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Effects of Integrated Nutrient Management on Soil Properties, Seed Germination and Seedling Vigour in Fabaceae Species

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Abstract

The present study evaluated the effects of organic and inorganic fertilizer treatments on soil physico-chemical properties, seed germination behaviour and seedling vigour in *Phaseolus vulgaris* (L.), *Vigna radiata* (L.) R. Wilczek and *Pisum sativum* (L.) of Fabaceae family. Treatments comprised farmyard manure (FYM), vermicompost (VER), rice straw char (RSC), inorganic fertilizer (IF) and their integrated combinations at varying doses. Significant variation was observed among treatments for soil quality and seedling performance parameters. Integrated treatments, particularly rice straw char with inorganic fertilizer (RSCIF) and vermicompost with inorganic fertilizer (VERIF), exhibited superior germination and seedling vigour. In contrast, germination was inhibited under excessive application of inorganic fertilizer (IFD) and control treatments owing to poor soil physical condition and extreme acidity (pH 3.8). Optimal seed germination and early growth of the studied seeds were observed at soil pH 7.1 to 7.8. Correlation analysis revealed strong positive relationship of pH, electrical conductivity (EC) and water holding capacity (WHC) with germination percentage (GP), vigour index (VI) and dry matter yield (DMW), while bulk density (BD) showed strong negative correlation with these variables. The results demonstrate that integrated nutrient management in adequate application dose improved soil health, seed germination, seedling vigour and biomass accumulation and can support better crop establishment.

Keywords: *Integrated nutrient management, Seed germination, seedling vigour, Soil pH, Bean, Pea, Moong*

Introduction

Seed germination is a critical physiological process that determines seedling establishment, crop stand development and ultimately agricultural productivity [1], [2]. The transition from a quiescent seed to an actively growing seedling is regulated by complex interactions among genetic, environmental and edaphic factors. Among these, soil physicochemical properties and nutrient availability play a crucial role in controlling water uptake, enzyme activation, reserve mobilization and metabolic activities necessary for successful germination. Consequently, nutrient management practices that improve the seedbed environment are essential for ensuring successful crop establishment [3]. Chemical fertilizers are widely used to enhance soil fertility through the supply of readily available nutrients required for plant growth and development. Although they contribute significantly to agricultural productivity, excessive and long-term application may increase soil acidity and osmotic stress, thereby negatively affecting seed germination and seedling growth [4]. Organic amendments such as farmyard manure (FYM)and vermicompost have been widely recognized for their ability to improve soil structure, enhance water-holding capacity, stimulate microbial activity and to provide a sustained release of nutrients essential for plant growth and development [5]. Similarly, rice straw char, are increasingly recognized as valuable soil amendments due to their ability to improve soil moisture retention, nutrient availability and soil physicochemical properties [6]. However, improper application rate of the same also increases soil electrical conductivity, release phytotoxic compounds or temporarily immobilize nutrients, potentially affecting seed germination and seedling growth [7].

In Assam, India, agricultural soils are predominantly acidic and sandy loam in nature [8]. Integrated nutrient management, involving the combined use of organic manures and inorganic fertilizers, has been recognized as

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an effective strategy for improving soil fertility, pH and crop productivity [9]. Such integration ensures balanced nutrient availability, thereby supporting germination, seedling vigour and early plant growth [10]. Moreover, the combined use of different organic amendments improves soil aggregation, water retention and microbial diversity, although their effectiveness depends largely on amendment type, quality and application rate [11].

The family Fabaceae comprises some of the most important pulse crops worldwide and plays a significant role in agricultural sustainability through biological nitrogen fixation. Fabaceae seeds are generally rich in proteins and depend on rapid root development for successful nodulation and nutrient acquisition during early growth [12]. Seed size is an important determinant of germination performance, as larger seeds possess greater nutrient reserves that support seedling growth under suboptimal environmental conditions [13]. In contrast, smaller seeds are often more sensitive to variations in soil conditions and nutrient availability, making the interaction between seed size and nutrient management particularly important for successful establishment.

Despite the recognized importance of organic and inorganic nutrient inputs, limited information is available regarding their combined effects on seed germination and seedling establishment of Fabaceae crops under the agroecological conditions of Assam. Most previous studies have focused primarily on crop yield and biomass production, while comparatively less attention has been given to early stage of germination processes. Furthermore, information regarding dose-dependent responses, seed size interactions and associated changes in seedbed soil properties remains limited. Therefore, understanding the influence of organic manures, inorganic fertilizers and their integrated combinations on germination and early seedling growth is essential for developing sustainable nutrient management strategies. In this context, the present study was undertaken to evaluate the effects of different organic and inorganic nutrient amendments on seed germination, seedling vigour and seedbed soil properties of selected crops of Fabaceae species under the soil conditions of Assam.

Methodology

The experiment was carried out during April 2026 at Mohanbari, Dibrugarh, Assam-768012, under ambient room temperature, natural sunlight and prevailing environmental conditions.

Collection and preparation of seed and soil:

Varied sized seeds of Fabaceae family were selected for the experiment. The seed selected are french bean (*Phaseolus vulgaris* L.), Moong (*Vigna radiata* L.) and Peas (*Pisum sativum* L.), which were collected from Naliapul market Dibrugarh, Assam, India.

Germination test was performed in 70% alcohol sterilized disposable dishes. Dishes were made ready for the treatments with the treatment tags. Seeds were washed with distilled water followed by dripped in 2% sodium hypochlorite (NaClO) solution for surface sterilization. After 30 minutes the seeds were rinsed with distilled water to remove the coating of NaClO.

Garden soil was collected (topsoil 15 cm depth) from an agricultural field and visible roots; debris and other unwanted particles were separated from the soil soon after collection. Properly mixed (100 gm) uniform particle of soil was taken in each pre sterilized disposable dish (calculated using metric conversions and bulk density of the soil).

Collection and preparation of FYM, Vermicompost, rice straw char and inorganic fertilizers:

FYM was collected from a local household in Mohanbari, Dibrugarh. The collected FYM was sun-dried for four days and then ground into a uniform material. Vermicompost was procured from a local retail seller in Mohanbari. Rice straw char was prepared by collecting raw rice straw from a nearby field, burning it under local environment conditions, and subsequently grinding it to obtain a uniform char material.

Treatments undertaken

Total 11 treatments were undertaken: FYM10 (Farm yard manure, 10 t ha^{-1}), FYM20 (Farm yard manure, 20 t ha^{-1}) , VER10 (Vermicompost, 10 t ha^{-1}), VER20 (Vermicompost, 20 t ha^{-1}), RSC10 (Rice straw char, 10 t ha^{-1}), RSC20 (Rice straw char, 20 t ha^{-1}), IF (Inorganic fertilizer recommended dose), IFD (Inorganic fertilizer double the recommended dose), FYMIF (FYM, 5 t ha^{-1} + Inorganic fertilizer, 50% of recommended dose), VERIF (Vermicompost, 5 t ha^{-1} + Inorganic fertilizer, 50% of recommended dose), RSCIF (Rice straw char 5 t ha^{-1} + Inorganic fertilizer, 50% of recommended dose, C: control. Where 10 t ha^{-1} = 5.54 g kg^{-1} and 20 t ha^{-1} = 11.08 g kg^{-1}. The *Package of Practices for Rabi Crops of Assam, 2023*, jointly published by Assam Agricultural University (AAU), Jorhat, and the Department of Agriculture, Government of Assam, was followed for the application of both organic manures and inorganic fertilizers.

According to the treatments undertaken, all the types of organic manures and inorganic fertilizers were added to disposable dishes containing 100 gm soil. Three replications were taken for each treatment. Ten seeds of each crop were allowed to germinate in one dish. Equal amount of distilled water required for germination was sprayed on every dish.

Germination Parameters:

Germination performance was observed till eight days of germination (after emergence of radicle and plumule). Number of seeds germinated in each day (24 h) was noted and the lengths of plumules and radicals were recorded at the end of the experiment. On completion of germination, the germinated seeds were uprooted, and soil samples were collected for further analysis.

To evaluate the germination performance of the tested seeds under applied treatments, percent germination was calculated following [14] Germination index, percent inhibition of germination, and vigour index were obtained as given by [15] and calculated using following formula:

$$\text{Percent germination (GP)} = \frac{No.of\ seeds\ germinated}{Total\ no.of\ seeds} \times 100$$

$$\text{Germination Index (GI)} = (8 \times n3) + (7 \times n4) + (6 \times n5) + (5 \times n6) + (4 \times n7) + (3 \times n8) + (2 \times n9) + (1 \times 10)$$

where, n1, n2, n3 are the no. of seeds germinated on 1st, 2nd and subsequent days until 8th day.

$$\text{Percent inhibition of germination (PIG)} = 100 - \left(\frac{\text{GI of treatmnet}}{\text{GI of control}} \times 100 \right)$$

$$\text{Vigour index (VI)} = (\text{Radicle length} + \text{Plumule length}) \times \text{Percent germination}$$

Seedling biomass

Uprooted seedlings were washed properly to remove the dart. Then the seedlings were oven dried for 1 hour at 60 ºC to remove the moisture and weight of dry biomass was recorded.

Influence of treatments on seedbed soil properties:

Short term influence of treatments on basic soil parameters were documented using the following methods in Silapathar Science College, Silapathar- 787059, Dhemaji, Assam. The pH and EC were measured by using the electrode of the pH and conductivity meter (Model: HI98130, Hanna Instruments) in sample suspension. WHC of the soils were estimated following the method of Tripathi [16]. Soil bulk density was estimated following Baruah and Borthakur [17].

Statistical analyses:

Statistical analyses were performed using SPSS 16 (SPSS Inc., Chicago, IL, USA) software package. Analysis of variance (one-way ANOVA) and Duncan's multiple range test (DMRT) was executed at $p \leq 0.05$ to process the data and to determine statistical difference between treatment means. Pearson's linear correlations between the variables were performed to estimate relationship between the studied parameters using Graph Pad Prism 8.

Results

Germination Parameters:

The GP of bean, moong and pea seeds varied significantly ($p < 0.05$) among the applied treatments. In bean, the highest germination percentage was recorded under RSCIF (90.52 ± 3.6%), closely followed by VERIF (90.41 ± 3.1%), In contrast, treatment IFD reduced germination to 20.11 ± 1.9% (Table 1). In moong, VERIF exhibited the maximum germination percentage (80.11 ± 3.1%), followed by RSCIF (79.24 ± 3.5%). The lowest germination was observed under IFD (16.27 ± 1.3%). Similarly, in pea, VERIF resulted in the highest germination percentage (90.01 ± 3.4%). However, IFD significantly suppressed germination, reducing the value to 26.41 ± 3.6%.

In bean, the maximum GI was recorded under RSCIF (172.29 ± 3.8), followed by VERIF (171.00 ± 4.6) (Table 2). The lowest GI was observed under IFD (93.10 ± 4.7). For moong, VERIF produced the highest GI (121.81 ± 1.9), followed by FYMIF (120.54 ± 3.1). Conversely, IFD markedly decreased the GI to 36.32 ± 3.8. In pea, VERIF recorded the highest GI (166.39 ± 2.1), followed by RSC10 (165.12 ± 4.9). Similar to other crops, IFD significantly reduced the GI to 90.21 ± 3.2.

The VI in bean, VERIF recorded the highest VI (952.3 ± 5.9) while IFD drastically reduced the VI to 513.0 ± 8.5. In moong, the maximum VI was obtained under RSCIF (362.3 ± 3.2) whereas, IFD caused a substantial reduction in VI, lowering the value to 134.2 ± 3.9. For pea, the highest VI was also observed under RSCIF (860.3 ± 4.2). The lowest of the same was recorded under IFD (441.2 ± 4.7).

The PIG was negligible or absent under most organic and integrated nutrient treatments (Figure 1). However, marked inhibition was observed under the IFD treatment in all crops. Bean seeds exhibited approximately 42% inhibition, while moong recorded the highest inhibition at nearly 66%. Pea seeds also showed considerable inhibition, reaching approximately 43%.

Dry matter weight (DW) of seedlings was significantly influenced by the different nutrient treatments across bean, moong and pea crops (Figure 2). In bean, the highest DW was recorded under RSCIF (192.32 mg seedling^{-1}), followed closely by VER10 (189.55 mg seedling^{-1}), FYM10 (188.54 mg seedling^{-1}) and VERIF (187.61 mg seedling^{-1}). In contrast, the lowest DW was observed under IFD (56.94 mg seedling^{-1}). In moong, FYM10 produced the maximum DW (72.30 mg seedling^{-1}), followed by VER10 (70.97 mg seedling^{-1}), whereas the control recorded a DW of 57.32 mg seedling^{-1}. Similar to bean, IFD drastically reduced the DW to 21.76 mg seedling^{-1}. For pea, the highest DW was recorded under FYM10 (118.64 mg seedling^{-1}), followed by VER10 (112.47 mg seedling^{-1}). The minimum DW was again observed under IFD (35.92 mg seedling^{-1}).

Soil parameters:

The post-harvest soil analysis revealed considerable variation in the studied soil parameters among the different nutrient management treatments (Table 4). The soil pH ranged from 3.8 to 8.8, indicating that the applied treatments significantly influenced soil reaction. Among the treatments, the highest soil pH was recorded in RSC20 (8.8) whereas, treatment IFD showed the lowest of the same (3.8). The lowest EC value was recorded in IFD (0.341 mS cm^{-1}) and the highest of the same was observed in RSCIF (0.506 mS cm^{-1}). The lowest WHC was recorded in IFD (49.3%), while the maximum WHC was observed in RSCIF (72.6%). The highest bulk density was recorded in the control (1.21 Mg m^{-3}) whereas, lowest bulk density was recorded in VER10 (0.74 Mg m^{-3}).

Correlation analysis revealed strong relationships between seedbed soil properties and germination performance of the studied species (Figure 3). The strong positive relationship was observed between pH, EC and WHC with germination and seedling growth parameters. In contrast, bulk density (BD) showed negative correlations with all germination and seedling growth parameters.

Table 1. Germination Percentage (GP) of bean, moong and pea seeds as influenced by the applied treatments**.**

Treatments	Bean	Impact %	Moong	Impact %	Pea	Impact %
C	80.67±1.2^{d}		64.65±2.3^{e}		76.77±3.4^{e}	
FYM10	81.3±2.3^{d}	0.78	73.3±2.9^{d}	13.38	81.3±3.8^{d}	5.90
FYM20	82.91±1.7cd	2.78	74.91±3.6^{cd}	15.87	82.81±3.6^{cd}	7.87
VER10	84.99±1.8b^{c}	5.36	74.93±3.1^{cd}	15.90	85.43±2.2c	11.28
VER20	89.64±2.9^{a}	11.12	78.62±2.5^{ab}	21.61	88.84±2.1^{ab}	15.72
RSC10	85.9±3.1^{bc}	6.48	77.23±2.2^{abc}	19.46	83.82±1.6^{cd}	9.18
RSC20	75.32±3.9^{e}	-6.63	73.56±2.6^{d}	13.78	77.13±2.8^{e}	0.47
IF	70.24±1.2^{f}	-12.93	42.79±1.9^{f}	-33.81	68.57±3.4^{f}	-10.68
IFD	20.11±1.9^{g}	-75.07	16.27±1.3^{g}	-74.83	26.41±3.6^{g}	-65.60
FYMIF	87.44±2.8^{ab}	8.39	75.92±3.4^{bcd}	17.43	85.87±3.3^{bc}	11.85
VERIF	90.41±3.1^{a}	12.07	80.11±3.1^{a}	23.91	90.01±3.4^{a}	17.25
RSCIF	90.52±3.6^{a}	12.21	79.24±3.5^{a}	22.57	89.12±3.7^{ab}	16.09
LSD	3.286		3.860		3.95	

Data are the means of 3 replicates. Mean values followed by the different letter are significantly different according to Duncan's multiple range test at $p<0.05$.

Table 2. Germination Index (GI) of bean, moong and pea seeds as influenced by the applied treatments.

Treatments	Bean	Impact %	Moong	Impact %	Pea	Impact %
C	160.33±3.5^{ef}		107.21±2.8^{cd}		158.54±3.5^{d}	
FYM10	162.03±4.2^{e}	1.06	108.43±2.5^{cd}	1.14	158.93±3.6^{d}	0.25
FYM20	162.97±4.5^{de}	1.65	109.58±3.6^{c}	2.21	159.44±2.6^{cd}	0.57
VER10	165.83±3.9^{cd}	3.43	112.95±3.1^{b}	5.35	162.51±2.9^{bc}	2.50
VER20	167.44±2.5^{bc}	4.43	106.66±4.9^{cd}	-0.51	158.4±4.4^{d}	-0.09
RSC10	165.32±2.6^{cd}	3.11	114.55±4.2^{b}	6.85	165.12±4.9^{ab}	4.15
RSC20	157.51±3.8^{fg}	-1.76	106.23±4.3^{d}	-0.91	157.24±4.1^{d}	-0.82
IF	156.95±3.5^{g}	-2.11	114.76±4.7^{b}	7.04	159.84±3.6^{cd}	0.82
IFD	93.1±4.7^{h}	-41.93	36.32±3.8^{e}	-66.12	90.21±3.2^{e}	-43.10
FYMIF	169.43±2.9^{ab}	5.68	120.54±3.1^{a}	12.43	163.83±2.5^{ab}	3.34
VERIF	171±4.6^{a}	6.66	121.81±1.9^{a}	13.62	166.39±2.1^{a}	4.95
RSCIF	172.29±3.8^{a}	7.46	120.42±4.3^{a}	12.32	164.46±4.7^{ab}	3.73
LSD	18.24		13.38		17.286	

Data are the means of 3 replicates. Mean values followed by the different letter are significantly different according to Duncan's multiple range test at $p<0.05$.

Table 3. Vigor Index (VI) of bean, moong and pea seeds as influenced by the applied treatments.

Treatments	Bean	Impact %	Moong	Impact %	Pea	Impact %
C	863.2±5.6^{h}		287.3±5.6^{g}		785.4±4.6^{h}	
FYM10	875.8±8.0^{g}	1.46	300.2±3.4^{f}	4.48	789.3±4.1^{g}	0.50
FYM20	878.1±8.3^{g}	1.73	306.2±3.9^{e}	6.60	797. ±4.9^{f}	1.59
VER10	897.4±4.9^{e}	3.97	324.7±6.4^{d}	13.02	811.3±5.1^{e}	3.30
VER20	854.4±5.8^{i}	-1.02	275.9±3.8^{i}	-3.96	762.0±4.8^{j}	-2.92
RSC10	914.5±6.4^{d}	5.94	347.2±2.5^{c}	20.84	834.2±5.2^{c}	6.21
RSC20	843.1±9.1^{j}	-2.33	281.1±5.1^{h}	-2.16	777.6±5.3^{i}	-0.99
IF	884.7±7.3^{f}	2.49	301.6±4.6^{f}	4.98	791.5±4.9^{g}	0.78
IFD	513.0±8.5^{k}	-40.57	134.2±3.9^{j}	-53.26	441.2±4.7^{k}	-43.82
FYMIF	937.7±5.3^{b}	8.64	348.9±2.1^{c}	21.44	815.4±5.9^{d}	3.83
VERIF	952.3±5.9^{a}	10.33	353.5±5.8^{b}	23.05	852.8±5.3^{b}	8.59
RSCIF	926.8±3.8^{c}	7.37	362.3±3.2^{a}	26.11	860.3±4.2^{a}	9.54
LSD	24.372		22.53		23.23	

Data are the means of 3 replicates. Mean values followed by the different letter are significantly different according to Duncan's multiple range test at *$p<0.05$*.

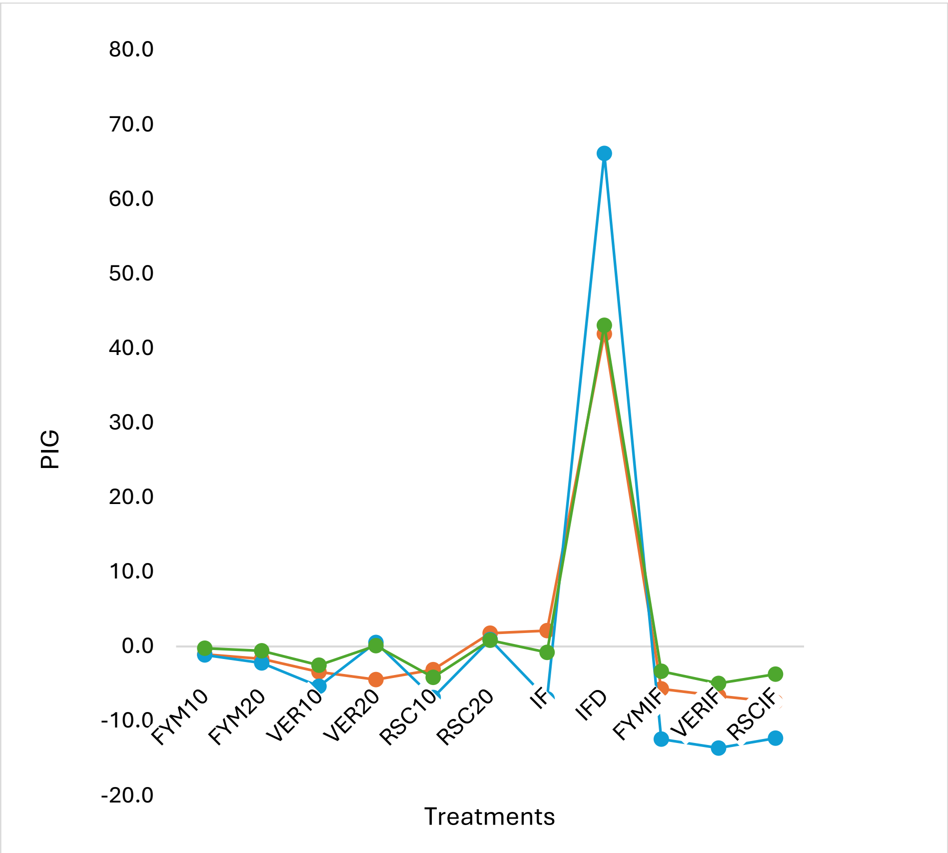

Fig 1. Percent Inhibition of Germination of bean, moong and pea seeds as influenced by the applied treatments. Data are the means of 3 replicates. PIG = percent inhibition of germination.

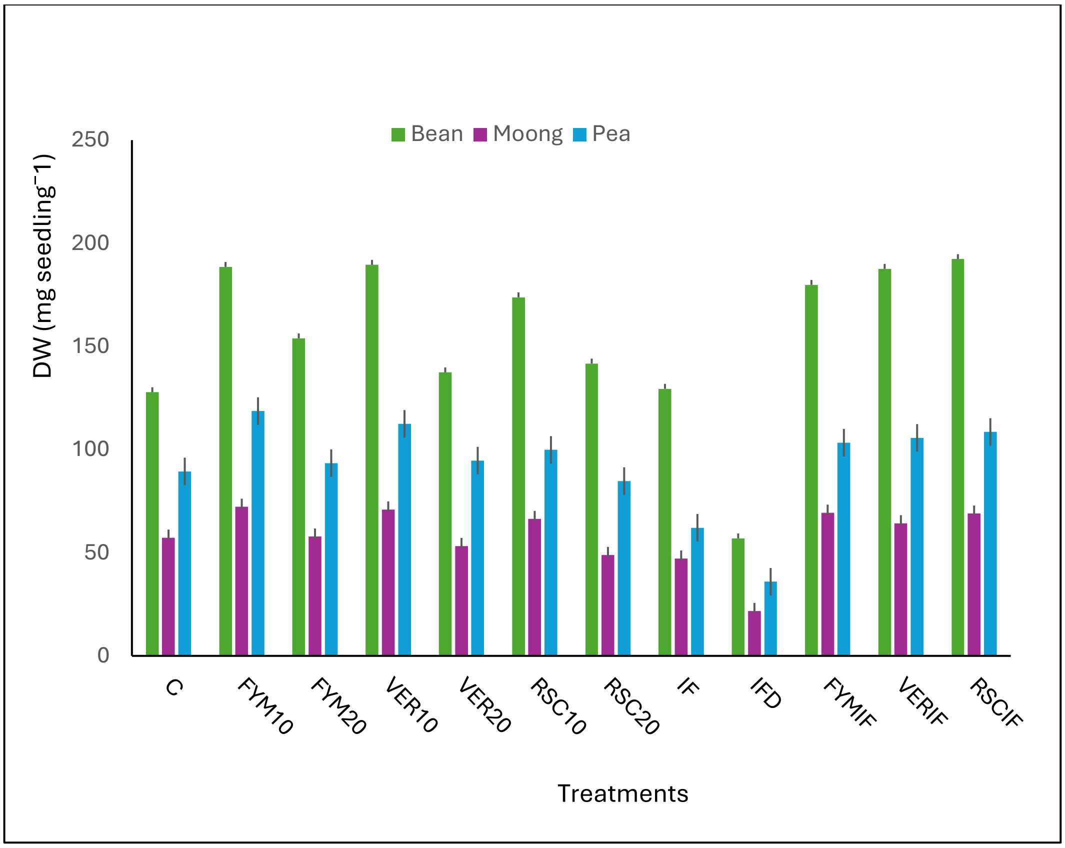

Fig 2. Dry matter weight of bean, moong and pea seeds as influenced by the applied treatments. Data are the means of 3 replicates. DW = dry matter.

Table 4. Influence of treatments on basic soil physico-chemical parameters of the seedbed

Treatments	pH	EC (mS cm^{-1})	WHC (%)	BD (mg m^{-3})
C	5.9±0.2^{b}	0.343±0.4^{c}	54.7±4.8^{b}	1.21±0.1^{a}
FYM10	6.9±0.2^{ab}	0.486±0.2^{ab}	62.5±3.2^{ab}	0.78±0.0^{ab}
FYM20	7.8±0.1^{a}	0.501±0.6^{a}	66.4±7.2^{ab}	0.78±0.0^{ab}
VER10	7.1±0.2^{a}	0.493±0.3^{a}	64.7±2.4^{ab}	0.74±0.2^{b}
VER20	7.3±0.3^{a}	0.498±0.4^{a}	66.3±5.3^{ab}	0.76±0.2^{ab}
RSC10	8.1±0.1^{a}	0.464±0.3^{b}	67.3±4.1^{ab}	0.78±0.1^{ab}
RSC20	8.8±0.2^{a}	0.476±0.3^{ab}	68.7±4.8^{ab}	0.8±0.3^{ab}
IF	6.2±0.1^{b}	0.418±0.2^{b}	57.8±2.9^{b}	0.86±0.1^{a}
IFD	3.8±0.0^{c}	0.341±0.4^{c}	49.3±6.2^{bc}	1.08±0.0^{a}
FYMIF	7.9±0.0^{a}	0.489±0.3^{ab}	67.5±3.7^{ab}	0.77±0.3^{ab}
VERIF	7.6±0.2^{a}	0.495±0.6^{a}	69.9±3.4^{a}	0.78±0.1^{ab}
RSCIF	7.8±0.2^{a}	0.506±0.3^{a}	72.6±3.1^{a}	0.79±0.2^{ab}
LSD	3.60	1.03	17.71	0.47

Data are the means of 3 replicates. Mean values followed by the different letter are significantly different according to Duncan's multiple range test at $p<0.05$.

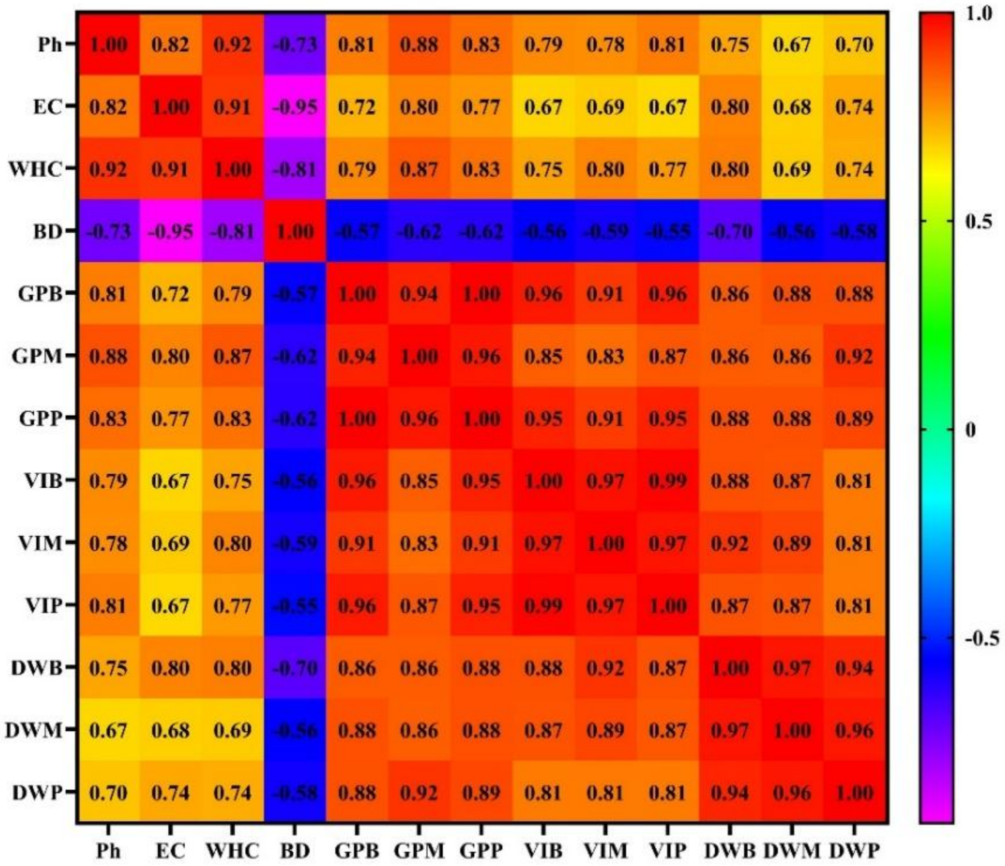

Fig 3. Pearson correlation matrix of soil parameters with GP, VI and DW of the seeds where, Ph = pH, EC = electrical conductivity, WHC = water holding capacity, BD = bulk density, GPB = germination percentage of Bean, GPM = germination percentage of moong, GPP = germination percentage of pea, VIB = vigour index of bean, VIM = vigour index of moong, VIP = vigour index of pea, DWB = dry weight of bean, DWM = dry weight of moong, DWP = dry weight of pea.

Discussion

Post-harvest soil analysis demonstrated that nutrient management treatments substantially altered seedbed physicochemical properties as compared to control. Organic and integrated nutrient treatments markedly improved soil quality. Organic amendments shifted soil pH towards near-neutral conditions through the release of basic cations and improvement of cation exchange capacity, thereby alleviating soil acidity and enhancing nutrient availability [18], [19]. Rice straw char exerted the greatest liming effect, although the relatively high pH observed under RSC20 may potentially reduce micronutrient availability in acidic soils [20]. In contrast, the IFD treatment resulted in severe soil acidification, likely due to fertilizer-induced nitrification and salt accumulation, creating unfavourable conditions for germination and seedling growth through increased H^+ toxicity and nutrient imbalance [21], [22].

Electrical conductivity was generally higher under integrated treatments, particularly RSCIF and VERIF, indicating improved nutrient release and retention. The observed moderate EC levels in these treatments likely enhanced nutrient availability, thereby supporting better germination and seedling development [23], [24].
The highest WHC was recorded under RSCIF, followed by VERIF, while BD decreased considerably in most organic and integrated treatments, indicating improved soil hydration, porosity, aggregation and root-zone conditions. Adequate moisture availability is essential for seed imbibition, enzyme activation, reserve mobilization and radicle emergence during germination [25]. The observed increased WHC and reduced BD also support previous reports that integrated nutrient management improves soil moisture retention, structure and nutrient availability through the combined action of organic amendments and inorganic fertilizers. The reduction in BD further indicates improved soil structure and aeration [26], [27].

The results exhibited the higher germination performance and seedling Vigor in bean followed by pea and lowest of the same was recorded in moong as has previously described that larger seeds consistently produced higher germination, vigour and dry matter accumulation than smaller seeds, likely because of their greater reserves of carbohydrates, proteins and minerals available for early growth [13], [28].

Correlation analysis further confirmed the importance of soil properties in regulating germination and seedling establishment. Soil pH, electrical conductivity and water-holding capacity were positively associated with germination percentage, vigour index and dry matter weight, whereas bulk density exhibited negative relationships with all growth parameters. These findings indicate that improvements in soil chemical conditions, moisture availability and soil structure directly contributed to enhanced germination and seedling development.

Conclusion

The study demonstrated that integrated nutrient management is more effective than sole organic or inorganic nutrient application in improving soil properties, seed germination and early seedling growth. Integrated treatment enhanced soil fertility, moisture retention and structural stability collectively promoted germination, seedling establishment and biomass accumulation. Among the treatments, RSCIF and VERIF performed well. In contrast, excessive inorganic fertilizer application adversely affected soil health through acidification, reduced moisture retention and poor physical quality, leading to lower germination and seedling growth. Optimal germination and early seedling development of bean, moong and pea were observed at soil pH 7.1-7.8. Bean exhibited the highest germination and seedling vigour, followed by pea and moong, reflecting the advantage of larger seed size and greater reserve food content. Overall, FYM, vermicompost and rice straw char represent sustainable nutrient sources that can reduce dependence on chemical fertilizers while enhancing soil quality, resource-use efficiency and long-term agricultural productivity.

Conflict of Interest

The authors declare that there is no conflict of interest

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