures were recorded as 26.50°C, 26.50°C and 26.34°C, respectively. The prevalent climatic conditions of the study site during the year 2021–2023 were presented in Fig. 2.

Soil Profile before the start of the experiment

The soil of area belongs to Typic Eutrochert at sub group level according to Soil Taxonomy of USDA. The soil physical and chemical properties of the experimental field estimated before start of the field trial are given in the Table 1.

Table 1
Soil physical and chemical properties of the experimental field
before sowing

Sr. No.	Parameters	S ₁	S ₂
1.	Bulk Density (g cm ⁻³)	1.39	1.43
2.	Particle Density (g cm ⁻³)	2.60	2.78
3.	Porosity (%)	46.67	48.51
4.	Soil Moisture (%)	6.95	6.84
5.	Soil EC (dS m ⁻¹)	0.156	0.125
6.	Soil pH (1:2)	6.69	6.54
7.	Organic Carbon (%)	0.76	0.74
8.	Available Nitrogen (kg ha ⁻¹)	235.39	220.32
9.	Available Phosphorus (kg ha ⁻¹)	28.83	27.04
10.	Available Potassium (kg ha ⁻¹)	246.66	237.52

Where, S₁: Under wild pomegranate based agroforestry system and S₂: open conditions

Experimental details

This research trial encompassed two distinct structural and functional components: wild pomegranate as a woody perennial and the cultivation of black gram (*Vigna mungo*) as intercrop within an agri-horticultural system. Furthermore, the study investigated the influence of integrated nutrient management on two planting conditions viz., S₁: Under wild pomegranate based agroforestry system and S₂: under open conditions (without tree). Wild pomegranate trees were planted in the July month of 2020 with the spacing of 2 × 4 m in East to West direction. Twelve manure and fertilizer doses were given alone as well as together in combination such as T₁: RDF (Recommended dose of Fertilizer), T₂: FYM (100% N equivalent basis), T₃: Vermicompost (100% N equivalent basis), T₄: Goat manure (100% N equivalent basis), T₅: Jeevamrut @ 500 l/ha, T₆: 50% RDF + 50% FYM, T₇: 50% RDF + 50% VC, T₈: 50% RDF + 50% GM, T₉: 50% RDF + 50% Jeevamrut, T₁₀: 50% RDF + 25% FYM + 25% VC, T₁₁: 50% RDF + 25% GM + 25% Jeevamrut and T₁₂: Control, to both the planting conditions in triplicate replications under Randomized Block Design (Factorial) to examine the production potential, soil properties and bio-economics. All the fertilizers application were calculated on per plot basis and applied to different plots randomly, however nitrogen was applied in three split doses, first at the time of sowing, second at the time of vegetative growth and third at the time of reproductive stage. Moreover the manures were evenly spread and thoroughly mixed with the soil. The standard procedure of liquid jeevamrut preparation consist of mixing of cow dung (1.25 kg), cow urine (1.25 L), jaggery (250 g), pulse flour (250 g) and 100 g field soil in 25 L of water in a container and after covering the mouth of the container with a gunny cloth the mixture was kept under shade for 15 days (Devakumar et al. 2014). The dose of jeevamrut was given as soil drench after the 30 days of sowing, thereafter application was given at the regular interval of 15 days in order to maintain the effect and enable the microbial growth till the final harvesting.

Cultural practices

Before sowing, the experimental site was ploughed thoroughly by tractor and leveled by removing pebbles, stones, residues of previous crop and weeds. A total of 72 plots of size 2 × 4 m were prepared and treatments were allocated according to the experimental layout for black gram var. Him Mash-1. The crop was sown in the month of June, 2022 with the spacing of 30 × 20 cm. FYM and vermicompost were applied as per treatment before sowing of the crop and incorporated in upper 10–15 cm layer of each plot. Half dose of the nitrogen and full dose of phosphorus and potassium was applied as basal dose at the time of sowing and the remaining half dose of nitrogen was top dressed at pre flowering stage as per treatment. The fertilizers (urea, SSP and muriate of potash) were applied by following the package of practices of CSKHPKV Palampur (Himachal Pradesh).

Jeevamrut was applied two times as a soil drench after 15 and 30 days of sowing. Thinning was carried out to maintain the optimum plant population at 20 days after sowing. The experimental plot was kept free from weed by hand weeding at 45 and 90 days after sowing. Harvesting, threshing and cleaning of the crop were done manually.

Growth and yield traits

Various growth and yield parameters of plant viz., plant height, number of branches plant⁻¹, number of pods plant⁻¹, pod length, number of grains pod⁻¹, number of grains plant⁻¹, 1000 seed weight, grain yield, biological yield and harvest index were measured at the time of harvest of the black gram. For this, five plants were selected as randomly from each treatment from all the replicates were selected and then analyzed.

Soil physical and chemical properties

Before the beginning of the experiment and after the crop harvest immediately three soil samples from each plot at depth of 0–30 cm were collected and combined into a single composite sample that will be the representative sample. Collected samples were placed in muslin cloths, labeled and send to the agroforestry laboratory. The samples were dried in the shade and grounded through mortar and pestle in order to refine the soil under 2 mm sieve and then subjected to various methods for assessing the physical and chemical properties of soil.

Bio-economics analysis

The bio-economic analysis was performed on per hectare basis for both the planting systems. The initial planting expenditures of wild pomegranate trees in the year of its plantation and the ensuing expenses associated with its upkeep were carefully considered while considering the annuity method. The cost of cultivation of *Vigna mungo* var. Him Mash-1 under agroforestry system and as sole cropping system was worked out on the per hectare basis. The requirement of labour and expenses on different operations such as ploughing, weeding, harvesting and threshing were calculated on the prevalent market rates. Cost of inputs such as seeds, fertilizers and manures were calculated on the basis of actual amount used in the land use system. The gross returns (Rs ha⁻¹) were worked out by multiplying the grain yield (q ha⁻¹) by the present market price (Rs q⁻¹) of the seed. Net returns were worked out by deducting cost of cultivation from the gross returns. BCR was calculated by dividing Gross returns from the Cost of cultivation.

Statistical analysis

The collected data of the experiment were subjected to analysis of variance as specified by Gomez and Gomez (1984) using R-Studio, version 4.3.2 software. The means were tested using the Shapiro-Wilk normality test with the least significant difference (LSD) at $p \leq 0.05$ and the graphs were prepared using Origin Pro Software with Holm-Sidak method.

Results and Discussion

Growth and yield attributes of *Vigna mungo*

The data enumerated in the Table 2 clearly indicates that all the growth and yield attributes of black gram suppressed under wild pomegranate than the sole cropping (open conditions). Statistical significant impact of planting conditions and nutrient sources was observed for all the studied parameters. The average maximum plant height (34.65 cm) was found in plants under sole cropping i.e. S₂, while the minimum height of plants (31.67 cm) was observed in plants under wild pomegranate canopy (S₁). In response to various integrated nutrient doses, the height was recorded highest (38.45 cm) in the T₆ and lowest (31.67 cm) was observed in T₁₂. The average pods per plant was observed highest (28.72) under S₂ (open conditions), while the lowest count (25.59) registered in S₁ (under wild pomegranate), indicating an average reduction of 10.90% under the wild pomegranate based agroforestry system as compared to open conditions. Regarding different doses of organic and inorganic manures, the maximum (31.15) pods per plant were found in T₆ (50% RDF + 50% FYM), while the minimum (23.63) in T₁₂ (no manure).

In terms of planting conditions, S₂ (sole crop) exhibited the highest count (132.02) for grains per plant as compared to agroforestry system i.e. S₁ (111.19). On an average, fall in grains per plant was reported to be 15.78% in S₁ (under agroforestry)

when compared to open conditions (S_2). Concerning integrated nutrient management, T_6 proved to be the most effective integrated nutrient approach, showing the maximum count (131.23) which was statistically at par with T_7 (128.98), while the minimum (110.30) was observed in T_{12} . The aggregated data across both years indicates that among different planting conditions, the highest 1000 grain weight (38.34 g) was observed in S_2 (open conditions), while the lowest (37.67 g) in S_1 (under tree). Regarding various doses of organic and inorganic manures, the maximum grain weight (41.38 g) was found in T_6 , whereas the minimum (34.21 g) was recorded in T_{12} (no manure).

Among planting conditions, S_2 (sole cropping) exhibited the highest grain yield (11.79 q ha^{-1}) compared with S_1 i.e. agroforestry system (10.23 q ha^{-1}). On an average, reduction in grain yield was found to be 13.23% in agroforestry system (S_1) when compared to open conditions (S_2). Similarly, in fertilizer applications, T_6 proved to be the best dose of integrated nutrient treatment, showed the highest grain yield (13.09 q ha^{-1}), statistically at par with T_7 and T_8 , while the minimum (8.78 q ha^{-1}) was observed in T_{12} . For biological yield the maximum (36.60 q ha^{-1}) biological yield was recorded in S_2 and minimum (33.16 q ha^{-1}) was recorded in S_1 . Moreover, in the average analysis of data, there was a 9.4% reduction in biological yield observed in the agroforestry system (S_1) when compared to the open conditions (S_2). Among different integrated nutrient management treatments, highest (40.93 q ha^{-1}) biological yield was recorded in treatment T_6 and lowest (30.07 q ha^{-1}) in T_{12} (control).

The present investigation revealed a significant impact on the growth and yield parameters of mash when cultivated beneath wild pomegranate trees (S_1) as compared to the sole cropping system (S_2). In the sole cropping condition, all attributes reached their maximum values, presenting a stark contrast to the agroforestry system centered on wild pomegranate. This divergence is primarily attributed to the reduced availability of photosynthetically active radiation (PAR) experienced under the canopy of wild pomegranate trees. Moreover, the presence of above and below ground competition, coupled with the shading effect of the trees, collectively imparts adverse effects on the yield parameters of mash. The intricate root of wild pomegranate trees further complicates matters by potentially interfering with the root system of the mash crop, creating a competitive environment for essential resources and impacting the nutrient absorption capacity of crop. In the context of the wild pomegranate based agroforestry system, the compromised light conditions contribute to an overall reduction in yield compared to the more favorable conditions availed by sole cropping. The outcomes of the present study are in alignment with the findings of Lodh et al. (2024), who observed a decline in all yield parameters of black gram in close proximity to *Grewia optiva* trees. Sharma et al. (2023) also revealed that yield of intercropped soybean increased with an increase in the distance of crop from aonla trees. Bhatia et al. (2022) also observed a reduction in yield parameters, including the number of grains per pod, 1000 grain weight, grain yield, and harvest index, by 6.38%, 2.33%, 12.24%, and 4.35%, respectively, under an *Emblica officinalis* based agroforestry system compared to sole mash cropping. The results of the present study are also in line with Ombase et al. (2023), Mevada et al. (2023), Sharma (2021), Pandey et al. (2019) and Bhusara et al. (2018).

Table 2

Effect of integrated nutrient management and planting conditions on growth and yield parameters of *Vigna mungo* under wild pomegranate based agroforestry system

Treatments System	Plant Height (cm)			Number of pods plant ⁻¹			Number of grains plant ⁻¹		
	S ₁	S ₂	Mean	S ₁	S ₂	Mean	S ₁	S ₂	Mean
T1	32.87 ^{efghi}	36.28 ^{bc}	34.58^{bc}	26.21 ^{fghi}	29.33 ^{bcd}	27.77^{bcd}	113.86 ^{jk}	137.03 ^b	125.44^d
T2	30.37 ^{kl}	34.73 ^{bcdef}	32.55^d	25.58 ^{ghi}	28.52 ^{bcdef}	27.05^{bcd}	111.46 ^{kl}	135.98 ^b	123.72^d
T3	30.23 ^{kl}	32.67 ^{fghij}	31.45^d	25.30 ^{ghi}	28.49 ^{bcdef}	26.90^{bcde}	109.51 ^{lm}	132.21 ^c	120.86^e
T4	30.17 ^{kl}	32.13 ^{ghijk}	31.15^d	24.90 ^{hi}	27.29 ^{defgh}	26.10^{de}	107.96 ^m	129.91 ^{cd}	118.93^{ef}
T5	29.20 ^{lm}	33.53 ^{defg}	31.37^d	23.79 ^{ij}	26.73 ^{efgh}	25.26^{ef}	103.20 ^{no}	122.68 ^{fg}	112.94^h
T6	36.40 ^{bc}	40.50 ^a	38.45^a	29.20 ^{bcde}	33.10 ^a	31.15^a	120.47 ^{gh}	142.00 ^a	131.23^a
T7	35.37 ^{bcd}	36.63 ^b	36.00^b	27.03 ^{defgh}	29.93 ^{bc}	28.48^b	118.56 ^{hi}	139.41 ^{ab}	128.98^{ab}
T8	33.60 ^{defg}	34.95 ^{bcde}	34.28^c	26.43 ^{fgh}	29.37 ^{bcd}	27.90^{bc}	117.88 ^{hi}	138.35 ^b	128.12^{bc}
T9	30.75 ^{ijkl}	34.22 ^{cdefg}	32.48^d	25.33 ^{ghi}	27.67 ^{cdefg}	26.50^{cde}	106.65 ^{mn}	124.68 ^{ef}	115.66^g
T10	33.10 ^{efgh}	36.27 ^{bc}	34.68^{bc}	26.08 ^{fghi}	30.50 ^b	28.29^b	115.33 ^{ij}	136.10 ^b	125.71^{cd}
T11	31.05 ^{hijkl}	33.33 ^{defg}	32.19^d	25.17 ^{ghi}	28.53 ^{bcdef}	26.85^{bcde}	107.97 ^m	126.84 ^{de}	117.40^f
T12	26.98 ^m	30.53 ^{kl}	28.76^e	22.06 ^j	25.20 ^{ghi}	23.63^f	101.51 ^o	119.09 ^h	110.30ⁱ
Mean	31.67^b	34.65^a		25.59^b	28.72^a		111.19^b	132.02^a	
CD _{0.05}	S	0.64		S	0.72		S	1.00	
	T	1.57		T	1.77		T	2.46	
	S×T	2.22		S×T	2.50		S×T	3.48	
*Mean values of each growth and yield parameters followed by the same letter are not significantly different at P= 0.05									
T: Treatments, S: Planting conditions, Y: Years, T1: RDF (Recommended dose of Fertilizer), T2: FYM (100% N equivalent basis), T3: Vermicompost (100% N equivalent basis), T4: Goat manure (100% N equivalent basis), T5: Jeevamrut @ 500 l/ha, T6: 50% RDF + 50% FYM, T7: 50% RDF + 50% VC, T8: 50% RDF + 50% GM, T9: 50% RDF + 50% Jeevamrut, T10: 50% RDF + 25% FYM + 25% VC, T11: 50% RDF + 25% GM + 25% Jeevamrut, T12: Control, S1: under wild pomegranate based agroforestry system and S2: Open conditions									

Conversely, the combined application of nutrients demonstrated a substantial impact on the yield parameters of mash. Among various nutrient treatments, the mash yield parameters reached their zenith when 50% of the recommended dose of fertilizer (RDF) was harmonized with 50% of farmyard manure (FYM) on a nitrogen equivalence basis. The attainment of this peak yield can be ascribed to the synergistic effects arising from the immediate and balanced nutrient supplied by RDF, addressing early stage nutritional requirements. This was complemented by the sustained release of nutrients and enhanced nutrient mobilization facilitated by FYM. Furthermore, the contribution of organic matter by FYM to the soil played a pivotal role. It not only acted as a source of nutrients but also promoted beneficial microbial activity, fostering nutrient cycling and availability in the soil. The microbial breakdown of organic matter in FYM rendered nutrients more easily accessible to plants, creating a nutrient-rich environment for the growth of mash. This integrated nutrient management approach goes beyond mere nutrient supply; it actively contributes to supporting essential physiological processes, culminating in an overall enhancement in mash yield. Similar results were also reported by Naushad et al. (2023) where they documented noteworthy enhancements in green gram, specifically in the number of pods per plant (31.43), number of seeds per pod (12.46), test weight (37.26 g), and harvest index

(34.90%) when treated with 100% recommended dose of fertilizer (RDF), 5.0 tonnes of farmyard manure (FYM) per hectare, and inoculation with Rhizobium and PSB. Similarly, Singh et al. (2018) also substantiated that the combination of recommended dose of nitrogen (RDN) with farmyard manure (FYM) resulted in the highest yield attributes and seed yield in *Vigna mungo* compared to RDN alone. The findings of present study are consistent with the findings of Tigga et al. (2022), Singh and Misal (2022), Sharma and Thakur (2019), Chophi et al. (2016) and Kumar et al. (2015). Collectively, these results underscore the impact of nutrient management practices on crop yields, emphasizing the intricate interplay between interactions within agroforestry and nutrient availability in shaping overall productivity.

Table 3
Effect of integrated nutrient management and planting conditions on growth and yield parameters of *Vigna mungo* under wild pomegranate based agroforestry system

Treatments System	1000 seed weight (g)			Grain yield (qha ⁻¹)			Biological yield (qha ⁻¹)		
	S ₁	S ₂	Mean	S ₁	S ₂	Mean	S ₁	S ₂	Mean
T1	38.17 ^{efg}	38.85 ^{cdef}	38.51 ^c	10.77 ^{ghij}	12.28 ^{bcde}	11.53 ^{cde}	34.26 ^{hi}	37.67 ^{de}	35.96 ^c
T2	38.12 ^{efg}	38.80 ^{cdef}	38.46 ^c	9.95 ^{ijkl}	11.63 ^{defg}	10.79 ^{efg}	32.41 ^{ijkl}	35.97 ^{fg}	34.19 ^{de}
T3	37.75 ^{fg}	38.43 ^{def}	38.09 ^{cd}	9.61 ^{ijkl}	11.34 ^{efgh}	10.48 ^{fgh}	30.98 ^{lmn}	35.14 ^{gh}	33.06 ^f
T4	36.77 ^{ghi}	37.45 ^{fgh}	37.11 ^d	9.22 ^{klm}	10.96 ^{fghi}	10.09 ^{ghi}	31.13 ^{klmn}	35.30 ^{gh}	33.22 ^{ef}
T5	34.64 ^{jk}	35.49 ^{ij}	35.06 ^{ef}	8.75 ^{lm}	10.31 ^{hijk}	9.53 ^{ij}	30.05 ^{mno}	32.46 ^{jk}	31.26 ^g
T6	40.98 ^{ab}	41.78 ^a	41.38 ^a	12.4 ^{bcde}	13.77 ^a	13.09 ^a	39.25 ^{bc}	42.60 ^a	40.93 ^a
T7	39.97 ^{bcd}	40.34 ^{abc}	40.16 ^b	11.78 ^{defg}	13.31 ^{ab}	12.55 ^{ab}	37.09 ^{def}	40.68 ^b	38.88 ^b
T8	39.86 ^{bcd}	40.27 ^{abc}	40.06 ^b	11.58 ^{defg}	13.08 ^{abc}	12.33 ^{abc}	36.18 ^{fg}	39.82 ^{bc}	38.00 ^b
T9	35.14 ^{jk}	36.13 ^{hij}	35.63 ^e	9.02 ^{lm}	10.69 ^{ghij}	9.85 ^{hi}	29.81 ^{no}	33.34 ^{ij}	31.57 ^g
T10	39.39 ^{cde}	40.07 ^{bc}	39.73 ^b	11.25 ^{efgh}	12.72 ^{abcd}	11.98 ^{bcd}	35.11 ^{gh}	38.42 ^{cd}	36.76 ^c
T11	37.43 ^{fgh}	37.84 ^{efg}	37.63 ^{cd}	10.29 ^{hijk}	12.04 ^{cdef}	11.16 ^{def}	33.06 ^{ij}	36.31 ^{efg}	34.69 ^d
T12	33.79 ^k	34.63 ^{jk}	34.21 ^f	8.15 ^m	9.40 ^{kl}	8.78 ^j	28.61 ^o	31.53 ^{klm}	30.07 ^h
Mean	37.67 ^b	38.34 ^a		10.23 ^b	11.79 ^a		33.16 ^b	36.60 ^a	
CD _{0.05}	S	0.45		S	0.36		S	0.42	
	T	1.05		T	0.88		T	1.05	
	S×T	1.56		S×T	1.24		S×T	1.48	

*Mean values of each growth and yield parameters followed by the same letter are not significantly different at P= 0.05

T: Treatments, S: Planting conditions, Y: Years, T1: RDF (Recommended dose of Fertilizer), T2: FYM (100% N equivalent basis), T3: Vermicompost (100% N equivalent basis), T4: Goat manure (100% N equivalent basis), T5: Jeevamrut @ 500 l/ha, T6: 50% RDF + 50% FYM, T7: 50% RDF + 50% VC, T8: 50% RDF + 50% GM, T9: 50% RDF + 50% Jeevamrut, T10: 50% RDF + 25% FYM + 25% VC, T11: 50% RDF + 25% GM + 25% Jeevamrut, T12: Control, S1: under wild pomegranate based agroforestry system and S2: Open conditions

Soil Attributes

All the soil properties (Fig. 3) were significantly improved under wild pomegranate based agroforestry systems. Planting conditions emerged as a pivotal factor influencing soil pH, with S₂ showcasing a higher pH (6.81) compared to S₁ (6.67).

Particularly under agroforestry conditions (S_1), there was a notable 2.09% reduction in pH compared to open conditions (S_2). Among various organic and inorganic treatments, the control plot with no manure (T_{12}) demonstrated the highest pH (7.01), while the lowest (6.44) pH was observed in the plot fertilized with 100% FYM (T_2). In general, the addition of organic manures abridges soil pH (Mahmood et al. 2017). This may be due to mineralization and later nitrification process by soil microbes present in the organic material as explicated by McCauley et al. (2017). Lower soil pH under agroforestry systems was also reported by Zahoor et al. (2022) and Sarvade et al. (2014). Likewise, Rathore et al. (2013) also reported lower soil pH (12.12–15.62%) in fruit based agrihorticultural system (mango + cowpea - toria) contrasted with the initial values which were recorded before the establishment of trial.

Among planting conditions, S_1 exhibited the highest electrical conductivity (0.233 dS m^{-1}) compared to S_2 (0.149 dS m^{-1}). In general, the reduction in electrical conductivity was reported to be 36.05% in S_2 (open conditions) when compared to agroforestry system (S_1). Among various integrated nutrient treatments studied, T_2 (100% FYM) marked the highest electrical conductivity (0.244 dS m^{-1}), which was statistically at par with T_6 and T_{10} whereas, the lowest (0.133 dS m^{-1}) under control plots (T_{12}). Parallel to our results, Uthappa et al. (2015) also reported that the use of FYM reinstates the damaged soil structure by reducing bulk density, particle density and improving conductivity and organic carbon.

The highest organic carbon (1.13%) was exhibited under S_1 (under agroforestry) compared to S_2 (1.05%). Overall, the reduction in organic carbon was found to be 7.61% in S_2 (open conditions) when compared to under agroforestry (S_1). Pertaining to different integrated nutrient treatments, T_2 (100% FYM) proved to be the best nutrient dose to mark highest organic carbon (1.18%), which was statistically at par with T_3 , whereas, lowest (1.00%) was registered under T_{12} (control). The annual deposition of leaf litter contributes to increase organic carbon phenomenon as the decomposition of the litter releases organic acids and carbon dioxide (CO_2), resulting in soil acidification and a subsequent decrease in pH. Additionally, tree roots release organic acids during their metabolic processes, further contributing to the soil acidity beneath the tree canopy. Sirohi et al. (2022) also stated that organic carbon was found highest under closer spacing of Poplar tree along with *Vigna unguiculata* as compared to sole cowpea. Subba and Dhara (2017) also announced increased soil organic matter content under agri-horti-silvi system when contrasted with the initial due to increased fertility of the soil through addition of fertilizers to the fruit trees and addition of organic matter from both the trees and intercrops. Palsaniya et al. (2009) also registered higher organic content in Subabul + maize treatment (0.72%) while in crop alone it was 0.48% only. Kibet et al. (2022) also worked out soil organic carbon stocks under sorghum based agroforestry systems in Western Kenya and found that higher content of organic carbon was incurred under agroforestry as compared to sole sorghum.

The average highest nitrogen ($323.52 \text{ kg ha}^{-1}$) content was registered in S_1 compared to S_2 ($306.09 \text{ kg ha}^{-1}$). In general, the decrease in nitrogen was found to be 5.38% in open conditions (S_2) when compared to S_1 (under agroforestry). Concerning different integrated nutrient treatments, T_2 (100% FYM) marked the highest nitrogen ($343.72.01 \text{ kg ha}^{-1}$), whereas, lowest ($262.67 \text{ kg ha}^{-1}$) was registered under T_{12} (no manure). Among planting conditions, S_1 (under agroforestry) recorded the highest value of available phosphorus (39.45 kg ha^{-1}) while lowest was observed under S_2 (35.45 kg ha^{-1}). The average reduction in phosphorus content was reported to be 10.13% in S_1 (open conditions) when compared to under agroforestry (S_2). Concerning different integrated nutrient treatments, T_2 (100% FYM) placed at the top for showing the highest (43.19 kg ha^{-1}) phosphorus content, which was statistically at par with T_3 , whereas, lowest (30.99 kg ha^{-1}) was registered under plots having no application of manure (T_{12}). In case of potassium, S_1 exhibited the highest available potassium content ($264.51 \text{ kg ha}^{-1}$) compared to S_2 ($250.87 \text{ kg ha}^{-1}$). Notably, the increase in available potassium was found to be 5.16% in S_1 (under agroforestry) compared to open conditions (S_2). Among various manure treatments, T_2 (100% FYM) emerged as the optimal integrated nutrient dose, showcasing the highest available potassium content ($276.29 \text{ kg ha}^{-1}$), while the lowest ($229.33 \text{ kg ha}^{-1}$) was observed under T_{12} (control).

All the soil properties after planting different crops under wild pomegranate trees enhanced significantly. The decomposition of tree leaves and fine roots enrich the soil surface with organic matter, providing soil stability and mineral elements through the

creation of stable humus (Adamczyk et al. 2019). Similar results were also exhibited by Prasad et al. (2019), where they found significant increase in soil organic carbon (0.67%), N ($181.50 \text{ kg ha}^{-1}$), P (18.36 kg ha^{-1}) and K ($140.66 \text{ kg ha}^{-1}$) under *Albizia procera* + wheat based agroforestry system as compared to pure crop exhibiting 0.52% organic carbon, $150.33 \text{ kg ha}^{-1}$ N, 11.32 kg ha^{-1} P and $113.16 \text{ kg kg ha}^{-1}$ K. Gebrewahid et al. (2019) reported a significant increase in soil pH, electrical conductivity, organic carbon, available nitrogen and phosphorus contents under the association of *Sesamum indicum*, *Sorghum bicolor* and *Gossypium* with *Oxytenanthera abyssinica* and *Dalbergia melanoxylon* as compared to the crops in open system. Similar findings were reported by Kar et al. (2019) who observed significant increase in electrical conductivity, organic carbon, nitrogen, phosphorous and potassium contents under *Grewia optiva* + garden pea agroforestry system as compared to sole cropping of garden pea. Singh et al. (2018) noticed significantly improved values of available N, P, K in agroforestry system (agrichiculture, agrisilviculture, agrihortisilviculture and silvopastoral) than sole agriculture cropping system. This might be because of dense root, quick microbial activity in positive condition, mycorrhizal affiliations and the impact of plant roots on soil and P dissolvability. Similar trend of increased soil available nitrogen in agri horticulture system was also reported by Salve et al. (2018). Similarly, the higher content of available potassium in tree based systems might be because of higher pumping of potassium from the subsoil by vegetation (Moges et al. 2013).

Bio-economics analysis

The bioeconomics of both sole *Vigna mungo* cropping and the *Vigna mungo* + wild pomegranate agroforestry system are detailed in Table 4. The results indicate that the *Vigna mungo* + wild pomegranate agroforestry system (S_1) achieved the highest average net return of US\$ 1094.09 ha^{-1} , whereas sole *Vigna mungo* cropping (S_2) registered a lower net return of US\$ 864.68 ha^{-1} . Among different fertilizer treatments, T_6 yielded the highest net return of US\$ 1196.80 ha^{-1} , while T_{12} had the lowest net return of US\$ 785.40 ha^{-1} . In terms of benefit-cost (BC) ratio, system S_1 recorded the highest value at 2.72, compared to 2.42 for S_2 . However for integrated nutrient treatments, T_8 showed the highest BC ratio of 2.89, closely followed by T_6 at 2.86, with T_{12} recording the lowest at 2.40.

The analysis suggests that agroforestry systems offer higher net returns and BC ratios compared to sole cropping, primarily due to the additional income from tree components. These findings align with research by Kombra et al. (2023), which found that a eucalyptus + wheat agroforestry system yielded the highest net return (Rs. 99,265.67 per hectare) compared to sole wheat cropping. Similarly, Kumar et al. (2023) noted higher net returns and BC ratios in a *Grewia* + Bhingraj intercropping system compared to a sole Bhingraj system. Bhatia et al. (2022) also reported higher net returns when field crops were combined with Harar and Aonla, and Thakur et al. (2019) found increased net returns and BC ratios in a *Pongamia pinnata*-based silvi-medicinal system compared to sole cropping of *Ocimum* species.

Additionally, this study observed the highest net returns and BC ratios with the integration of organic and inorganic fertilizers. This is consistent with findings by Kumar et al. (2023), Saakshi et al. (2022), and Garima and Pant (2017), who also reported the highest net returns with combinations of organic and inorganic fertilizers. Bhatia et al. (2023) similarly found a higher BC ratio (2.26) in an agroforestry system (soybean + Harar) compared to sole soybean cropping.

Table 4
Effect of planting conditions and integrated nutrient management on the bioeconomics (US \$ ha⁻¹) of Mash (*Vigna mungo*) under wild pomegranate based agroforestry system

Treatments/ Systems	Net Returns (\$ ha ⁻¹)			B:C ratio		
	S ₁	S ₂	Mean	S ₁	S ₂	Mean
T1	1178.53	907.62	1043.07	2.90	2.58	2.74
T2	994.69	785.60	890.15	2.38	2.18	2.28
T3	935.40	731.78	833.59	2.24	2.09	2.16
T4	972.89	754.83	863.86	2.49	2.25	2.37
T5	976.09	752.05	864.07	2.68	2.36	2.52
T6	1317.68	1075.92	1196.80	3.05	2.66	2.86
T7	1252.18	1018.37	1135.28	2.91	2.56	2.73
T8	1270.01	1037.73	1153.87	3.11	2.67	2.89
T9	992.84	780.97	886.90	2.69	2.36	2.52
T10	1192.62	957.50	1075.06	2.81	2.49	2.65
T11	1130.03	919.09	1024.56	2.93	2.51	2.72
T12	916.09	654.72	785.40	2.51	2.30	2.40
Mean	1094.09	864.68		2.72	2.42	

1 US\$=81.956 INR, T: Treatments, S: Planting conditions, Y: Years, T1: RDF (Recommended dose of Fertilizer), T2: FYM (100% N equivalent basis), T3: Vermicompost (100% N equivalent basis), T4: Goat manure (100% N equivalent basis), T5: Jeevamrut @ 500 l/ha, T6: 50% RDF + 50% FYM, T7: 50% RDF + 50% VC, T8: 50% RDF + 50% GM, T9: 50% RDF + 50% Jeevamrut, T10: 50% RDF + 25% FYM + 25% VC, T11: 50% RDF + 25% GM + 25% Jeevamrut, T12: Control, S1: under wild pomegranate based agroforestry system and S2: Open conditions

Conclusion

In the current scenario, the integration of *Vigna mungo* with wild pomegranate, supplemented by integrated nutrient doses, presents a vital model for sustaining livelihoods and ensuring food security in developing countries facing decreasing land areas and rapidly increasing populations. This fruit + pulse based agroforestry system has proven to be economically viable, offering a benefit-cost ratio of 2.5-3.0, thereby supporting the achievement of sustainable development goals. Given the rising demand for natural and organic farming for health purposes, this model is also recommended as it reduces reliance on inorganic fertilizers by effectively interlinking organic and inorganic nutrient sources. Particularly in the mid-hill north western Himalayas region, the combination of wild pomegranate + *Vigna mungo* has demonstrated significant economic benefits for local farmers and should be adopted on a larger scale. Nonetheless, further research is necessary to fully validate and optimize this model.

Declarations

Author Contribution

Avinash Kumar Bhatia: Written original draft, Methodology, Investigation, Formal analysis, Data collection, analysis, figures. K S Pant: Writing, review & editing, Validation, Supervision, Resources. Prem Prakash: Supervision, methodology, review and editing. Praveen Kumar: Review & editing, Formal analysis, Data validation. Harish Sharma: Visualization, reviewed, Validation & Investigation. Saakshi: Writing, review & editing, Investigation, data collection, Conceptualization. Prakash: Data collection, analysis, validation and editing. Babita: Review & editing, Visualization, Data analysis, graphs.

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Data Availability

Data is provided within the manuscript and supplementary information files.

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Figures

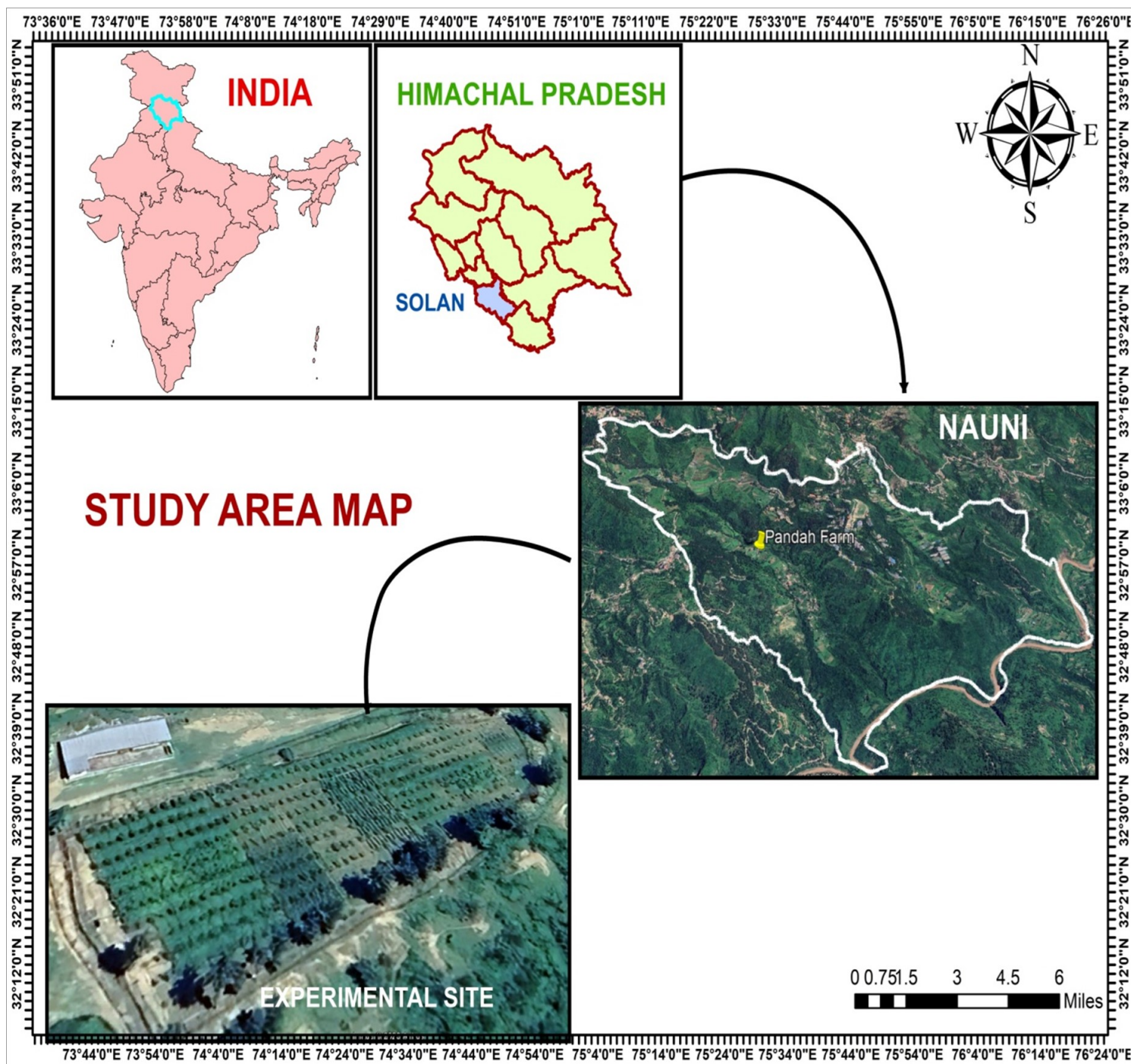


Figure 1

Study area map

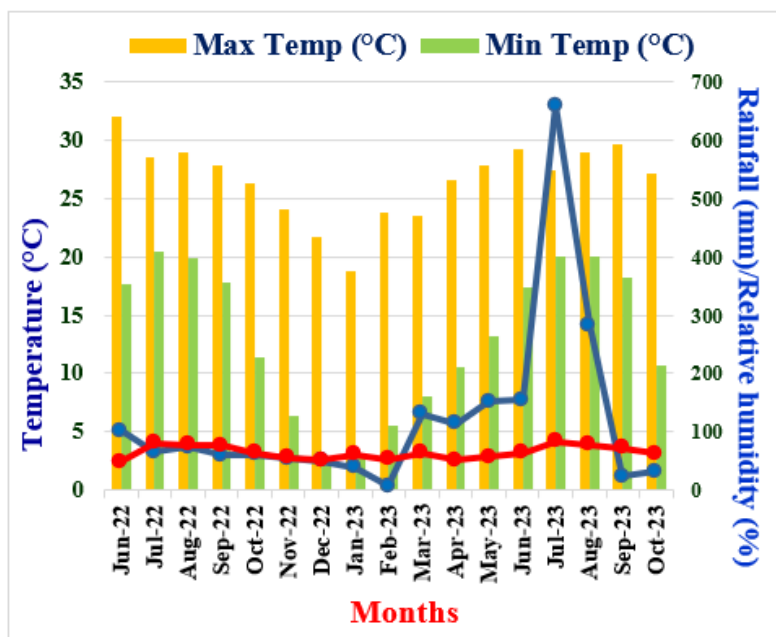
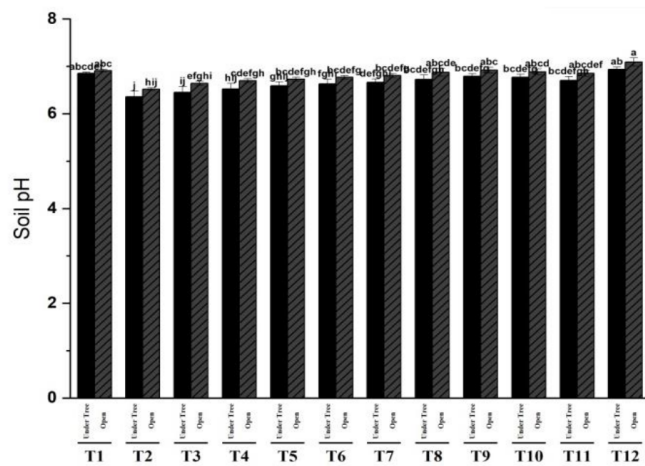
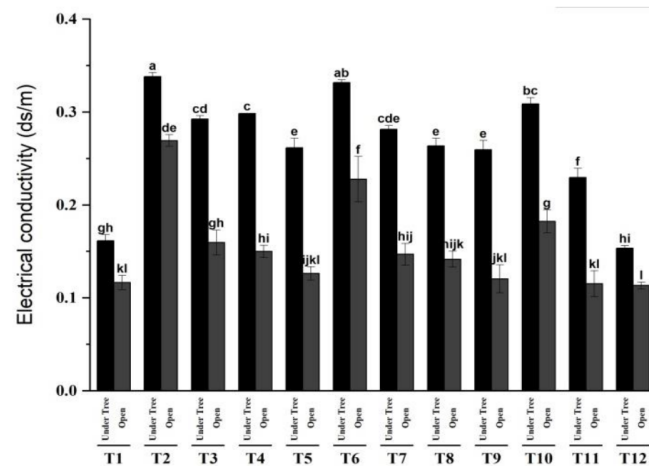


Figure 2

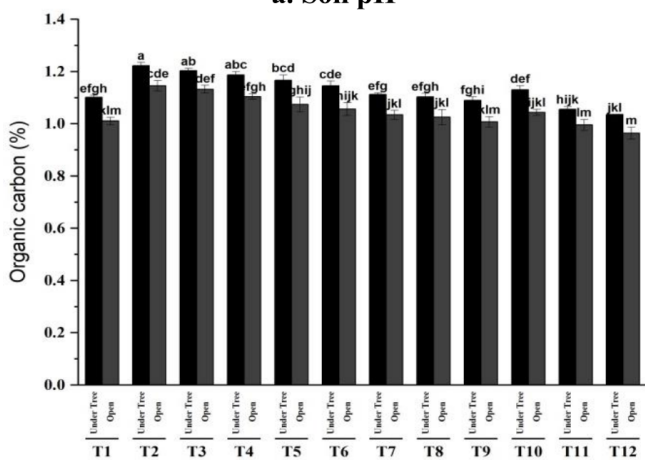
Meteorological data



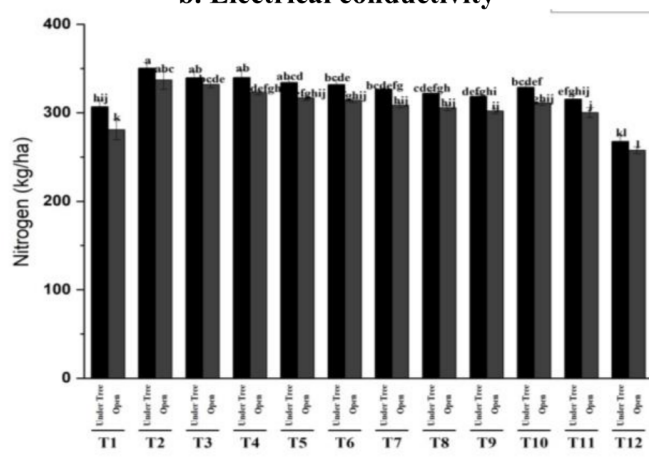
a. Soil pH



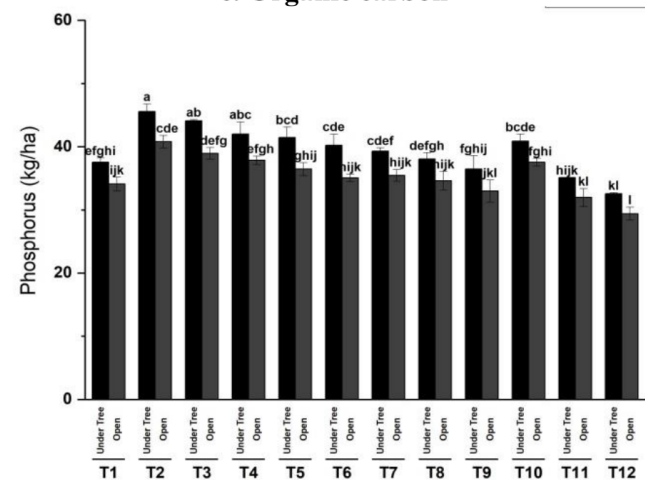
b. Electrical conductivity



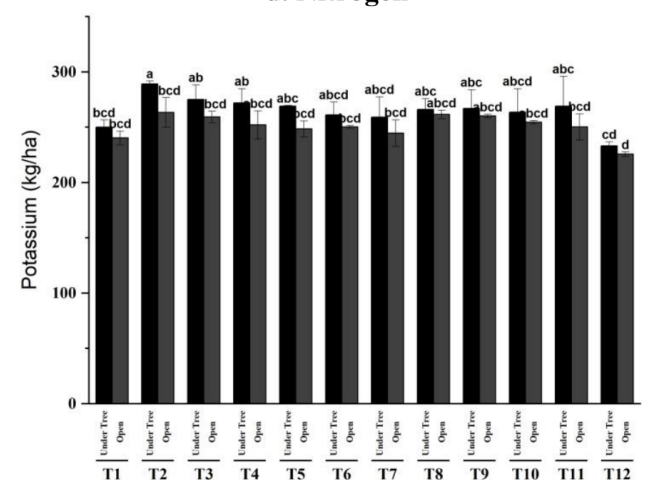
c. Organic carbon



d. Nitrogen



e. Phosphorus



f. Potassium

Figure 3

Soil attributes (a,b,c,d,e and f)

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