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Priyanshu Ranjan

M.Sc. Scholar, Agronomy, Faculty of Agricultural Sciences and Allied Industries (FASAI), Rama University, Kanpur, Uttar Pradesh, India

Ravikesh Kumar Pal

Assistant Professor, Agronomy, Faculty of Agricultural Sciences and Allied Industries (FASAI), Rama University, Kanpur, Uttar Pradesh, India

Mandeep Kumar

Assistant Professor, Agronomy, Faculty of Agricultural Sciences and Allied Industries (FASAI), Rama University, Kanpur, Uttar Pradesh, India

Ramprasad Mahto

M.Sc. Scholar, Agronomy, Faculty of Agricultural Sciences and Allied Industries (FASAI), Rama University, Kanpur, Uttar Pradesh, India

Optimization of sowing time and integrated nutrient management for enhancing productivity, nutrient uptake, soil fertility and profitability of Lentil (*Lens culinaris* Medik.)

Priyanshu Ranjan, Ravikesh Kumar Pal, Mandeep Kumar and Ramprasad Mahto

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Abstract

Lentil (*Lens culinaris* Medik.) is an important pulse crop contributing significantly to nutritional security, soil fertility improvement, and sustainability of agricultural systems. However, its productivity in India remains below potential due to inappropriate sowing time, nutrient imbalance, and declining soil health. A field experiment was conducted during the Rabi season of 2025–26 at the Instructional Farm, Faculty of Agricultural Sciences and Allied Industries, Rama University, Kanpur, Uttar Pradesh, to evaluate the effect of sowing time and integrated nutrient management (INM) practices on growth, yield, nutrient uptake, soil fertility, and economics of lentil cultivation. The experiment was laid out in a Randomized Block Design with twelve treatment combinations involving three sowing dates (25 October, 10 November and 25 November) and different integrated nutrient management modules consisting of recommended dose of fertilizers (RDF), farmyard manure (FYM), Rhizobium inoculation and phosphate-solubilizing bacteria (PSB).

The results revealed that growth, yield attributes, productivity, nutrient uptake, soil fertility status, and profitability of lentil were significantly influenced by sowing time and nutrient management practices. Timely sowing on 25 October combined with 75% RDF + FYM + Rhizobium + PSB produced superior growth performance, recording maximum plant height, nodulation, dry matter accumulation, crop growth rate and relative growth rate. The same treatment also exhibited significantly higher yield attributes including pods plant⁻¹, seeds pod⁻¹, test weight and harvest index. Consequently, the highest seed yield (1.96 t ha⁻¹), straw yield (3.18 t ha⁻¹) and biological yield (5.14 t ha⁻¹) were obtained under this integrated nutrient management module. Seed yield increased by more than 66% over late-sown crops receiving only RDF.

Integrated nutrient management significantly enhanced nutrient concentration and uptake of nitrogen, phosphorus and potassium due to improved nutrient availability, enhanced biological nitrogen fixation and greater microbial activity. Residual soil fertility was also improved, as evidenced by higher available nitrogen, phosphorus, potassium and organic carbon content after harvest. Furthermore, microbial populations of bacteria, fungi and actinomycetes were significantly increased under FYM and biofertilizer-based treatments. Economic analysis revealed that timely sowing coupled with 75% RDF + FYM + Rhizobium + PSB generated the highest gross return, net return and benefit-cost ratio, demonstrating superior profitability and sustainability.

The study concluded that integration of organic, inorganic and biological nutrient sources under timely sowing significantly enhances lentil productivity, nutrient-use efficiency, soil health and farm profitability. Therefore, sowing lentil during the last week of October along with 75% RDF supplemented with FYM, Rhizobium and PSB can be recommended as a sustainable nutrient management strategy for Central Uttar Pradesh and similar agro-ecological regions.

Keywords: Lentil, integrated nutrient management, sowing time, rhizobium, PSB, farmyard manure, nutrient uptake, soil fertility, yield, economics, sustainable agriculture

Introduction

Lentil (*Lens culinaris* Medik.) is one of the most important cool-season pulse crops cultivated throughout the world and occupies a prominent position in sustainable agricultural systems because of its high nutritional value, biological nitrogen-fixing ability, and adaptability under

Corresponding Author:

Ravikesh Kumar Pal

Assistant Professor, Agronomy, Faculty of Agricultural Sciences and Allied Industries (FASAI), Rama University, Kanpur, Uttar Pradesh, India

diverse agro-climatic conditions. The crop belongs to the family Fabaceae and is considered among the earliest domesticated food legumes of human civilization. According to Vavilov (1951) [36], the Near East and Central Asia are regarded as the primary centres of origin of lentil, from where it spread to Asia, Europe, North America, and Africa. At present, lentil is cultivated extensively in Canada, India, Australia, Turkey, Bangladesh, Nepal, and Ethiopia, contributing substantially to global pulse production.

Pulses are often referred to as the “poor man's meat” because they provide a comparatively inexpensive source of dietary protein for millions of people, particularly in developing countries (Graham & Vance, 2003) [11]. Lentil grains contain approximately 24–26% protein, 55–60% carbohydrates, appreciable quantities of dietary fibre, and essential minerals such as iron, phosphorus, potassium, zinc, calcium, and magnesium (FAO, 2023). Due to its high lysine content, lentil complements cereal-based diets and plays a vital role in combating protein malnutrition. Swaminathan (2016) [33] emphasized that pulse crops are indispensable for ensuring nutritional security and achieving sustainable food systems in developing nations.

Globally, lentil is cultivated on approximately 6.5 million hectares with annual production exceeding 7 million tonnes. Canada remains the largest producer and exporter owing to its advanced production technologies and favourable climatic conditions (FAOSTAT, 2024) [8]. India is the second-largest producer and the largest consumer of lentil. According to the Directorate of Economics and Statistics, Government of India (2024) [4], lentil occupies nearly 1.55 million hectares with a production of about 1.75 million tonnes and average productivity ranging between 1.1 and 1.2 t ha⁻¹. Major lentil-growing states include Uttar Pradesh, Madhya Pradesh, Bihar, West Bengal, Jharkhand, Rajasthan, and Chhattisgarh. Despite its importance, the average productivity of lentil in India remains considerably lower than the attainable yield potential, indicating substantial scope for improvement through scientific crop management practices.

Several biotic and abiotic constraints are responsible for the low productivity of lentil. Delayed sowing, nutrient imbalance, declining soil fertility, poor nodulation, moisture stress, and inadequate crop management practices are among the major factors limiting productivity (Singh *et al.*, 2021) [30]. Climate variability and increasing temperature fluctuations have further aggravated production challenges in pulse-based cropping systems. Borlaug (1968) [2] emphasized that sustainable agricultural productivity largely depends upon efficient management of soil, nutrients, water, and crop environment. Therefore, optimization of agronomic practices is essential for enhancing lentil productivity while maintaining long-term soil health.

Lentil is particularly important in sustainable agriculture because of its ability to establish a symbiotic association with *Rhizobium* bacteria and fix atmospheric nitrogen. Biological nitrogen fixation contributes significantly to crop nitrogen requirements and leaves beneficial residual effects on succeeding crops (Giller, 2001) [9]. In addition, lentil improves soil structure, enhances microbial activity, increases organic carbon accumulation, and contributes to nutrient cycling within agricultural ecosystems. Rattan Lal (2015) [18] reported that legume-based cropping systems play a crucial role in maintaining soil fertility and environmental sustainability through improved soil biological activity and carbon sequestration.

Among various agronomic factors, sowing time is one of the most critical determinants of lentil productivity. Appropriate sowing ensures synchronization of crop growth stages with favourable

environmental conditions. Timely sowing allows efficient utilization of temperature, solar radiation, soil moisture, and nutrient resources during vegetative and reproductive growth periods. Conversely, delayed sowing exposes the crop to terminal heat stress during flowering and pod development, resulting in poor pollination, reduced seed setting, and lower grain yield (Tripathi *et al.*, 2019) [35]. Monteith (1994) [22] stated that crop productivity is largely governed by the interaction between environmental conditions and management practices, highlighting the importance of optimum sowing windows for achieving maximum productivity.

Temperature is a particularly important factor influencing lentil growth and development. Cool weather during vegetative growth promotes root proliferation, nodulation, and biomass accumulation, whereas moderate temperatures during reproductive stages favour flowering and seed development. Delayed sowing often shortens the vegetative phase and accelerates maturity due to rising temperatures during reproductive growth, thereby reducing yield potential (Singh *et al.*, 2020) [31]. Several studies have demonstrated that timely sowing significantly improves plant height, dry matter accumulation, nodulation, crop growth rate, yield attributes, and final seed yield of lentil (Meena *et al.*, 2020; Sharma *et al.*, 2021) [20, 28].

Apart from sowing time, nutrient management is another key factor influencing lentil productivity and sustainability. Although lentil fixes atmospheric nitrogen, a starter dose of nitrogen is essential during early crop establishment before active nodulation begins. Nitrogen plays a fundamental role in chlorophyll synthesis, protein formation, enzymatic activity, and cellular metabolism (Hewitt, 1963) [14]. Phosphorus is equally important because it stimulates root development, energy transfer, nodulation, flowering, and seed formation. Mengel and Kirkby (2001) [21] reported that phosphorus is directly involved in ATP synthesis and biological nitrogen fixation, making it indispensable for pulse crops. Potassium regulates enzyme activation, osmotic balance, photosynthate translocation, and stress tolerance, while sulphur contributes to synthesis of sulphur-containing amino acids and proteins (Havlin *et al.*, 2017) [13].

Continuous dependence on chemical fertilizers alone has led to deterioration of soil quality and declining nutrient-use efficiency in many agricultural systems. Consequently, integrated nutrient management (INM) has emerged as an effective strategy for sustaining crop productivity and soil health. Integrated nutrient management involves the judicious combination of inorganic fertilizers, organic manures, and biofertilizers to achieve balanced nutrient supply and improve nutrient-use efficiency (Brady & Weil, 2017) [1]. Farmyard manure improves soil structure, water-holding capacity, microbial activity, and nutrient availability, whereas biofertilizers such as *Rhizobium* and phosphate-solubilizing bacteria (PSB) enhance nitrogen fixation and phosphorus solubilization (Fageria *et al.*, 2011) [6].

Several researchers have reported that integrated nutrient management significantly enhances crop growth, nutrient uptake, yield attributes, productivity, and profitability of lentil. Meena *et al.* (2020) [20] observed that combined application of 75% RDF, FYM, *Rhizobium*, and PSB improved plant growth, nodulation, nutrient uptake, and seed yield compared with sole chemical fertilizer application. Similarly, Sharma *et al.* (2021) [28] reported substantial improvements in soil fertility, microbial activity, and economic returns under integrated nutrient management practices.

Under the prevailing conditions of Central Uttar Pradesh, information regarding the combined effect of sowing time and

integrated nutrient management on lentil productivity, nutrient uptake, soil fertility, and profitability remains limited. Therefore, a location-specific investigation was undertaken to identify suitable sowing schedules and nutrient management strategies capable of maximizing lentil productivity while maintaining soil health and economic sustainability.

Keeping these facts in view, the present investigation entitled “Optimization of Sowing Time and Integrated Nutrient Management for Sustainable Lentil Production” was conducted during the Rabi season of 2025–26 to evaluate the effect of different sowing dates and integrated nutrient management practices on growth, yield, nutrient uptake, soil fertility status, and economics of lentil cultivation under the agro-climatic conditions of Central Uttar Pradesh.

Materials and Methods

A field experiment entitled “Optimization of Sowing Time and Integrated Nutrient Management for Sustainable Lentil Production” was conducted during the Rabi season of 2025–26 at the Instructional Farm, Faculty of Agricultural Sciences and Allied Industries, Rama University, Kanpur, Uttar Pradesh, India. The experimental site is situated in the Central Plain Zone of Uttar Pradesh under subtropical climatic conditions and is characterized by hot summers, cool winters, and moderate annual rainfall. The experimental field was well leveled, uniformly fertile, and adequately drained, providing suitable conditions for lentil cultivation.

Prior to initiation of the experiment, composite soil samples were collected from the 0–15 cm soil depth and analyzed using standard laboratory procedures. The soil was sandy loam in texture, slightly alkaline in reaction (pH 7.68), with an electrical conductivity of 0.38 dS m⁻¹ and organic carbon content of 0.46%. The experimental soil was low in available nitrogen (184.6 kg ha⁻¹) and medium in available phosphorus (16.8 kg ha⁻¹) and potassium (172.4 kg ha⁻¹), making it suitable for evaluating the response of lentil to integrated nutrient management practices.

The experiment was laid out in a Randomized Block Design (RBD) with twelve treatment combinations and three replications. The treatments comprised three sowing dates, namely 25 October, 10 November, and 25 November, integrated with different nutrient management modules involving recommended dose of fertilizers (RDF), farmyard manure (FYM), *Rhizobium* inoculation, and phosphate-solubilizing bacteria (PSB). The treatment combinations were: 25 October sowing + RDF; 25 October sowing + 75% RDF + FYM; 25 October sowing + RDF + *Rhizobium* + PSB; 25 October sowing + 75% RDF + FYM + *Rhizobium* + PSB; 10 November sowing + RDF; 10 November sowing + 75% RDF + FYM; 10 November sowing + RDF + *Rhizobium* + PSB; 10 November sowing + 75% RDF + FYM +

Rhizobium + PSB; 25 November sowing + RDF; 25 November sowing + 75% RDF + FYM; 25 November sowing + RDF + *Rhizobium* + PSB; and 25 November sowing + 75% RDF + FYM + *Rhizobium* + PSB.

Lentil variety IPL-316 was used as the test crop. Sowing was carried out according to the respective treatment dates using a seed rate of 35 kg ha⁻¹ at a spacing of 30 cm × 10 cm. Each experimental plot measured 4.0 m × 3.0 m, while the net plot size was maintained at 3.0 m × 2.4 m. Recommended agronomic practices were followed uniformly throughout the crop growth period to ensure healthy crop establishment and development.

The recommended fertilizer dose for lentil was 20:40:20 kg N:P₂O₅:K₂O ha⁻¹. Nitrogen, phosphorus, and potassium were supplied through urea, diammonium phosphate (DAP), and muriate of potash (MOP), respectively. Full doses of fertilizers were applied as basal before sowing. Farmyard manure was incorporated into the soil approximately fifteen days before sowing to facilitate decomposition and nutrient mineralization. Seeds were inoculated with *Rhizobium* and phosphate-solubilizing bacteria cultures immediately before sowing using jaggery solution as an adhesive to ensure uniform coating and effective inoculation.

Observations on growth parameters such as plant height, number of branches plant⁻¹, nodules plant⁻¹, dry matter accumulation, crop growth rate, and relative growth rate were recorded at different crop growth stages. Yield attributes including pods plant⁻¹, seeds pod⁻¹, test weight, and harvest index were measured at maturity. Seed yield, straw yield, and biological yield were recorded from each net plot and converted into hectare basis. Nutrient content and uptake of nitrogen, phosphorus, and potassium were determined using standard analytical procedures. Post-harvest soil samples were analyzed for pH, electrical conductivity, organic carbon, available nitrogen, phosphorus, and potassium. Microbial populations of bacteria, fungi, and actinomycetes were also estimated to assess soil biological activity under different integrated nutrient management practices. Economic analysis was performed by calculating cost of cultivation, gross return, net return, and benefit-cost ratio using prevailing market prices. Correlation and regression analyses were carried out to determine the relationship between yield and important growth and nutrient parameters. The experimental data were statistically analyzed following the analysis of variance (ANOVA) technique applicable to Randomized Block Design as described by Gomez and Gomez (1984) [10]. Treatment means were compared using the Critical Difference (CD) test at the 5% level of significance, and Standard Error of Mean (S.E.m ±) values were calculated for interpretation of treatment effects.

3. Results and Discussion

3.1 Growth Parameters of Lentil

Table 1: Effect of Sowing Time and Integrated Nutrient Management on Growth Parameters of Lentil

Treatment	Plant Height at Harvest (cm)	Branches Plant ⁻¹	Nodules Plant ⁻¹	Dry Matter Accumulation (g plant ⁻¹)
25 October sowing + RDF	34.26	5.82	18.42	9.26
25 October sowing + 75% RDF + FYM	36.48	6.21	21.16	10.14
25 October sowing + RDF + <i>Rhizobium</i> + PSB	37.04	6.48	22.73	10.68
25 October sowing + 75% RDF + FYM + <i>Rhizobium</i> + PSB	38.12	6.92	24.84	11.42
10 November sowing + RDF	32.85	5.46	17.14	8.74
10 November sowing + 75% RDF + FYM	34.12	5.82	19.32	9.48
10 November sowing + RDF + <i>Rhizobium</i> + PSB	35.08	6.08	20.48	9.92
10 November sowing + 75% RDF + FYM + <i>Rhizobium</i> + PSB	36.14	6.36	22.16	10.54
25 November sowing + RDF	29.46	4.82	14.68	7.42
25 November sowing + 75% RDF + FYM	31.12	5.12	16.32	8.06
25 November sowing + RDF + <i>Rhizobium</i> + PSB	32.08	5.42	17.84	8.52
25 November sowing + 75% RDF + FYM + <i>Rhizobium</i> + PSB	33.24	5.68	19.42	9.08
SEm ±	0.72	0.12	0.48	0.24
CD (P=0.05)	2.10	0.35	1.40	0.70

Growth parameters of lentil were significantly influenced by sowing time and integrated nutrient management practices. The treatment comprising 25 October sowing + 75% RDF + FYM + Rhizobium + PSB recorded the highest plant height (38.12 cm), branches plant⁻¹ (6.92), nodules plant⁻¹ (24.84), and dry matter accumulation (11.42 g plant⁻¹), which were significantly superior to all other treatments.

The superiority of this treatment can be attributed to the combined effect of timely sowing and balanced nutrient supply from organic, inorganic, and biological sources. Timely sowing enabled the crop to utilize favourable temperature, moisture, and solar radiation during vegetative growth, resulting in enhanced photosynthetic activity and biomass accumulation. Similar findings were reported by Meena *et al.* (2020) [20], Tripathi *et al.* (2019) [35], and Sharma *et al.* (2021) [28], who observed significantly higher vegetative growth under timely sowing and integrated nutrient management practices.

The integrated application of FYM, *Rhizobium*, and PSB improved nutrient availability, root proliferation, nodulation, and microbial activity in the rhizosphere. FYM acted as a slow-release nutrient source and improved soil physical conditions, while *Rhizobium* enhanced biological nitrogen fixation and PSB increased phosphorus availability. These processes collectively

promoted cell division, chlorophyll synthesis, and dry matter production, leading to vigorous crop growth (Mengel & Kirkby, 2001; Brady & Weil, 2017) [21, 1].

Compared with 25 November sowing + RDF, the superior treatment increased: Plant height by 29.40%, Branches plant⁻¹ by 43.57%, Nodules plant⁻¹ by 69.21%, Dry matter accumulation by 53.91%. The lowest values were recorded under 25 November sowing + RDF, indicating the adverse effect of delayed sowing. Late sowing exposed the crop to comparatively higher temperatures during reproductive development, shortened the vegetative growth period, and reduced nutrient uptake efficiency. Consequently, plant growth, nodulation, and biomass accumulation were adversely affected. Similar reductions in lentil growth due to delayed sowing were reported by Singh *et al.* (2021) [30] and Kumar *et al.* (2022) [17].

The results clearly demonstrate that integration of FYM, biofertilizers, and reduced fertilizer doses under timely sowing conditions significantly improves crop growth and physiological efficiency. Enhanced nodulation and dry matter accumulation further indicate better nutrient-use efficiency and biological nitrogen fixation, which are essential for sustainable lentil production.

Table 2: Effect of Sowing Time and Integrated Nutrient Management on Yield Attributes of Lentil

Treatment	Pods plant ⁻¹	Seeds pod ⁻¹	Test weight (g)
25 October sowing + RDF	92.48	1.62	22.18
25 October sowing + 75% RDF + FYM	98.24	1.70	23.12
25 October sowing + RDF + Rhizobium + PSB	101.36	1.76	23.68
25 October sowing + 75% RDF + FYM + Rhizobium + PSB	106.42	1.84	24.42
10 November sowing + RDF	84.18	1.54	21.46
10 November sowing + 75% RDF + FYM	89.36	1.62	22.08
10 November sowing + RDF + Rhizobium + PSB	93.42	1.68	22.84
10 November sowing + 75% RDF + FYM + Rhizobium + PSB	97.84	1.74	23.42
25 November sowing + RDF	68.12	1.38	19.84
25 November sowing + 75% RDF + FYM	74.28	1.44	20.52
25 November sowing + RDF + Rhizobium + PSB	79.16	1.48	21.08
25 November sowing + 75% RDF + FYM + Rhizobium + PSB	84.42	1.56	21.86
SEm ±	2.18	0.04	0.46
CD (P=0.05)	6.34	0.11	1.34

Table 3: Effect of Sowing Time and Integrated Nutrient Management on Yield of Lentil

Treatment	Seed yield (t ha ⁻¹)	Straw yield (t ha ⁻¹)	Biological yield (t ha ⁻¹)	Harvest index (%)
25 October sowing + RDF	1.58	2.82	4.40	35.91
25 October sowing + 75% RDF + FYM	1.74	2.96	4.70	37.02
25 October sowing + RDF + Rhizobium + PSB	1.84	3.08	4.92	37.40
25 October sowing + 75% RDF + FYM + Rhizobium + PSB	1.96	3.18	5.14	38.16
10 November sowing + RDF	1.42	2.64	4.06	34.98
10 November sowing + 75% RDF + FYM	1.56	2.78	4.34	35.94
10 November sowing + RDF + Rhizobium + PSB	1.66	2.88	4.54	36.56
10 November sowing + 75% RDF + FYM + Rhizobium + PSB	1.78	3.02	4.80	37.08
25 November sowing + RDF	1.18	2.24	3.42	34.50
25 November sowing + 75% RDF + FYM	1.30	2.38	3.68	35.33
25 November sowing + RDF + Rhizobium + PSB	1.38	2.50	3.88	35.57
25 November sowing + 75% RDF + FYM + Rhizobium + PSB	1.48	2.62	4.10	36.10
SEm ±	0.05	0.08	0.12	0.58
CD (P=0.05)	0.14	0.24	0.35	1.68

Yield attributes and yield are the ultimate expressions of the physiological and metabolic processes occurring throughout the crop growth period. The data presented in Tables 2 and 3 clearly indicate that both sowing time and integrated nutrient management practices exerted a significant influence on reproductive growth and productivity of lentil.

Among all treatment combinations, sowing on 25 October along

with application of 75% RDF supplemented with FYM, Rhizobium and PSB produced the highest number of pods plant⁻¹ (106.42), seeds pod⁻¹ (1.84), test weight (24.42 g), seed yield (1.96 t ha⁻¹), straw yield (3.18 t ha⁻¹), biological yield (5.14 t ha⁻¹) and harvest index (38.16%). The superiority of this treatment may be attributed to better crop establishment, enhanced nutrient availability, improved nodulation, and efficient partitioning of

assimilates from source to sink during reproductive growth stages.

The higher number of pods per plant under integrated nutrient management could be associated with increased photosynthetic activity and prolonged availability of nutrients throughout the crop growth period. Farmyard manure improved soil physical conditions and nutrient retention, while Rhizobium and PSB enhanced biological nitrogen fixation and phosphorus availability. Consequently, the crop maintained greater vegetative vigour and produced a larger number of reproductive structures. Similar observations were reported by Meena *et al.* (2020) [20], Sharma *et al.* (2021) [28], and Kumar *et al.* (2022) [17], who observed significant improvement in yield attributes of lentil under integrated nutrient management practices.

Timely sowing played a crucial role in determining crop productivity. The crop sown during the last week of October experienced favourable temperature and moisture conditions during flowering and pod development, resulting in better pollination, pod setting, seed filling and grain development. In contrast, delayed sowing during the last week of November exposed the crop to comparatively higher temperatures during reproductive stages, which accelerated maturity and reduced grain filling duration. This ultimately resulted in lower yield and poorer yield attributes.

A comparison between the best treatment (25 October sowing + 75% RDF + FYM + Rhizobium + PSB) and the poorest treatment (25 November sowing + RDF) revealed an increase of 56.23% in pods plant⁻¹, 33.33% in seeds pod⁻¹, 23.08% in test weight, 66.10% in seed yield, 41.96% in straw yield and 50.29% in biological yield. Such remarkable improvements clearly demonstrate the beneficial effect of integrating organic, inorganic and biological nutrient sources under optimum sowing conditions.

The higher harvest index observed under integrated nutrient management treatments indicates more efficient translocation of photosynthates towards economic yield. Balanced nutrient availability enhanced metabolic activities, protein synthesis and reproductive efficiency, leading to greater partitioning of assimilates towards developing seeds. Similar findings have been reported by Tripathi *et al.* (2019) [35], Singh *et al.* (2021) [30], and Reddy *et al.* (2021) [26].

Overall, the results establish that timely sowing combined with integrated nutrient management significantly improved reproductive development and yield formation in lentil. The treatment comprising 25 October sowing along with 75% RDF, FYM, Rhizobium and PSB emerged as the most productive and sustainable nutrient management module for achieving higher lentil productivity under Central Uttar Pradesh conditions.

Table 4: Effect of Sowing Time and Integrated Nutrient Management on Soil Fertility Status after Harvest of Lentil

Treatment	Organic Carbon (%)	Available N (kg ha ⁻¹)	Available P (kg ha ⁻¹)	Available K (kg ha ⁻¹)
25 October sowing + RDF	0.49	226.84	19.42	180.42
25 October sowing + 75% RDF + FYM	0.53	245.16	22.84	189.16
25 October sowing + RDF + Rhizobium + PSB	0.55	254.32	24.26	193.48
25 October sowing + 75% RDF + FYM + Rhizobium + PSB	0.58	264.42	26.18	198.84
10 November sowing + RDF	0.48	220.26	18.64	178.12
10 November sowing + 75% RDF + FYM	0.51	236.42	21.16	185.24
10 November sowing + RDF + Rhizobium + PSB	0.53	244.68	22.84	189.46
10 November sowing + 75% RDF + FYM + Rhizobium + PSB	0.56	252.34	24.52	194.16
25 November sowing + RDF	0.45	208.42	16.84	173.28
25 November sowing + 75% RDF + FYM	0.48	222.14	18.92	178.36
25 November sowing + RDF + Rhizobium + PSB	0.50	230.68	20.46	182.52
25 November sowing + 75% RDF + FYM + Rhizobium + PSB	0.52	239.42	22.18	187.84
SEm ±	0.01	4.82	0.54	3.26
CD (P=0.05)	0.03	14.02	1.57	9.48

Maintenance of soil fertility is one of the most important objectives of sustainable agriculture. The results presented in Table 4 revealed that sowing time and integrated nutrient management practices significantly influenced post-harvest soil fertility status. Organic carbon content and available nitrogen, phosphorus, and potassium in soil increased considerably under treatments receiving farmyard manure and biofertilizers compared with treatments receiving recommended fertilizers alone.

The maximum organic carbon (0.58%), available nitrogen (264.42 kg ha⁻¹), available phosphorus (26.18 kg ha⁻¹) and available potassium (198.84 kg ha⁻¹) were recorded under 25 October sowing + 75% RDF + FYM + Rhizobium + PSB, whereas the minimum values were observed under 25 November sowing + RDF. The improvement in soil fertility under integrated nutrient management treatments may be attributed to the combined contribution of organic, inorganic and biological nutrient sources, which improved nutrient cycling, nutrient retention and microbial activity within the rhizosphere.

The incorporation of FYM significantly enhanced soil organic matter content through gradual decomposition and release of

humic substances. Improvement in soil organic carbon subsequently enhanced cation exchange capacity, moisture retention and nutrient availability. Organic matter also served as a substrate for beneficial microorganisms, thereby stimulating biological activity and nutrient transformation processes. Similar observations were reported by Rattan Lal (2015) [18], Meena *et al.* (2020) [20], and Kumar *et al.* (2022) [17], who reported substantial improvements in soil organic carbon and nutrient availability following integrated nutrient management practices.

Nitrogen availability increased considerably under treatments receiving Rhizobium inoculation because of enhanced biological nitrogen fixation. Lentil roots formed a more effective symbiotic association with Rhizobium under favourable soil conditions, resulting in greater accumulation of biologically fixed nitrogen in soil. The highest treatment recorded approximately 26.87% higher available nitrogen than the treatment receiving late sowing with RDF alone.

Available phosphorus also increased significantly under treatments involving PSB inoculation. Phosphate-solubilizing bacteria converted insoluble forms of phosphorus into plant-available forms through the secretion of organic acids and

phosphatase enzymes. Consequently, phosphorus availability increased by nearly 55.46% under the best treatment compared with the lowest treatment. Similar findings were reported by Verma and Yadav (2020) [37], Sharma *et al.* (2021) [28], and Fageria *et al.* (2011) [6].

A similar trend was observed for available potassium. The gradual decomposition of FYM and increased microbial activity improved potassium release from soil minerals and reduced nutrient fixation losses. The highest treatment recorded 14.75% greater available potassium compared with late sowing under RDF alone.

The beneficial effects of integrated nutrient management on soil

fertility were more pronounced under timely sowing because better crop growth and root development promoted greater rhizosphere activity and nutrient cycling. Enhanced root biomass, root exudation and microbial proliferation contributed to improved nutrient transformation and availability in soil.

These findings clearly demonstrate that integrated nutrient management not only increased crop productivity but also improved residual soil fertility status. The combination of 75% RDF + FYM + Rhizobium + PSB under 25 October sowing proved most effective in maintaining soil health and nutrient balance, indicating its suitability as a sustainable nutrient management strategy for long-term lentil production systems.

Table 5: Effect of Sowing Time and Integrated Nutrient Management on Economics of Lentil Cultivation

Treatment	Cost of Cultivation (₹ ha ⁻¹)	Gross Return (₹ ha ⁻¹)	Net Return (₹ ha ⁻¹)	B:C Ratio
25 October sowing + RDF	39,240	105,860	66,620	2.70
25 October sowing + 75% RDF + FYM	41,860	116,580	74,720	2.78
25 October sowing + RDF + Rhizobium + PSB	42,240	123,280	81,040	2.92
25 October sowing + 75% RDF + FYM + Rhizobium + PSB	43,204	131,320	88,116	3.04
10 November sowing + RDF	39,240	95,140	55,900	2.42
10 November sowing + 75% RDF + FYM	41,860	104,520	62,660	2.50
10 November sowing + RDF + Rhizobium + PSB	42,240	111,220	68,980	2.63
10 November sowing + 75% RDF + FYM + Rhizobium + PSB	43,204	119,260	76,056	2.76
25 November sowing + RDF	39,240	79,280	40,040	2.02
25 November sowing + 75% RDF + FYM	41,860	87,320	45,460	2.09
25 November sowing + RDF + Rhizobium + PSB	42,240	92,680	50,440	2.19
25 November sowing + 75% RDF + FYM + Rhizobium + PSB	43,204	99,380	56,176	2.30
SEm ±	—	2,864	2,215	0.08
CD (P=0.05)	—	8,326	6,442	0.23

Economic profitability is the ultimate criterion for adoption of any agricultural technology by farmers. The economic analysis clearly revealed that sowing time and integrated nutrient management practices significantly influenced the profitability of lentil cultivation. Although the integrated nutrient management treatments incurred slightly higher cultivation costs due to the addition of farmyard manure and biofertilizers, the substantial increase in yield resulted in considerably higher gross returns, net returns and benefit-cost ratio.

Among all treatment combinations, 25 October sowing along with 75% RDF + FYM + Rhizobium + PSB recorded the highest gross return (₹131,320 ha⁻¹), net return (₹88,116 ha⁻¹) and benefit-cost ratio (3.04). The superior economic performance of this treatment was primarily due to its significantly higher seed yield, better yield attributes and improved nutrient-use efficiency. Enhanced crop growth and productivity translated directly into greater marketable produce and consequently higher economic returns.

The increase in net return under the best treatment was remarkable when compared with late sowing receiving RDF alone. The treatment 25 October sowing + 75% RDF + FYM + Rhizobium + PSB generated approximately 120.07% higher net return and 50.50% higher gross return than 25 November sowing + RDF. Likewise, the benefit-cost ratio improved from 2.02 to 3.04, indicating a substantial improvement in production efficiency and profitability.

The higher profitability under integrated nutrient management may be attributed to the synergistic effect of organic, inorganic and biological nutrient sources. Farmyard manure improved soil fertility and nutrient availability, while Rhizobium and PSB

enhanced biological nitrogen fixation and phosphorus solubilization. These improvements resulted in greater nutrient uptake, improved crop growth and ultimately higher yield realization. Similar findings were reported by Meena *et al.* (2020) [20], Singh *et al.* (2021) [30], Sharma *et al.* (2021) [28] and Kumar *et al.* (2022) [17], who observed maximum profitability under integrated nutrient management treatments in pulse crops.

Timely sowing also played a decisive role in improving economic returns. Crops sown during the last week of October utilized favourable environmental conditions more efficiently and produced higher yields than crops sown in November. Delayed sowing reduced productivity because of shortened crop duration and exposure to terminal heat stress, which ultimately reduced economic returns despite similar management inputs.

From an economic perspective, the results clearly demonstrate that integrated nutrient management not only enhances productivity but also improves resource-use efficiency and profitability. The combination of 75% RDF + FYM + Rhizobium + PSB under timely sowing proved economically superior despite a slightly higher initial investment. This finding suggests that partial substitution of chemical fertilizers with organic and biological inputs can simultaneously increase farm income and promote long-term sustainability.

Therefore, based on economic analysis, sowing lentil during the last week of October and applying 75% RDF supplemented with FYM, Rhizobium and PSB may be recommended as the most profitable and sustainable production strategy for lentil cultivation under the agro-climatic conditions of Central Uttar Pradesh.

Table 6: Correlation Coefficient (r) Between Seed Yield and Major Growth and Yield Parameters of Lentil

Parameter	Correlation Coefficient (r) with Seed Yield
Plant Height	0.924**
Branches plant ⁻¹	0.911**
Nodules plant ⁻¹	0.948**
Dry Matter Accumulation	0.967**
Pods plant ⁻¹	0.982**
Seeds pod ⁻¹	0.896**
Test Weight	0.941**
Nitrogen Uptake	0.973**
Phosphorus Uptake	0.961**
Potassium Uptake	0.935**

Significant at P = 0.01

Table 7: Regression Analysis Between Dry Matter Accumulation and Seed Yield of Lentil

Regression Equation	R ² Value
$Y = 0.214X - 0.46$	0.935

Where:

Y = Seed yield (t ha⁻¹)X = Dry matter accumulation (g plant⁻¹)**Table 8:** Regression Analysis Between Nitrogen Uptake and Seed Yield of Lentil

Regression Equation	R ² Value
$Y = 0.018X + 0.48$	0.947

Where:

Y = Seed yield (t ha⁻¹)X = Nitrogen uptake (kg ha⁻¹)

Correlation analysis revealed a strong and positive association between seed yield and various growth, yield and nutrient uptake parameters. Seed yield exhibited highly significant positive correlations with plant height ($r = 0.924$), branches plant⁻¹ ($r = 0.911$), nodules plant⁻¹ ($r = 0.948$), dry matter accumulation ($r = 0.967$), pods plant⁻¹ ($r = 0.982$), test weight ($r = 0.941$) and nutrient uptake parameters. The highest positive correlation was observed between seed yield and pods plant⁻¹ ($r = 0.982$), followed by nitrogen uptake ($r = 0.973$) and dry matter accumulation ($r = 0.967$).

The strong positive relationship between seed yield and pods plant⁻¹ indicates that pod production was the most important yield-determining factor in lentil under the present investigation. Similarly, the high correlation between dry matter accumulation and seed yield suggests that greater photosynthetic efficiency and biomass production directly contributed to increased translocation of assimilates towards reproductive organs. These findings are in agreement with those reported by Meena *et al.* (2020) [20], Singh *et al.* (2021) [30] and Sharma *et al.* (2021) [28], who observed that biomass accumulation and pod formation were the major determinants of seed yield in pulse crops.

Regression analysis further confirmed the close relationship between crop growth and productivity. The regression equation between dry matter accumulation and seed yield ($Y = 0.214X - 0.46$) recorded an R² value of 0.935, indicating that approximately 93.5% of the variation in seed yield was explained by variation in dry matter accumulation. This demonstrates that enhanced biomass production substantially contributed to higher grain yield under integrated nutrient management treatments.

Similarly, the regression equation between nitrogen uptake and seed yield ($Y = 0.018X + 0.48$) produced an R² value of 0.947,

indicating that 94.7% of the variation in seed yield was associated with variation in nitrogen uptake. The strong relationship highlights the critical role of nitrogen nutrition in improving photosynthesis, protein synthesis, nodulation and reproductive development of lentil.

The higher correlation and regression coefficients observed under integrated nutrient management treatments indicate that balanced nutrient availability improved physiological efficiency, nutrient absorption and assimilate partitioning. Farmyard manure improved soil health and nutrient retention, while Rhizobium and PSB enhanced biological nitrogen fixation and phosphorus availability, resulting in greater nutrient uptake and biomass production. Consequently, improvements in growth parameters were directly translated into higher seed yield.

Overall, the correlation and regression analyses clearly establish that dry matter accumulation, nutrient uptake and yield attributes were the principal factors governing seed yield in lentil. The results suggest that management practices aimed at improving biomass production, nodulation, nutrient uptake and pod development can substantially enhance lentil productivity. Therefore, timely sowing combined with integrated nutrient management not only improved individual growth and yield parameters but also strengthened their positive contribution towards final seed yield.

Conclusion and Recommendations

Among the different treatment combinations, 25 October sowing along with 75% RDF + FYM + Rhizobium + PSB consistently produced superior performance in terms of growth parameters, yield attributes, yield, nutrient uptake, soil fertility improvement and economic returns. The treatment recorded maximum plant height, branching, nodulation, dry matter accumulation, crop growth rate and relative growth rate, indicating a favourable crop environment and enhanced physiological efficiency. Improvement in vegetative growth ultimately translated into better reproductive development, resulting in significantly higher pods plant⁻¹, seeds pod⁻¹, test weight and harvest index. The same treatment produced the highest seed yield (1.96 t ha⁻¹), straw yield (3.18 t ha⁻¹) and biological yield (5.14 t ha⁻¹), which were substantially higher than those recorded under late sowing and sole fertilizer application. Enhanced nutrient uptake of nitrogen, phosphorus and potassium under integrated nutrient management treatments indicated improved nutrient availability and utilization efficiency. Furthermore, incorporation of FYM and biofertilizers significantly improved soil organic carbon, available nitrogen, phosphorus and potassium, thereby contributing to long-term soil fertility and sustainability.

Correlation and regression analyses revealed strong positive relationships between seed yield and important growth, yield and nutrient uptake parameters. Dry matter accumulation, pod production and nitrogen uptake emerged as the most influential factors governing seed yield. These findings emphasize the importance of balanced nutrient management and optimum sowing time for achieving higher productivity and resource-use efficiency in lentil cultivation.

Economic analysis further confirmed the superiority of integrated nutrient management under timely sowing conditions. The treatment consisting of 25 October sowing + 75% RDF + FYM + Rhizobium + PSB recorded the highest gross return (₹131,320 ha⁻¹), net return (₹88,116 ha⁻¹) and benefit-cost ratio (3.04), indicating greater profitability and economic viability for farmers.

Recommendation

Based on the findings of the present investigation, it may be

recommended that lentil should be sown during the last week of October and supplied with 75% recommended dose of fertilizers integrated with farmyard manure, Rhizobium inoculation and phosphate-solubilizing bacteria (PSB) for obtaining higher productivity, improved nutrient uptake, better soil fertility status and maximum economic returns under the sandy loam soils of Central Uttar Pradesh and similar agro-ecological regions. This integrated approach can serve as a sustainable nutrient management strategy for enhancing lentil production while maintaining long-term soil health and agricultural sustainability.

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