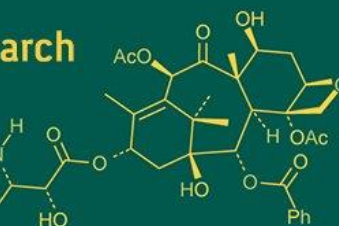
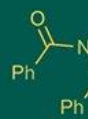


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Impact of permanent beds and zero tillage on soil primary nutrient availability under maize-based cropping systems

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Abstract

Conservation agriculture practices such as permanent raised beds (PB) and zero tillage (ZT) have shown potential to improve soil fertility, water management, and nutrient dynamics in maize-based cropping systems. This study evaluates the effect of ten years of tillage and crop establishment practices on soil primary nutrient availability under diversified maize-based rotations. The experiment, initiated in 2008 at ICAR-Indian Institute of Maize Research (IIMR), New Delhi, employed a split-plot design with three tillage systems—permanent raised beds (PB), zero till flat (ZT), and conventional tillage flat (CT)—and four intensified crop rotations: maize-wheat-mungbean (MWMb), maize-chickpea-sesbania (MCS), maize-mustard-mungbean (MMuMb), and maize-maize-sesbania (MMS). Soil samples collected during 2018-19 at 0-5 cm, 5-15 cm, and 15-30 cm depths were analyzed for available nitrogen (N), phosphorus (P), and potassium (K). Results indicated that PB and ZT treatments showed significantly higher soil organic carbon (SOC) and nutrient availability compared to CT across depths. Residue retention and continuous reduced tillage improved nutrient cycling and biological activity. Among cropping systems, MWMb and MCS enhanced available N and P, while MMS accumulated more K due to continuous maize residues. Overall, permanent raised beds with residue retention sustained higher nutrient availability and soil quality, supporting long-term productivity and sustainability of maize-based systems in semi-arid environments.

Keywords: Permanent bed, zero tillage, maize system, conservation agriculture, residue management, nutrient availability, India

Introduction

Intensive conventional tillage practices have long characterized Indian agriculture, but their sustainability has been increasingly questioned due to soil degradation, nutrient depletion, and declining productivity. Particularly in maize-based systems of north-western India, continuous tillage and residue removal have impaired soil physical and chemical health (Lal, 2015; Jat *et al.*, 2019) [12, 7, 8]. Conservation agriculture (CA), integrated around minimal soil disturbance, residue retention, and diversified crop rotations, offers a pathway toward soil resilience and sustainable intensification (Kassam *et al.*, 2009) [9].

Permanent raised beds (PB) and zero tillage (ZT) systems represent key CA technologies aimed at improving water-use efficiency, soil organic carbon (SOC), and nutrient cycling. Studies in the Indo-Gangetic Plains (IGP) report that ZT and PB systems enhance nitrogen mineralization and microbial biomass due to favorable soil microclimate and residue-mediated nutrient release (Gupta *et al.*, 2022) [3].

Maize, a versatile C4 crop, forms the backbone of numerous double and triple cropping sequences in India, including maize-wheat-mungbean (MWMb) and maize-chickpea-sesbania (MCS) rotations (Jat *et al.*, 2020) [6]. Incorporating legumes such as mungbean and sesbania can enhance nitrogen fixation and organic matter content, thereby improving soil nutrient dynamics (Ladha *et al.*, 2016) [11]. Meanwhile, sustainable management of crop residues plays a decisive role in nutrient recycling, soil structure maintenance, and erosion prevention (Pittelkow *et al.*, 2015) [14, 15].

Despite the widespread adoption of conservation tillage in wheat-rice systems, limited long-term data exists on its influence on nutrient availability within maize-based rotations under semi-arid conditions. This research investigates the cumulative effects of tillage and cropping system interactions over a decade on the availability of N, P, and K, serving as indicators of soil productivity and sustainability.

Materials and Methods

Study Site Description

The field experiment was conducted at the research farm of ICAR-Indian Institute of Maize Research (IIMR), New Delhi, India (28°40' N, 77°12' E, elevation 229 m), under a semi-arid subtropical climate. The site experiences hot, dry summers and cool winters, with an average annual rainfall of 707 mm, 80% of which occurs from July to September. Rainfall during the 2018-19 cropping year was 854 mm (kharif), 143 mm (rabi), and 68 mm (summer). Mean temperatures ranged from 40 °C (maximum) in kharif to 11 °C (minimum) in rabi. The soil is classified as sandy loam, neutral in reaction (pH 7.8), with 64.3% sand, 13.8% silt, and 22.0% clay. The initial (2008) bulk density and SOC concentration were 1.65 Mg m⁻³ and 4.31 g kg⁻¹, respectively. Baseline nutrient levels were 158 kg ha⁻¹ available N, 11.6 kg ha⁻¹ available P, and 248 kg ha⁻¹ available K.

Experimental Design and Treatments

The experiment was conducted using a split-plot design with three replications. The main plot treatments consisted of three tillage and crop establishment practices, namely zero till permanent beds with residue retention (PB), zero till flat with residue retention (ZT), and conventional till flat with residue retention (CT). The subplot treatments included four maize-based cropping systems: maize-wheat-mungbean (MWMB), maize-chickpea-sesbania (MCS), maize-mustard-mungbean (MMuMb), and maize-maize-sesbania (MMS). Each subplot measured 16.5 × 4.0 m. The experiment began in 2008, and the present data correspond to 2018-19 sampling.

Field Preparation and Crop Management

Fields were laser-leveled and initially deep-tilled (30 cm) to break compact layers. Permanent beds were shaped at 67 cm width with 37 cm flat tops and 15 cm furrows, maintained annually using a raised-bed planter. CT plots underwent disc harrowing, rotavation, and tine cultivation before sowing, while ZT plots employed direct drilling using a ZT multi-crop planter. Residue management followed sustainable protocols: from 2008-2015, 30% residue was retained; from 2015 onward, complete mungbean and sesbania residues were conserved. The quality protein maize hybrid HQPM-1 was sown at 20 kg ha⁻¹, with appropriate spacing during kharif (July) and winter (October-November).

Soil Sampling and Analysis

Soil samples were collected post-harvest (2018-19) from three depths: 0-5 cm, 5-15 cm, and 15-30 cm. Composite samples from each treatment were air-dried, sieved (<2 mm), and analyzed for available nutrients. Available Nitrogen estimated following method of alkaline potassium permanganate method (Subbiah & Asija, 1957) [18], Olsen's method for available phosphorus (P) estimation (Olsen *et*

al., 1954) [13] and similarly neutral normal ammonium acetate extraction (Hanway & Heidel, 1952) [4] for determination of available potassium (K). All data were statistically analyzed using ANOVA appropriate for split-plot design, and treatment means were compared using the least significant difference (LSD) test at P≤0.05.

Results

Available nitrogen

Soil available nitrogen (N) was significantly affected by both tillage methods and cropping systems at 0-5 and 5-15 cm soil depths (Table 1). Conservation-based practices, particularly permanent beds (PB), maintained the highest N availability, followed by zero till flat (ZT-flat), whereas conventional till flat (CT-flat) recorded the lowest values. Relative to CT-flat, PB enhanced available N by 30.3% and 34.2%, while ZT-flat increased it by 19.7% and 26.2% at 0-5 and 5-15 cm depths, respectively. Among cropping systems, the maize-chickpea-sesbania (MCS) sequence showed the greatest improvement in available N, followed by maize-wheat-mungbean (MWMB). Compared with maize-maize-sesbania (MMS), MCS improved available N by 28.0% and 30.8%, whereas MWMB increased it by 23.0% and 24.2% at the respective soil depths.

Available phosphorus

Available phosphorus (P) content varied significantly under different tillage practices and cropping systems (Table 2). Among tillage treatments, permanent beds (PB) recorded the highest available P (34.8 and 28.6 kg ha⁻¹ at 0-5 and 5-15 cm depths, respectively), followed by ZT-flat, while CT-flat recorded the lowest values. Compared with CT-flat, PB increased available P by 20.4% and 17.2%, whereas ZT-flat increased it by 15.2% and 11.1% at 0-5 and 5-15 cm depths, respectively. Among cropping systems, maize-chickpea-sesbania (MCS) recorded the highest available P, which was statistically at par with maize-wheat-mungbean (MWMB). Compared with maize-maize-sesbania (MMS), MCS increased available P by 16.7% and 20.6%, while MWMB improved it by 12.0% and 15.2% at 0-5 and 5-15 cm depths, respectively.

Available potassium

Available potassium (K) content in soil varied significantly due to tillage practices and cropping systems at both 0-5 and 5-15 cm depths (Table 3). Permanent beds (PB) recorded the highest available K, followed by ZT-flat, while CT-flat maintained the lowest values. Compared with CT-flat, PB increased available K by 19.2% and 17.1%, whereas ZT-flat improved it by 12.8% and 14.4% at 0-5 and 5-15 cm depths, respectively. Among cropping systems, maize-chickpea-sesbania (MCS) recorded the maximum available K, followed by maize-wheat-mungbean (MWMB). Relative to maize-maize-sesbania (MMS), MCS enhanced available K by 29.0% and 25.7%, while MWMB increased it by 21.5% and 21.1% at the respective soil depths.

Discussion

Effect of tillage practices on soil nutrient availability

The higher availability of nitrogen (N), phosphorus (P), and potassium (K) under permanent beds (PB) and zero tillage flat (ZT-flat) compared with conventional tillage flat (CT-flat) may be attributed to reduced soil disturbance and continuous residue retention under conservation agriculture

practices. Reduced tillage minimizes oxidation losses of soil organic matter and promotes nutrient accumulation in the surface soil layer. Crop residue retention enhances microbial activity and gradual nutrient mineralization, thereby improving soil fertility and nutrient cycling.

The significantly higher available nitrogen under PB and ZT systems may be due to enhanced soil organic carbon buildup and improved microbial-mediated mineralization processes. Conservation tillage creates favorable soil conditions for microbial biomass and nutrient turnover. Similar findings were reported by Jat *et al.* (2019) [7, 8], who observed significantly greater soil available N under conservation agriculture practices in maize-based systems. Gathala *et al.* (2011) [1] also reported that zero tillage with residue retention improved soil nitrogen dynamics and nutrient-use efficiency in the Indo-Gangetic Plains.

Higher phosphorus availability under PB and ZT treatments could be associated with surface stratification of phosphorus due to minimum soil disturbance and decomposition of retained residues. Organic acids released during residue decomposition reduce phosphorus fixation and improve phosphorus solubility. Comparable results were reported by Singh *et al.* (2022) [16], who found improved available phosphorus under conservation agriculture systems because of enhanced biological activity and residue-mediated nutrient recycling. Similar observations were also documented by Pittelkow *et al.* (2015) [14, 15], who reported improved phosphorus availability and nutrient retention under long-term zero tillage systems.

The greater potassium availability under PB and ZT treatments may be attributed to recycling of potassium from retained crop residues, as potassium is readily released during residue decomposition. Conservation tillage also reduces nutrient losses through runoff and erosion. Verhulst *et al.* (2010) [19] observed that residue retention and reduced tillage significantly increased exchangeable potassium in surface soil layers. Likewise, Jat *et al.* (2018) [5] reported higher available potassium under permanent bed systems due to improved residue recycling and reduced soil degradation.

Effect of diversified cropping systems on soil nutrient availability

Cropping systems involving legumes such as chickpea, mungbean, and sesbania significantly improved soil nutrient availability compared with cereal-dominated systems. The maize-chickpea-sesbania (MCS) and maize-wheat-mungbean (MWMB) systems recorded significantly higher available N, P, and K than maize-mustard-mungbean (MMuMb) and maize-maize-sesbania (MMS) systems. Inclusion of legumes improves soil fertility through biological nitrogen fixation, addition of high-quality biomass, and enhanced nutrient recycling.

Higher available nitrogen in MCS may be attributed to biological nitrogen fixation by chickpea and sesbania, which enriches soil nitrogen pools and improves subsequent nutrient availability. Similar findings were reported by Kumar *et al.* (2018) [10], who observed enhanced soil nitrogen status in legume-based diversified cropping systems under conservation agriculture. Ghosh *et al.* (2012) [2] also reported that incorporation of legumes significantly improved soil nitrogen availability and soil health.

Improved phosphorus availability in legume-inclusive systems may result from greater root exudation of organic acids, which mobilize native soil phosphorus and improve phosphorus uptake efficiency. Enhanced microbial activity

in legume rhizospheres also contributes to phosphorus solubilization. Similar findings were reported by Srinivasarao *et al.* (2014) [17], who observed increased phosphorus availability in diversified cropping systems involving legumes.

The higher potassium content under MCS and MWMB systems could be due to greater biomass production and efficient nutrient recycling through residue decomposition. Legume residues generally decompose faster and release nutrients more efficiently than cereal residues. Similar observations were reported by Lal (2015) [12], who highlighted the beneficial role of diversified conservation agriculture systems in improving soil nutrient dynamics and long-term soil fertility.

Overall, the present study demonstrated that long-term adoption of conservation agriculture practices along with legume-based diversified cropping systems substantially improved soil nutrient availability and contributed to sustainable soil health management in maize-based systems.

Table 1: Impacts of tillage practices and diversified cropping systems on available nitrogen (kg ha^{-1}) in soil at 0-5 cm and 5-15 cm layer

Treatments	0-5 cm	5-15 cm
Tillage		
PB	305 ^a	271 ^a
ZT-flat	280 ^a	255 ^a
CT-flat	234 ^b	202 ^b
LSD (0.05)	38.7	31.1
Cropping system		
MWMB	294 ^a	262 ^a
MCS	306 ^a	276 ^a
MMuMb	253 ^b	221 ^b
MMS	239 ^b	211 ^b
LSD (0.05)	36.1	23.6

Table 2: Impacts of tillage practices and diversified cropping systems on available phosphorus (kg ha^{-1}) in soil at 0-5 cm and 5-15 cm layer

Treatments	0-5 cm	5-15 cm
Tillage		
PB	34.8 ^a	28.6 ^a
ZT-flat	33.3 ^a	27.1 ^a
CT-flat	28.9 ^b	24.4 ^b
LSD (0.05)	3.16	2.58
Cropping system		
MWMB	33.5 ^a	28.0 ^a
MCS	34.9 ^a	29.3 ^a
MMuMb	31.0 ^b	25.2 ^b
MMS	29.9 ^b	24.3 ^b
LSD (0.05)	2.32	1.69

Table 3: Impacts of tillage practices and diversified cropping systems on available potassium (kg ha^{-1}) in soil at 0-5 cm and 5-15 cm layer

Treatments	0-5 cm	5-15 cm
Tillage		
PB	149 ^a	130 ^a
ZT-flat	141 ^a	127 ^a
CT-flat	125 ^b	111 ^b
LSD (0.05)	16.7	14.5
Cropping system		
MWMB	147 ^a	132 ^a
MCS	156 ^a	137 ^a
MMuMb	128 ^b	114 ^b
MMS	121 ^b	109 ^b
LSD (0.05)	10.2	7.98

Conclusions

After ten years of continuous implementation under semi-arid conditions, permanent raised beds (PB) and zero tillage (ZT) systems substantially improved soil nutrient availability compared with conventional tillage (CT). Combined with strategic residue retention and inclusion of leguminous crops, these systems enhanced N, P, and K availability across surface and subsurface layers. Among the tested rotations, maize-wheat-mungbean (MWMb) and maize-chickpea-sesbania (MCS) were most effective in improving soil nutrient availability due to synergistic effects of legumes and diverse residue inputs. This long-term evidence underscores the feasibility of CA-based maize systems as climate-smart solutions that conserve resources, improve nutrient-use efficiency, and ensure the sustainability of intensive cereal systems in the Indian IGP and similar agro-ecologies.

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