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Effect of Conservation Tillage and Integrated Nutrient Management on Growth, Yield, of Chickpea (*Cicer arietinum* L.) under Pearl Millet–chickpea Cropping System in the Indo-gangetic Plains

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

Chickpea (*Cicer arietinum* L.) is an important pulse crop that contributes to food and nutritional security while improving soil fertility through biological nitrogen fixation in cereal-based cropping systems. Conservation tillage and integrated nutrient management are considered promising approaches for enhancing crop productivity and sustaining soil health under resource-conserving agriculture. A field experiment was conducted during the rabi seasons of 2022–23 and 2023–24 at the research farm of the ICAR–Indian Institute of Pulses Research (IIPR), Kanpur, Uttar Pradesh, India, to evaluate the influence of tillage management and integrated nutrient management on the growth, nodulation and productivity of chickpea grown in a pearl millet–chickpea cropping system. The experiment was laid out in a split-plot design with three replications, comprising four tillage management practices [zero tillage–zero tillage (ZT–ZT), zero tillage–conventional tillage (ZT–CT), conventional tillage–zero tillage (CT–ZT) and conventional tillage–conventional tillage (CT–CT)] in the main plots and four integrated nutrient management treatments [100% recommended dose of fertilisers (RDF), 75% RDF + 100% crop residue, 50% RDF + 100% crop residue + farmyard manure (FYM) @ 5 t ha^{-1}, and FYM @ 10 t ha^{-1} + 100% crop residue + biofertilisers (*Rhizobium* + phosphate-solubilising bacteria)] in the sub-plots. The pooled analysis revealed that ZT–ZT significantly improved plant height (52.84 cm), dry matter accumulation (18.76 g plant^{-1}), nodules per plant (32.45), nodule dry weight (145.62 mg plant^{-1}), root biomass (3.86 g plant^{-1}) and grain yield (21.84 q ha^{-1}) compared with CT–CT, which recorded 47.35 cm plant height, 15.68 g plant^{-1} dry matter accumulation, 25.92 nodules per plant and 18.45 q ha^{-1} grain yield. Among the nutrient management treatments, FYM @ 10 t ha^{-1} + 100% crop residue + biofertilisers produced the highest plant height (53.53 cm), dry matter accumulation (18.94 g plant^{-1}), nodules per plant (33.12), grain yield (22.18 q ha^{-1}), straw yield (33.42 q ha^{-1}) and biological yield (55.60 q ha^{-1}), representing a 17.23% increase in grain yield over 100% RDF. The integrated application of organic and inorganic nutrient sources, together with conservation tillage, promoted better crop establishment, enhanced nodulation and improved biomass accumulation, resulting in higher productivity. The findings suggest that continuous zero tillage integrated with FYM @ 10 t ha^{-1}, crop residue retention and biofertiliser inoculation is an effective and sustainable management strategy for improving chickpea productivity in the pearl millet–chickpea cropping system under the Indo-Gangetic Plains.

Keywords: Chickpea; Cicer arietinum L.; conservation tillage; zero tillage; integrated nutrient management; farmyard manure; crop residue retention; biofertilisers; nodulation; pearl millet–chickpea system; Indo-Gangetic Plains; grain yield.

1. Introduction

Chickpea (*Cicer arietinum* L.) is one of the most important grain legumes cultivated globally and constitutes a vital component of human nutrition, particularly in developing countries where it serves as a primary source of plant-based protein, carbohydrates, dietary fibre, vitamins and essential minerals (Jukanti et al., 2012; FAOSTAT, 2023). In addition to its nutritional importance, chickpea plays a significant role in ensuring food and nutritional security, especially among vegetarian populations (Varshney et al., 2013). Globally, chickpea is cultivated over an area of about 14–15 million hectares with an annual production exceeding 17 million tonnes and an average productivity of approximately 1100–1200 kg ha^{-1} (FAOSTAT, 2023). India dominates global chickpea production, contributing nearly 70–75% of the total area and output, with cultivation spread over 10–11 million hectares and production exceeding 12 million tonnes (Directorate of Economics and Statistics, 2022). Despite its significance, the productivity of chickpea in India remains relatively low compared to its genetic potential, primarily due to constraints such as declining soil fertility, imbalanced nutrient application, moisture stress, and sub-optimal crop management practices (Kumar et al., 2017; Jat et al., 2020). Furthermore, climate variability and increasing pressure on natural resources have added new challenges to sustaining chickpea productivity (IPCC, 2021).

In the Indo-Gangetic Plains (IGP), chickpea is predominantly grown as a rabi season crop following rainy-season cereals such as rice and pearl millet. It plays a pivotal role in enhancing cropping system sustainability through its ability to fix atmospheric nitrogen via symbiotic association with *Rhizobium* spp., thereby contributing to soil nitrogen economy and reducing dependence on synthetic fertilisers (Giller, 2001; Peoples et al., 2009). Chickpea can fix approximately 60–140 kg N ha^{-1} under favourable conditions, significantly improving soil fertility for subsequent crops (Peoples et al., 2009; Herridge et al., 2008). In addition to nitrogen fixation, chickpea contributes to improved soil structure and microbial diversity through root exudates and residue incorporation (Dakora and Phillips, 2002). However, the efficiency of biological nitrogen fixation is highly influenced by soil physical properties, nutrient availability, microbial activity and agronomic practices (Hungria and Vargas, 2000). Continuous conventional tillage practices often result in soil structure degradation, reduced soil organic carbon, increased bulk density and diminished microbial activity, ultimately impairing nodulation, nutrient uptake and crop productivity (Lal, 2015; Six et al., 2004). These adverse effects highlight the need for alternative soil management practices that can sustain soil health and crop performance.

Conservation agriculture (CA) has emerged as a sustainable approach to address these challenges by enhancing resource-use efficiency and maintaining soil health. The core principles of CA include minimal soil disturbance (zero or reduced tillage), permanent soil cover through crop residues, and diversified crop rotations (Hobbs et al., 2008; Kassam et al., 2009). Zero tillage has been shown to improve soil moisture retention, enhance soil aggregation, reduce erosion losses and promote beneficial soil microbial populations (Derpsch et al., 2010; Jat et al., 2020). It also reduces fuel and labour requirements, thereby lowering the cost of cultivation. These improvements collectively facilitate better root proliferation, nutrient uptake and crop growth. Empirical evidence suggests that conservation tillage practices can increase pulse crop productivity by 10–25% while simultaneously improving soil organic carbon and nutrient cycling in cereal–legume systems (Jat et al., 2020; Thierfelder et al., 2015). Moreover, conservation agriculture contributes to climate change mitigation by enhancing carbon sequestration and reducing greenhouse gas emissions (Lal, 2015; Smith et al., 2008). Recent evidence from a pearl millet–chickpea system also indicates that zero-tillage with residue retention and system intensification can improve chickpea productivity and moisture-stress tolerance, while longer-term rice–chickpea studies in the northern Gangetic Plains have emphasised the need to evaluate yield and profitability under conservation tillage (Bana et al., 2023; Nath et al., 2024).

Integrated nutrient management (INM) is another critical strategy for achieving sustainable and resilient agricultural production. INM involves the judicious combination of chemical fertilisers, organic manures and biofertilisers to ensure balanced nutrient supply and improved nutrient-use efficiency (Singh et al., 2014; Baligar et al., 2001). Organic inputs such as farmyard manure (FYM) and crop residues enhance soil physical properties, increase cation exchange capacity and stimulate microbial activity (Palm et al., 2001), while biofertilisers such as *Rhizobium* and phosphate-solubilising bacteria (PSB) improve nutrient availability and biological nitrogen fixation (Vessey, 2003; Richardson et al., 2009). In addition, integrated nutrient management helps in reducing nutrient losses through leaching and volatilisation, thereby improving fertiliser-use efficiency (Baligar et al., 2001). Studies have demonstrated that integrated application of organic and inorganic nutrient sources can significantly enhance nodulation, dry matter accumulation, grain yield and soil fertility compared to sole application of chemical fertilisers (Kumar et al., 2017; Meena et al., 2019). Such integrated approaches are essential for maintaining long-term soil productivity and environmental sustainability. Recent chickpea and rhizosphere-focused studies further indicate that biofertiliser-supported nutrient strategies can improve nutrient mobilisation, nodulation and yield when integrated with organic or inorganic nutrient sources (Adal, 2023; Kumar et al., 2025; Nabati et al., 2025).

The pearl millet–chickpea cropping system is widely practised in semi-arid and sub-humid regions of northern India due to its adaptability, efficient resource utilisation and contribution to soil fertility enhancement (Yadav et al., 2012). Pearl millet, being a hardy crop, performs well under low-input conditions and provides resilience against climatic uncertainties, while chickpea complements the system by improving soil nitrogen status and overall system productivity (Yadav et al., 2012). This cropping system also offers opportunities for better utilisation of residual soil moisture and nutrients. However, there is limited comprehensive information on the synergistic effects of conservation tillage and integrated nutrient management on chickpea performance within this cropping system. Understanding these interactions is crucial for developing sustainable production strategies that enhance productivity while conserving natural resources and maintaining soil health.

Although the preceding discussion establishes the relevance of conservation tillage and integrated nutrient management, location-specific evidence on their combined influence on chickpea growth, nodulation and yield within a pearl millet–chickpea system in the Indo-Gangetic Plains remains limited.

Therefore, the present investigation was undertaken to evaluate the effect of different tillage practices and integrated nutrient management strategies on growth parameters, dry matter accumulation, nodulation and yield of chickpea under a pearl millet–chickpea cropping system in the Indo-Gangetic Plains.

2. Materials and Methods

The field experiment was conducted during the rabi seasons of 2022–23 and 2023–24 at the research farm of the ICAR–Indian Institute of Pulses Research (IIPR), Kanpur, Uttar Pradesh, India, situated in the Central Plain Zone of the Indo-Gangetic Plains. The experimental site is located at 26°27′ N latitude and 80°14′ E longitude, at an altitude of approximately 126 m above mean sea level. The region experiences a subtropical climate characterised by hot summers and cool winters, which is typical for pulse-based cropping systems in northern India. Prior to the initiation of the experiment, composite soil samples were collected from the 0–15 cm depth and analysed following standard scientific procedures. Soil pH and electrical conductivity were determined using the methods described by Jackson (1973). Organic carbon content was estimated by the Walkley and Black (1934) method. Available nitrogen was determined using the alkaline permanganate method as described by Subbiah and Asija (1956), available phosphorus by Olsen et al., (1954), and available potassium by flame photometry following extraction with neutral ammonium acetate as outlined by Jackson (1973). The soil was sandy loam in texture and slightly alkaline in reaction, with a pH of 7.84 and electrical conductivity of 0.42 dS m^{-1}. The organic carbon content was 0.42%. The available nitrogen, phosphorus, and potassium contents were 182.4 kg ha^{-1}, 16.2 kg ha^{-1}, and 164.8 kg ha^{-1}, respectively. Based on these values, the soil was categorised as low in available nitrogen and medium in available phosphorus and potassium.

The experiment was laid out in a split-plot design with three replications following the methodology described by Gomez and Gomez (1984). The main plot treatments consisted of four tillage management practices: zero tillage in both pearl millet and chickpea (ZT–ZT), zero tillage in pearl millet and conventional tillage in chickpea (ZT–CT), conventional tillage in pearl millet and zero tillage in chickpea (CT–ZT), and conventional tillage in both crops (CT–CT). The sub-plot treatments comprised four integrated nutrient management strategies: N_1 (100% recommended dose of fertilisers in both crops), N_2 (75% RDF combined with 100% crop residue), N_3 (50% RDF along with 100% crop residue and farmyard manure at 5 t ha^{-1}), and N_4 (FYM at 10 t ha^{-1} combined with 100% crop residue and biofertilisers, namely *Rhizobium* and phosphate-solubilising bacteria, applied in chickpea). Chickpea variety IPC 2005-62 was grown during both experimental years following pearl millet. All agronomic practices were carried out in accordance with recommended scientific guidelines (ICAR, 2018). Biofertiliser inoculation with *Rhizobium* and phosphate-solubilising bacteria (PSB) was performed using the seed inoculation technique described by Vincent (1970). Crop residue retention and FYM application were implemented as per the treatment specifications.

Growth parameters, including plant height and dry matter accumulation, were recorded at different phenological stages following standard procedures (Panse and Sukhatme, 1985). Nodulation characteristics, such as the number of nodules per plant and nodule biomass, were assessed at peak flowering using the method described by Vincent (1970). At physiological maturity, grain yield, straw yield, biological yield, and harvest index were recorded following standard agronomic procedures (Gomez and Gomez, 1984). The experimental data collected over the two years were subjected to statistical analysis using analysis of variance (ANOVA) appropriate for a split-plot design as described by Gomez and Gomez (1984). Treatment means were compared using the critical difference (CD) test at the 5% level of significance as outlined by Panse and Sukhatme (1985). Pooled analysis across years was performed wherever the treatment effects were found to be homogeneous.

3. Results and Discussion

3.1 Plant Height of Chickpea

Plant height is an important indicator of vegetative growth and reflects the combined influence of soil moisture availability, nutrient supply, root development and photosynthetic activity. The pooled data revealed that plant height increased progressively from 30 DAS to harvest under all treatments and was significantly influenced by both tillage management and integrated nutrient management (Table 1 and Fig. 1).

Among the tillage management practices, ZT–ZT recorded the highest plant height at all growth stages, measuring 28.45 cm at 30 DAS, 41.62 cm at 60 DAS and 52.84 cm at harvest. This was followed by ZT–CT (27.36, 39.85 and 50.67 cm) and CT–ZT (26.98, 39.12 and 49.92 cm), whereas CT–CT recorded the lowest plant height (25.74, 37.28 and 47.35 cm, respectively). Compared with CT–CT, continuous zero tillage increased plant height by 10.53%, 11.64% and 11.59% at 30 DAS, 60 DAS and harvest, respectively. The improved plant growth under zero tillage can be attributed to better conservation of soil moisture, reduced soil disturbance, improved soil aggregation and greater biological activity, all of which created favourable conditions for root proliferation and efficient nutrient uptake throughout the crop growth period.

Table 1. Effect of Tillage Management and Integrated Nutrient Management on Plant Height of Chickpea at Different Growth Stages (Pooled Data)

Treatments	30 DAS (cm)	60 DAS (cm)	At Harvest (cm)
Tillage Management			
ZT–ZT	28.45	41.62	52.84
ZT–CT	27.36	39.85	50.67
CT–ZT	26.98	39.12	49.92
CT–CT	25.74	37.28	47.35
SEm ±	0.52	0.68	0.82
CD (P=0.05)	1.53	2.01	2.41
Integrated Nutrient Management			
100% RDF in Both Crops	25.36	36.94	46.78
75% RDF + Crop Residue (100%)	26.87	38.92	49.63
50% RDF + Crop Residue (100%) + FYM @ 5 t ha^{-1}	28.12	40.76	51.84
FYM @ 10 t ha^{-1} + Crop Residue (100%) + Biofertilisers	29.04	42.18	53.53
SEm ±	0.48	0.63	0.76
CD (P=0.05)	1.41	1.85	2.23

Integrated nutrient management also exerted a significant influence on plant height. The treatment comprising FYM @ 10 t ha^{-1} + 100% crop residue + biofertilisers recorded the highest plant height, with values of 29.04 cm at 30 DAS, 42.18 cm at 60 DAS and 53.53 cm at harvest. The next best treatment was 50% RDF + 100% crop residue + FYM @ 5 t ha^{-1}, which produced 28.12, 40.76 and 51.84 cm at the respective growth stages. In contrast, the 100% RDF treatment recorded the lowest plant height (25.36, 36.94 and 46.78 cm). Compared with 100% RDF, the integrated application of FYM @ 10 t ha^{-1} + crop residue + biofertilisers increased plant height by 14.51% at 30 DAS, 14.19% at 60 DAS and 14.43% at harvest.

The superior plant growth observed under integrated nutrient management may be attributed to the complementary effects of organic and inorganic nutrient sources. Farmyard manure improved soil structure, water-holding capacity and microbial activity, while crop residue retention enhanced soil organic carbon and nutrient recycling. Biofertiliser inoculation further promoted biological nitrogen fixation and nutrient mobilisation, ensuring a balanced and sustained nutrient supply throughout the crop growth period. These favourable conditions improved root development, chlorophyll synthesis and photosynthetic efficiency, ultimately resulting in greater vegetative growth.

The present findings are consistent with those reported by Kumar et al., (2017), who observed improved crop growth under conservation agriculture and integrated nutrient management in cereal-based systems. Similar improvements in plant growth due to enhanced soil health and balanced nutrient supply have also been reported by Jat et al., (2018), Parihar et al., (2018) and Choudhary et al., (2021).

3.2 Dry Matter Accumulation of Chickpea

Dry matter accumulation is an important indicator of crop growth, reflecting the efficiency of photosynthesis, nutrient utilisation and assimilate production throughout the growing period. The pooled data showed that dry matter accumulation increased progressively from 30 DAS to harvest under all treatments and was significantly influenced by both tillage management and integrated nutrient management (Table 2 and Fig. 2).

Table 2. Effect of tillage management and integrated nutrient management on dry matter accumulation of chickpea at different growth stages (Pooled data)

Treatments	30 DAS (g plant^{-1})	60 DAS (g plant^{-1})	At Harvest (g plant^{-1})
Tillage Management			
ZT–ZT	2.85	8.92	18.76
ZT–CT	2.63	8.15	17.42

Treatments	**30 DAS (g plant^{-1})**	**60 DAS (g plant^{-1})**	**At Harvest (g plant^{-1})**
Tillage Management			
CT–ZT	2.48	7.86	16.95
CT–CT	2.21	7.12	15.68
SEm ±	0.08	0.21	0.42
CD (P=0.05)	0.24	0.63	1.26
Integrated Nutrient Management			
100% RDF in Both Crops	2.32	7.35	15.92
75% RDF + Crop Residue (100%)	2.54	7.98	16.84
50% RDF + Crop Residue (100%) + FYM @ 5 t ha^{-1}	2.71	8.46	17.68
FYM @ 10 t ha^{-1} + Crop Residue (100%) + Biofertilisers	2.96	9.12	18.94
SEm ±	0.07	0.19	0.38
CD (P=0.05)	0.21	0.57	1.14

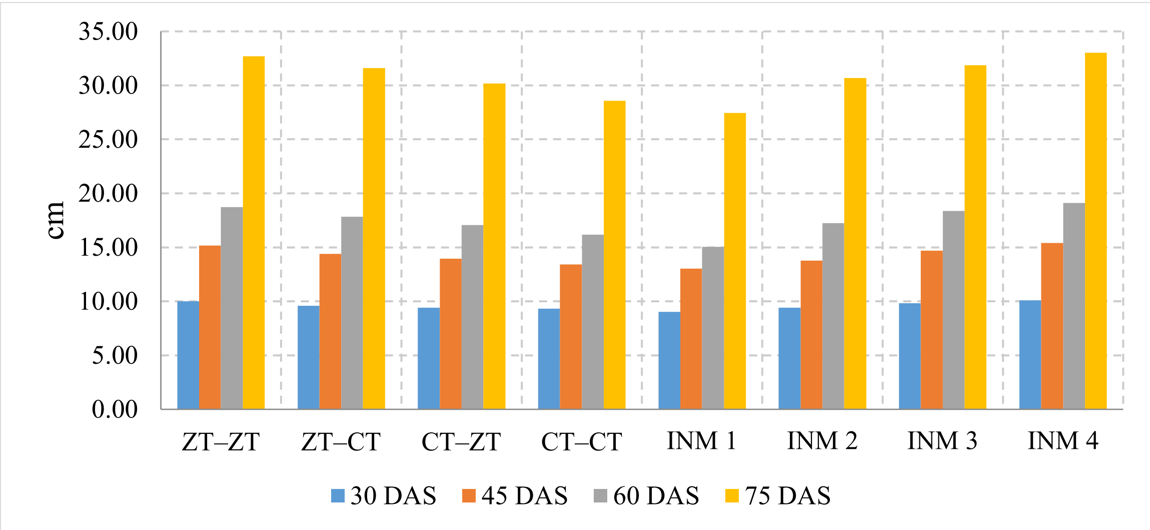

Fig. 1. Graph showing Effect of Tillage Management and Integrated Nutrient Management on Plant Height of Chickpea (Pooled Data)

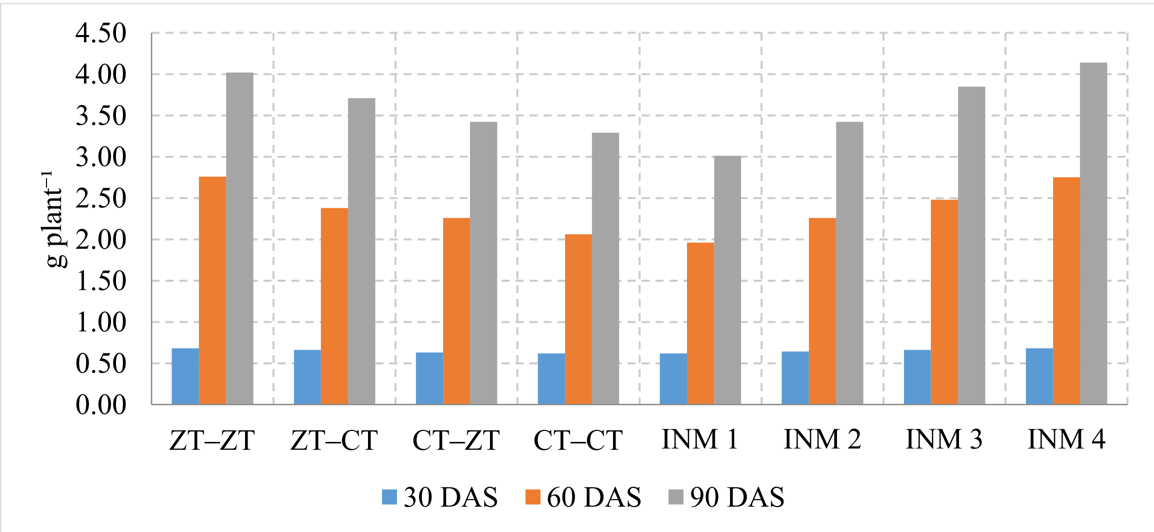

Fig. 2. Graph showing Effect of Tillage Management and Integrated Nutrient Management on Dry Weight per Plant of Chickpea (Pooled Data)

Among the tillage management practices, ZT–ZT recorded the highest dry matter accumulation at all growth stages, producing 2.85, 8.92 and 18.76 g plant⁻¹ at 30 DAS, 60 DAS and harvest, respectively. In contrast, CT–CT recorded the lowest dry matter accumulation (2.21, 7.12 and 15.68 g plant⁻¹, respectively). Continuous zero tillage increased dry matter accumulation by 28.96% at 30 DAS, 25.28% at 60 DAS and 19.64% at harvest over continuous conventional tillage. The treatments ZT–CT and CT–ZT also produced significantly greater dry matter than CT–CT, indicating that reduced soil disturbance and improved soil moisture conservation promoted vegetative growth and biomass production. The favourable soil environment created under zero tillage enhanced root proliferation and nutrient uptake, which ultimately resulted in greater dry matter accumulation throughout the crop growth period.

Integrated nutrient management also had a pronounced effect on biomass production. The treatment comprising FYM @ 10 t ha⁻¹ + 100% crop residue + biofertilisers recorded the highest dry matter accumulation, producing 2.96, 9.12 and 18.94 g plant⁻¹ at 30 DAS, 60 DAS and harvest, respectively. This was followed by 50% RDF + 100% crop residue + FYM @ 5 t ha⁻¹, which recorded 2.71, 8.46 and 17.68 g plant⁻¹ at the respective growth stages. The lowest dry matter accumulation was observed under 100% RDF, with values of 2.32, 7.35 and 15.92 g plant⁻¹. Compared with 100% RDF, the integrated application of FYM @ 10 t ha⁻¹ + crop residue + biofertilisers increased dry matter accumulation by 27.59% at 30 DAS, 24.08% at 60 DAS and 18.97% at harvest.

The higher biomass production under integrated nutrient management can be attributed to the balanced and continuous supply of nutrients through the combined application of organic and inorganic sources. Farmyard manure and crop residues improved soil organic matter, moisture retention and microbial activity, while biofertiliser inoculation enhanced nutrient availability and root growth. These favourable soil conditions supported greater photosynthetic activity and efficient conversion of assimilates into plant biomass throughout the growing period. Similar responses have been reported by Kumar et al. (2017), Jat et al. (2018), Parihar et al. (2018) and Choudhary et al. (2021), who observed significant improvements in crop biomass under conservation agriculture integrated with balanced nutrient management.

3.3 Nodulation and Root Biomass of Chickpea

Nodulation and root biomass are important indicators of biological nitrogen fixation and overall crop vigour in chickpea. These parameters directly influence nitrogen availability, nutrient uptake and subsequent crop productivity. The pooled results revealed that both tillage management and integrated nutrient management significantly influenced the number of nodules per plant, nodule dry weight and root biomass of chickpea (Table 3 and Fig. 3).

Table 3. Effect of tillage management and integrated nutrient management on nodulation and root biomass of chickpea (Pooled data)

Treatments	Nodules Plant⁻¹	Nodule Dry Weight (mg plant⁻¹)	Root Biomass (g plant⁻¹)
Tillage Management			
ZT–ZT	32.45	145.62	3.86
ZT–CT	29.78	132.48	3.54
CT–ZT	28.36	125.74	3.32
CT–CT	25.92	118.36	3.05
SEm ±	0.92	3.84	0.09
CD (P=0.05)	2.76	11.52	0.27
Integrated Nutrient Management			
100% RDF in Both Crops	26.84	120.52	3.12
75% RDF + Crop Residue (100%)	28.96	130.84	3.38
50% RDF + Crop Residue (100%) + FYM @ 5 t ha⁻¹	30.74	138.92	3.62
FYM @ 10 t ha⁻¹ + Crop Residue (100%) + Biofertilisers	33.12	148.36	3.94
SEm ±	0.88	3.62	0.08
CD (P=0.05)	2.64	10.86	0.24

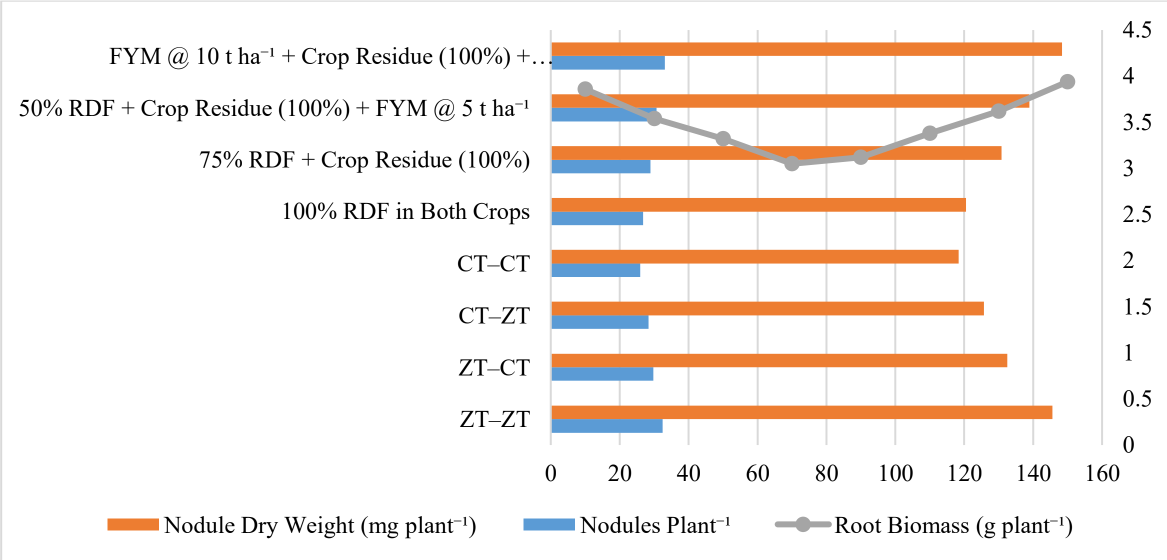

Fig. 3. Graph showing Effect of Tillage Management and Integrated Nutrient Management on Nodulation and Root Biomass of Chickpea (Pooled Data)

Among the tillage management practices, ZT–ZT recorded the highest number of nodules (32.45 plant^{-1}), nodule dry weight (145.62 mg plant^{-1}) and root biomass (3.86 g plant^{-1}), whereas CT–CT recorded the lowest values (25.92 nodules plant^{-1}, 118.36 mg plant^{-1} and 3.05 g plant^{-1}, respectively). Continuous zero tillage increased the number of nodules, nodule dry weight and root biomass by 25.19%, 23.04% and 26.56%, respectively, over continuous conventional tillage. The superior nodulation and root growth under zero tillage may be attributed to improved soil structure, greater soil moisture conservation, reduced mechanical disturbance and enhanced microbial activity, which created a favourable rhizosphere environment for root development and effective symbiosis between chickpea roots and *Rhizobium*.

Integrated nutrient management also produced a significant improvement in nodulation and root biomass. The treatment comprising FYM @ 10 t ha^{-1} + 100% crop residue + biofertilisers recorded the highest number of nodules (33.12 plant^{-1}), nodule dry weight (148.36 mg plant^{-1}) and root biomass (3.94 g plant^{-1}), followed by 50% RDF + 100% crop residue + FYM @ 5 t ha^{-1}, which recorded 30.74 nodules plant^{-1}, 138.92 mg plant^{-1} nodule dry weight and 3.62 g plant^{-1} root biomass. Compared with 100% RDF, the integrated application of organic and inorganic nutrient sources increased nodules per plant by 23.40%, nodule dry weight by 23.10% and root biomass by 26.28%. The combined application of farmyard manure, crop residues and biofertilisers improved soil organic matter, stimulated microbial activity and enhanced the survival and effectiveness of *Rhizobium*, resulting in greater biological nitrogen fixation and better root development.

The present findings are consistent with those of Hungria and Vargas (2000), who reported that efficient biological nitrogen fixation depends on an active *Rhizobium*–legume association supported by favourable soil conditions. Similar improvements in nodulation and nutrient acquisition following biofertiliser inoculation have been reported by Vessey (2003). Furthermore, Antil & Raj (2019) emphasised that integrated nutrient management improves soil biological activity, nutrient availability and root growth, thereby enhancing nodulation and crop productivity under sustainable production systems.

3.4 Grain Yield, Straw Yield and Harvest Index of Chickpea

Grain yield, straw yield, biological yield and harvest index (Table 4 and Fig. 4) are the most important indicators of crop productivity and reflect the cumulative influence of crop growth, biomass accumulation, assimilate partitioning and nutrient utilisation. The pooled analysis over two consecutive years demonstrated that both tillage management and integrated nutrient management significantly affected grain yield, straw yield and biological yield of chickpea, whereas differences in harvest index were comparatively smaller.

Table 4. Effect of tillage management and integrated nutrient management on grain yield, straw yield, biological yield and harvest index of chickpea (Pooled data)

Treatments	Grain Yield (q ha^{-1})	Straw Yield (q ha^{-1})	Biological Yield (q ha^{-1})	Harvest Index (%)
Tillage Management				
ZT–ZT	21.84	32.76	54.60	40.00
ZT–CT	20.36	31.42	51.78	39.32
CT–ZT	19.72	30.85	50.57	39.00
CT–CT	18.45	29.68	48.13	38.33
SEm ±	0.52	0.84	1.12	0.68
CD (P=0.05)	1.56	2.52	3.36	2.04
Integrated Nutrient Management				
100% RDF in Both Crops	18.92	30.12	49.04	38.58
75% RDF + Crop Residue (100%)	19.86	31.08	50.94	39.00
50% RDF + Crop Residue (100%) + FYM @ 5 t ha^{-1}	20.94	32.18	53.12	39.43
FYM @ 10 t ha^{-1} + Crop Residue (100%) + Biofertilisers	22.18	33.42	55.60	39.89
SEm ±	0.48	0.78	1.04	0.62
CD (P=0.05)	1.44	2.34	3.12	1.86

Among the tillage management practices, ZT–ZT recorded the highest grain yield (21.84 q ha^{-1}), followed by ZT–CT (20.36 q ha^{-1}) and CT–ZT (19.72 q ha^{-1}), while the lowest grain yield (18.45 q ha^{-1}) was recorded under CT–CT. Compared with continuous conventional tillage, continuous zero tillage increased grain yield by 18.37%. A similar trend was observed for straw and biological yield. The maximum straw yield (32.76 q ha^{-1}) and biological yield (54.60 q ha^{-1}) were obtained under ZT–ZT, whereas CT–CT produced the minimum straw yield (29.68 q ha^{-1}) and biological yield (48.13 q ha^{-1}). Continuous zero tillage improved straw yield by 10.38% and biological yield by 13.45% over conventional tillage. Although harvest index varied only marginally among the tillage treatments, the highest value (40.00%) was recorded under ZT–ZT, followed by ZT–CT (39.32%), while the lowest harvest index (38.33%) was observed under CT–CT. The improvement in crop productivity under zero tillage may be attributed to better conservation of soil moisture, improved soil structure, enhanced root growth and greater nutrient availability, which together promoted higher biomass production and more efficient translocation of assimilates towards grain development.

Integrated nutrient management also exerted a significant influence on crop productivity. The treatment comprising FYM @ 10 t ha^{-1} + 100% crop residue + biofertilisers recorded the highest grain yield (22.18 q ha^{-1}), straw yield (33.42 q ha^{-1}) and biological yield (55.60 q ha^{-1}), followed by 50% RDF + 100% crop residue + FYM @ 5 t ha^{-1}, which produced 20.94 q ha^{-1} grain yield, 32.18 q ha^{-1} straw yield and 53.12 q ha^{-1} biological yield. In contrast, the 100% RDF treatment recorded the lowest grain yield (18.92 q ha^{-1}), straw yield (30.12 q ha^{-1}) and biological yield (49.04 q ha^{-1}). Compared with 100% RDF, the integrated application of FYM @ 10 t ha^{-1} + crop residue + biofertilisers increased grain yield by 17.23%, straw yield by 10.96% and biological yield by 13.38%. The harvest index ranged from 38.58% under 100% RDF to 39.89% under FYM @ 10 t ha^{-1} + crop residue + biofertilisers, although the differences among nutrient management treatments were relatively small.

The superior performance of integrated nutrient management can be attributed to the complementary effects of organic and inorganic nutrient sources. Farmyard manure and crop residues improve soil physical properties, moisture retention and microbial activity, while biofertiliser inoculation enhances biological nitrogen fixation and nutrient availability in the rhizosphere. The balanced and sustained supply of nutrients throughout the crop growth period promotes vigorous vegetative growth, greater dry matter accumulation and efficient assimilate partitioning, resulting in higher grain and biological yields. Similar responses have been reported under conservation agriculture and integrated nutrient management in legume- and cereal-based production systems by Choudhary et al., (2021), Kumar et al., (2017), Parihar et al., (2018), Jat et al., (2018) and Gathala et al., (2020).

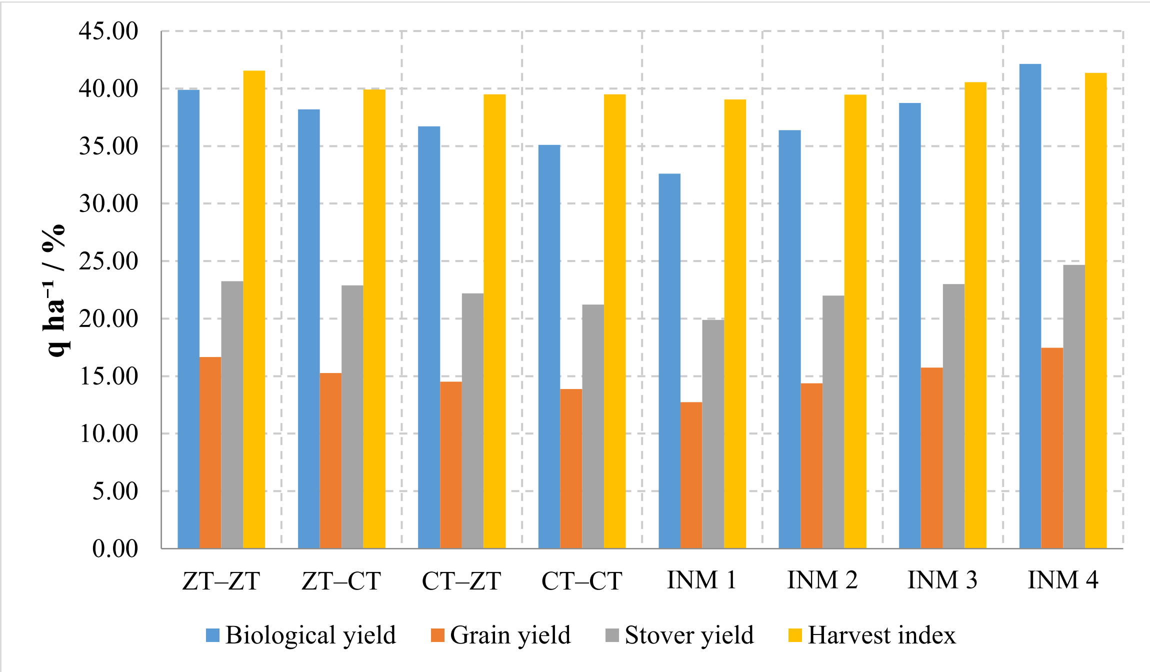

Fig. 4. Graph showing Effect of Tillage Management and Integrated Nutrient Management on Biological Yield, Grain Yield, Stover Yield and Harvest Index of Chickpea

4. Conclusion

The study showed that tillage management and integrated nutrient management significantly influenced growth, nodulation and yield of chickpea in the pearl millet–chickpea cropping system. Continuous zero tillage recorded superior plant height, dry matter accumulation, nodulation, root biomass and yield compared with continuous conventional tillage. Among nutrient management treatments, the application of FYM @ 10 t ha^{-1} with crop residue retention and biofertilisers produced the highest values for plant growth, nodulation, grain yield, straw yield and biological yield. This treatment recorded a grain yield of 22.18 q ha^{-1} compared with 18.92 q ha^{-1} under 100% RDF. The results suggest that combining conservation tillage with organic nutrient sources and biofertiliser inoculation can improve chickpea performance under the studied agro-ecological conditions. Further validation over more seasons and locations would help confirm the stability and wider applicability of these findings.

5. Limitations

The study was conducted at a single location over two rabi seasons; therefore, the results may vary under different soil types, rainfall patterns and management conditions. The manuscript presents pooled data, but year-wise results and detailed tillage × nutrient management interactions are limited. Long-term effects on soil physical, chemical and biological properties also require further evaluation before wider recommendation.

6. Recommendation

Based on the results of the present investigation, continuous zero tillage (ZT–ZT) combined with FYM @ 10 t ha^{-1} + crop residue retention (100%) + biofertilisers (*Rhizobium* + PSB) may be recommended for chickpea cultivation under the pearl millet–chickpea cropping system in the Indo-Gangetic Plains. This treatment combination produced the highest plant height, dry matter accumulation, nodulation, root biomass, grain yield (22.18 q ha^{-1}), straw yield (33.42 q ha^{-1}) and biological yield (55.60 q ha^{-1}), while also improving nutrient-use efficiency and soil health. Therefore, adoption of this integrated conservation agriculture approach can enhance chickpea productivity, profitability and long-term sustainability of pulse-based cropping systems.

Declaration of AI Use

This manuscript was prepared through the combined contributions of all author(s), including contributions to the study design, data, content development, results, interpretation, and related scholarly work. The author(s) acknowledge the use of Grammarly and ChatGPT to assist with grammar checking, language refinement, reference formatting. These AI-assisted tools were not used as authors and did not replace the intellectual contributions or scholarly judgment of the author(s). All AI-assisted outputs, including content, references, and interpretations, were carefully reviewed, revised, verified, and approved by the author(s). The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that no competing interests exist.

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