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Improving soil health and crop productivity through conservation agriculture and nitrogen management in rice-mustard-maize systems

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ABSTRACT

Context: Conventional crop production practices, including crop establishment using intensive soil tillage, low use of fertilization, low-yielding varieties, and the removal or burning of crop residues, in the Terai region of Nepal have led to low crop yields and nutrient imbalances. Conservation agriculture (CA) offers a potential solution by integrating no-tillage, residue retention, and optimized nitrogen (N) management, yet its impact in this region remains underexplored.
Objectives: This study investigated the effects of CA practices combined with varying N rates on soil physico-chemical properties, nutrient uptake, and crop yields in rice-mustard-maize- systems.
Methodologies: A two-year field experiment (2011–2013) was conducted in farmers' fields in the Western Terai region using a strip-split plot design. Treatments included: (i) two establishment methods (CA: no-till with residue retention vs. conventional tillage (CT): conventional tillage without residue retention, (ii) two crop varieties (improved or hybrid vs. local), and (iii) four N rates (0, 60, 120, and 180 kg ha^{-1} for rice and 0, 30, 60, and 90 kg ha^{-1} for mustard in both years whereas for maize, 0, 60, 120, and 180 kg ha^{-1} in the first year and 0, 80, 160, and 240 kg ha^{-1} in the second year). Soil properties, crop yields, and crop nutrient uptake were assessed.
Results and discussion: CA enhanced soil fertility and structure, with significant increase in soil organic carbon (15.4 %) and total nitrogen (14.6 %) at 0–10 cm depth, reduced bulk density, and improved moisture retention. In CA, Nitrogen uptake increased by 3 % in rice and 11 % in maize, while yield increased by 7 % and 9 %, respectively. Hybrid maize and rice outperformed local varieties, yielding 47 % and 3 % higher, respectively. Mustard performed variably, with 'Bikash' yielding 44 % more than 'Goldie'. System productivity increased by 5 % under CA. Optimal yields were achieved with 180 kg ha^{-1} for rice and maize and 90 kg ha^{-1} for mustard. Increased N application reduced barrenness and sterility percentage across varieties.
Conclusions: CA combined with optimized N management significantly improves soil health, nutrient dynamics, and crop productivity in intensive rice-based systems. Hybrid varieties exhibit higher productivity under CA than open-pollinated or inbred types. Thus, adopting CA with appropriate N management and variety can sustainably intensify cropping systems, bridging yield gaps while preserving soil health. These findings have implications for broader adoption across Nepal's Terai and similar agroecological zones of Indo-Gangetic Plains, addressing food security and environmental challenges.

1. Introduction

In Nepal, rice and maize are the first two staple food crops, while mustard is the main oilseed crop (Dahal et al., 2022; MoALD, 2023; Timsina et al., 2010), grown under 1.44, 0.94, and 0.19 Mha, respectively. The national average yields of rice (3.7 t ha^{-1}), maize (3.1 t ha^{-1}) and mustard (1.1 t ha^{-1}) (MoALD, 2023) are significantly lower than the attainable yields of > 8.0 t ha^{-1} for rice and maize (Devkota et al., 2015,

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2021) and mustard (1.6 t ha^{-1}) (NARC, 2014; Devkota et al., 2018), indicating substantial yield gaps. Current rice production of 5.43 million tons is not sufficient to meet the current national demand of 6.08 million tons, and by 2030, rice production must be increased by 1.87 million tons, which is equivalent to an overall increase of 34 % in the next 6 years (MoALD, 2023; Timsina et al., 2023; Devkota et al., 2022). Likewise, the production of maize and mustard must be increased by 272 % and 46 % respectively to meet the current national demand (CIMMYT, 2022; FAO, 2024; Devkota et al., 2022). Given the limited scope for expanding cultivated areas, these increases must rely on increasing yields. However, achieving these targets will be challenging due to declining water availability, labor shortages, and rising production costs. Therefore, adopting improved agronomic practices and technological innovations is urgently needed to address these constraints and ensure the long-term sustainability of these critically important crops.

The conventional rice establishment practices such as puddling and seedling transplanting, offer certain benefits like reducing percolation loss of water, controlling weeds, facilitating easy seedling establishment, and creating anaerobic conditions that enhance nutrient availability () but adversely affect soil's physical properties by destroying soil aggregates, reducing permeability, and forming hard pans in the plow layer (Chaudhary et al., 2023; Tater and Vashisht, 2024; Timsina and Connor, 2001). It also requires excessive water, reduces trafficability for machinery and field operations, and creates difficulty in regenerating soil structure after the crop harvest (Gathala et al., 2011; Ishfaq et al., 2021, 2020a; Pradhan et al., 2015). These adverse effects would ultimately affect the performance of succeeding non-rice crops (Tripathi et al., 2005; Timsina and Connor, 2001). Further, puddling and transplanting practices could delay rice establishment by up to three weeks and demand a large volume of scarce water and more expensive labor, which ultimately increases production costs and reduces net profits (Ishfaq et al., 2020a). Conventional maize cultivation typically involves broadcasting or planting behind the plough, followed by residue burning, harrowing, leveling, sub-optimal fertilizer application, planting low-yielding varieties, and manual weeding. These practices not only increase the cost of production, weed infestation, and soil erosion but also decline soil fertility and crop yield (Yang et al., 2020). Intensive soil tillage further depletes soil organic matter and reduces nutrient use efficiency (Jakab, 2023). Current conventional methods of cereal-cereal rotation, residue removal or burning, and low and unbalanced fertilization application have led to soil and nutrient loss, soil compaction, lower fertilizer efficiency, and low economic benefits that threaten the productivity, profitability, and sustainability of rainfed cropping systems (Lal, 2016; Tilman et al., 2002).

Conservation agriculture (CA) - no or minimum tillage, full or partial residue retention, and diversified crop rotation - is defined as the resource-conserving crop production system to achieve acceptable profits together with high and sustained production while at the same time conserving natural resources and environment (FAO, 2015; Sarker et al., 2022). No- or minimum soil tillage has several advantages over conventional tillage, including minimum soil disturbance, increased infiltration rate, lower evaporation, improved water availability, reduced erosion, higher soil carbon and nutrient availability, lower energy requirement, reduced production, and equal or higher yields (Sainju et al., 2009; Romero-Perezgrovas et al., 2014; Kassam et al., 2009). These practices reduced production costs and increased net benefits by using less water and lower land management charges compared to TPR (Ishfaq et al., 2020b, 2022). Similarly, crop residue retention can improve soil physical, chemical, and biological properties (Murphy et al., 2016), reduce soil evaporation (Bezborodov et al., 2010), and increase infiltration and soil water-holding capacity (Li et al., 2011). The inclusion of mustard in a cereal-based system like the Rice-Mustard-Maize system is an effective crop rotation strategy that improves soil health, resource efficiency, and economic stability (Shekhawat et al., 2016). Mustard utilizes residual moisture and nitrogen after rice, making it suitable for rainfed areas (Rashmi et al., 2023). Incorporating oilseeds between two cereal crops helps diversify cropping systems, reducing the depletion of soil nutrients that occurs in continuous cereal cultivation (Kirkegaard et al., 2008). Its short growing period allows timely maize planting in spring.

Puddling in transplanted rice cultivation stabilizes nitrogen (N) in the form of NH_4^+ - N, which is less prone to leaching compared to NO_3^- - N, which is predominant under aerobic conditions, such as in CA practices like dry-seeded rice (DSR) (Devkota et al., 2013a). In DSR, nitrate prevalence increases the risk of N losses through leaching and denitrification during frequent aerobic-anaerobic cycles (Al-Kaisi and Licht, 2004; Devkota et al., 2013a). The retention of crop residues under CA, while beneficial for soil health, can also increase microbial activity, leading to further N losses via denitrification (Zhang et al., 2023) or immobilization (Ma et al., 2020), thereby reducing overall crop N availability. These dynamics necessitate tailored N management strategies in CA systems, which differ significantly from conventional systems. Short-term adjustments may involve increasing N application rates by approximately 25 % to offset the immobilization effects in CA (Devkota et al., 2013b). Over the long term, however, enhanced N uptake and efficiency in CA systems can allow for reduced N inputs without compromising yield (Grahmann et al. (2014). These findings emphasize the need for revising N recommendations that align with the unique N dynamics of CA systems.

Varietal choice further influences nutrient dynamics and crop productivity. Inbred or open-pollinated varieties (OPV) exhibit greater genetic diversity, making them resilient to local biotic and abiotic stresses, thus offering a stable yield (Joshi et al., 2023; Salgotra and Chauhan, 2023). However, their lower yield potential may fail to meet the current and future food demands, making hybrid varieties a preferable alternative for maximizing productivity. Hybrids are characterized by high yield potential but require higher N inputs to realize their yield potential (Khan et al., 2015; Devkota et al., 2016). Understanding the differential N uptake between hybrid and inbred/OPV varieties is essential for optimizing N use efficiency, reducing N losses, and maintaining soil health over time. Given these considerations, the present study was designed to evaluate the effects of CA and conventional systems on soil physico-chemical properties, nutrient uptake, and crop productivity in the rice-mustard-maize cropping system of Nepal's Western Terai. Furthermore, it aims to optimize N management strategies tailored for hybrids and OPVs to enhance productivity and sustainability in intensive cropping systems.

2. Materials and methods

2.1. Soil

The experiment was conducted during 2011–2013 in four farmers' fields located in Sunawal village, Nawalparasi district, Western Terai region of Nepal (27°36'N and 83°38'E and 131 m asl). The fields previously used for rice cultivation in summer and wheat in winter were selected to assess the impact of CA and N management strategies. The details of soil properties at 0–10, 10–20, and 20–30 cm depths are presented in Table 1. The experimental fields had loam soil with an almost neutral pH. Soil fertility based on the National Agricultural Research Council (NARC) criteria (Karki et al., 2015), revealed low to medium total N levels, low soil organic carbon (SOC) and potassium (K), and medium phosphorus (P); indicating low to medium soil fertility status (Table 1).

2.2. Climate of the experimental site

The experimental fields lie within a sub-tropical humid climatic zone, characterized by cool and dry winters and hot summers, with three distinct seasons: rainy, cool winter, and hot spring. The monthly rainfall, average maximum and minimum temperatures, and relative humidity data for the experimental sites were collected from the agro-

Table 1
Initial mean soil physico-chemical properties of the experimental fields in Sunawal, Nawalparasi, Nepal.

Soil properties	Soil depth (cm)			Methods and references
	0–10	10–20	20–30	
pH	7.15	7.20	6.90	Potentiometric 1:2 (Jackson, 1967)
Organic C (%)	1.17 ± 0.03	1.14 ± 0.01	1.05 ± 0.02	Walkley and Black (Walkley and Black, 1934)
Total N (%)	0.097 ± 0.003	0.103 ± 0.003	0.093 ± 0.003	Kjeldahl distillation (Bremner and Mulvaney, 1982)
Available P (kg ha^{-1})	31.00 ± 0.58	35.33 ± 3.93	33.33 ± 2.19	Modified Olsen's (Olsen, 1954)
Available K (kg ha^{-1})	97.00 ± 0.58	113.67 ± 7.51	105.67 ± 4.63	Ammonium acetate (Jackson, 1967)
Soil texture	Loam			Hydrometer (Bouyoucos, 1962)
Sand (%)	50.33 ± 6.69			
Silt (%)	29.33 ± 5.33			
Clay (%)	20.33 ± 2.73			

Note: values after ± indicate the standard error of the mean

meteorological station of the National Wheat Research Program (NWRP) in Rupandehi and solar radiation from the NASA-POWER (NASA-POWER, 2015). The weekly total rainfall and average relative humidity increased as the season progressed. Temperatures fluctuated with a peak in the third week of April (33.2 °C), followed by a drop in early May (26.9 °C) and peaking again in early June (33.1 °C). Rainfall was sporadic in April but increased significantly in late May and mid-June, totaling 212.5 mm during the experimental period. Rainfall was concentrated mainly in the monsoon period from June to September, with peaks exceeding 250.0 mm in July and remaining low for the rest of the year. Relative humidity generally increased over the period, starting lower in April and reaching its highest in late May and mid-June. Solar radiation increased from March to May, peaking at 20–25 MJ m^{-2}, then decreased in winter months before rising again as the year progressed Fig. 1.

2.3. Experimental design and treatments

The experiment was conducted in a strip-split plot design comprising three factors, viz., two crop establishment methods, two varieties, and four N rates in 4 replicates (4 farmers' fields). Establishment methods and varieties were evaluated in two strips and N rates in the subplots. The experimental plots measured 22.68 m^2 (4.2 m x 5.4 m).

Rice: Two establishment methods, i.e., (i) dry direct seeded rice (DSR) at 20 cm row spacing under no-till with residue retention (ii) puddle transplanted rice (PTR) without residue retention using 21 days rice seedlings transplanted at 20 cm× 20 cm spacing.

Maize: Two establishment methods, i.e., (i) line sowing at 60 cm row-to-row and 25 cm plant–to-plant spacing under no-till with residue retention (ii) line sowing at 60 cm row-to-row and 25 cm plant-to-plant spacing under conventional tillage without residues.

Mustard: Two establishment methods i.e., (i) line sowing at 20 cm row spacing by push row garden-planter under no-till with residue retention and (ii) broadcasting of mustard under conventional till without residue.

In the CA treatments/plots (no-tillage and residue retention), residues of previous crops were retained, and the amount depended upon the residue produced. At the start of the experiment with maize in March

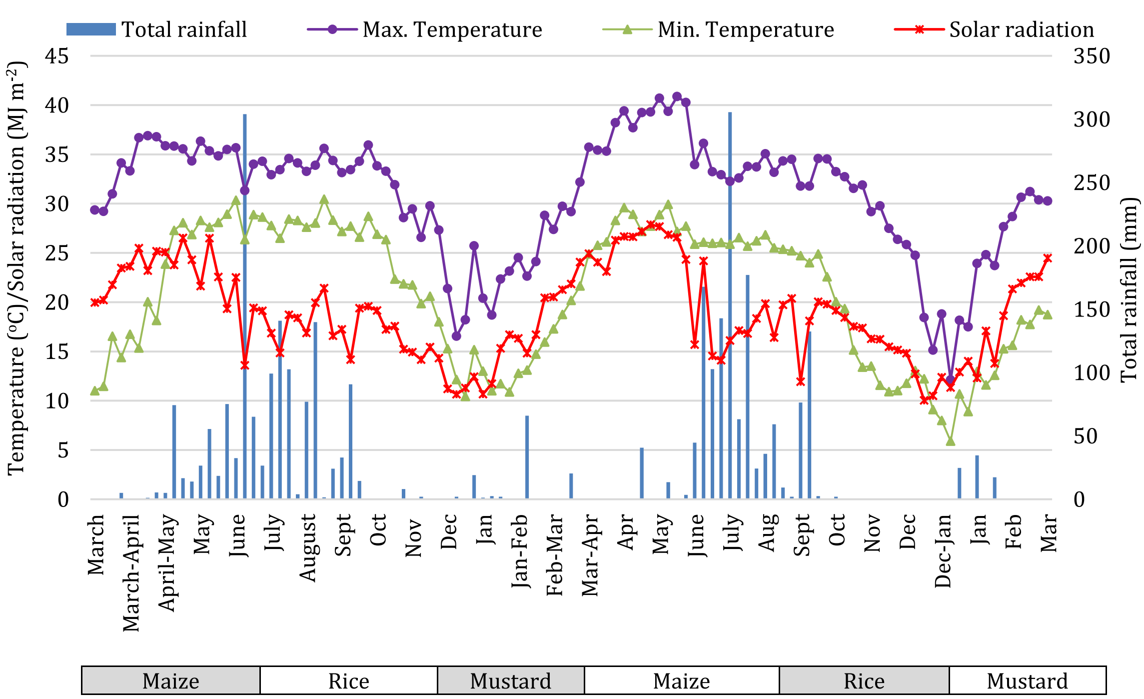

Fig. 1. Average weekly temperatures (minimum and maximum) and solar radiation, and total weekly rainfall during the experimental period in unawal, Nawalparasi, Nepal.

2011, the mustard residue at 1.32 t ha^{-1} was obtained externally and was equally distributed in all CA plots before maize sowing. In rice, 30–35 cm bottom residues of maize were kept stand and the remaining residue was chopped and applied before the land preparation. Similarly, 30–35 cm standing rice residues were kept for mustard in all plots.

The study evaluated two varieties for each crop. They were: improved variety Radha-4 and a hybrid Loknath-509 for rice, OPV Rampur Composite and hybrid Rajkumar for maize, and an improved Nepalese variety Bikash and an improved Indian variety Goldie for mustard. These varieties were selected based on key criteria to ensure they fit the farming system and meet farmer needs. Maturity is crucial, with early or medium-duration varieties preferred to allow three crops per year. Yield potential is also important, with farmers favoring hybrid or improved varieties. Growth habit was another factor, focusing on high tillering, strong plant architecture, and traits like lodging resistance and pest tolerance. These features ensured the varieties could withstand stresses and support productivity, making them suitable for efficient and sustainable farming systems. Similarly, four N rates (0, 60, 120 and 180 kg ha^{-1} for rice and 0, 30, 60 and 90 kg ha^{-1} for mustard in both years; 0, 60, 120 and 180 kg ha^{-1} in 2011 and 0, 80, 160 and 240 kg ha^{-1} in 2012 for maize) were evaluated. These N rates were categorized as N_1, N_2, N_3, and N_4, representing from lowest to highest rates to simplify the presentation of the results.

2.4. Crop management

Before sowing, Glyphosate-47 SL @5 ml per liter was applied in the CA treatment for all crops. This herbicide application aimed to control existing weeds and minimize weed competition during crop establishment.

Rice: For dry DSR, the crop was sown on June 25, 2011 and July 1, 2012, using a seed rate of 45 kg ha^{-1}. For puddle transplanted rice (PTR), the nursery was established on the same day as DSR in both years in a 25 m^2 area for each variety, seeded with 100 g m^{-2} in the nursery to maintain a seed rate of 45 kg ha^{-1} in the main field. The nursery bed was fertilized with 100 kg N, 35 kg P, and 66 kg of K ha^{-1} and frequent irrigation was provided to help the seedlings recover from drought. Nitrogen applied in the nursery bed, intended to support early seedling growth before transplanting, was not counted as part of the N treatment. Twenty-one-day-old seedlings were transplanted on July 17, 2011, and July 23, 2012. In DSR, immediately after rice seeding, Pendimethalin, a pre-emergence herbicide, was applied @ 1 kg a.i. ha^{-1}. In addition, in all treatments, two manual weeding were carried out.

Maize: In CA treatments, seeds were sown directly in the no-till field, while the field was plowed twice and planked to ensure the soil was in good tilth and well-leveled in the conventional system treatment. For both CA and conventional system, maize seeds were sown on March 2, 2011, and February 26, 2012, using a seed-cum-fertilizer drill at a seed rate of 15 kg ha^{-1}, maintaining a spacing of 60 cm× 25 cm. Atrazine, a pre-emergence herbicide, was applied @ 1.5 kg a.i. ha^{-1} followed by hand pulling of weeds at 20 days after sowing (DAS) in CA, while two manual weeding were carried out at 23–25 and 42–45 DAS in the conventional system. Supplementary irrigation was applied when the crop showed the symptoms of temporary wilting.

Mustard: Seeds were sown directly on the no-till field (November 10, 2011, and November 14, 2012) using a garden planter with a row spacing of 20 cm and a seed rate of 8 kg ha^{-1}. In contrast, conventional system plots were prepared with two plowings followed by planking, and seeds were broadcasted in the field at a rate of 8 kg ha^{-1} on the same date as for the no-till case.

The amount of fertilizer application depends upon the treatment combinations. Recommended rates of P (26.2 kg P ha^{-1} for rice and maize and 17.5 kg P ha^{-1} for mustard) and K (33.2 kg K ha^{-1} for rice and maize and 16.6 kg K ha^{-1} for mustard) (MoALD, 2011) were applied in all plots as basal while N rates varied among the treatments. In N-applied treatments, half rate of N was applied as basal, and the remaining N was applied in two equal splits for rice (first split at 35 DAS in CA and 20 days after transplanting (DAT) in conventional practice (BBCH 23) and second split as 55 DAS on CA and 35 DAT on conventional practice (BBCH 37)) and maize (first split at 35 DAS (BBCH 17/32) and second split as 42–45 DAS (BBCH 53)) while as one single split was applied at 25 DAS for mustard (BBCH 33). Rice was harvested at the over-ripe stage (BBCH 92) when the grains were very hard and could not be dented by a thumbnail. Mustard was harvested when 70 % of the fruits were ripe (BBCH 87). Maize was harvested at full ripeness (BBCH 89) when the kernels were hard and shiny.

2.5. Sampling and measurements

2.5.1. Yield and yield components

Rice and mustard were sampled from the net plot area (12.6 m^2; 15 rows). Plants were harvested manually at ground level with sickles in the conventional practice but harvested at a height of 30–35 cm in CA. The total above-ground biomass was sampled from the fifteen central rows of rice and mustard, and four rows of maize from each plot. Harvested plants were left in situ in the field for 3–4 days for sun drying. Samples were threshed by a simple mechanical thresher, cleaned by winnowing, and weighed at their exact moisture. In maize, cobs were harvested manually from the net plot area of 10.08 m^2 (4 rows). Dehusking of cobs was done separately for each plot on the threshing floor. After the shelling of grains, seeds were carefully separated, dried, and weighed and moisture percent recorded. After removing the cobs, the cut stover was sun-dried for a few days and weighed. The stover was subsampled to determine its dry weight. They were dried in an oven at 65°C until a constant weight was achieved. For mustard, plants were uprooted from a net plot area of 12.6 m^2 and were threshed manually after in-situ drying for 3–4 days. Seeds from the respective plots were weighed at their exact moisture content.

Additionally, in rice, the number of effective tillers m^{-2}, number of grains panicle^{-1}, sterility percentage, and thousand-grain weight were collected. The number of panicles bearing tillers was counted from the two quadrants of 1 m^2. Twenty panicles were randomly selected from each plot to count the average number of grains panicle^{-1} and sterility percentage. In maize, plant population at harvest, bareness percentage, number of grains cob^{-1}, sterility percentage, and thousand-grain weight were recorded. To determine the number of grains cob^{-1}, ten cobs were selected randomly, and grains were separated from the cob and then counted. From the same cob, the sterility percentage was recorded. After threshing, the seeds were cleaned and weighed. A sample of 250 grains was weighed from each replication to derive thousand grain weight. Seed moisture content was measured using a Farmcomp Grain Moisture Meter (Wile 55). Total biomass (dry matter basis) and grain yield (adjusted to a moisture content of 12.5 %), recorded on a plot basis, were converted to kg ha^{-1} for statistical analysis.

2.5.2. Soil and plant analysis

The sampled straw and grain were used to determine their nutrient concentrations (N, P, and K). Plant samples were dried at 65 °C for 120 hours, ground to pass through a 0.5 mm sieve, and kept in a brown paper bag for nutrient analysis. Plant samples were analyzed in the Soil Science Division of NARC, Lalitpur. Total plant N concentration was determined using the Kjeldahl digestion method (Nelson and Sommers, 1973). Plant P concentration was determined by a spectrophotometer using Olsen's method after dry ashing followed by its extraction in diluted H_2SO_4 (Estefan et al., 2013). A flame photometer analyzed the K concentration in the same dry ash sample from the plant (Estefan et al., 2013). Soil samples from the depth of 0–10, 10–20, and 20–30 cm were collected after harvesting of rice in the second year. Four samples were taken from each plot and combined into one composite sample per plot. Soil samples were analyzed for chemical properties following the same procedures described above.

2.5.3. Bulk density and infiltration

Bulk density and infiltration were determined only after completing two years of experiments (2011 and 2012) with a rice-mustard-maize rotation. Bulk density was measured at depths of 0–7.5 cm, 7–15 cm, and 15–22.5 cm in each plot using core samplers that were 7.32 cm in height and 6.84 cm in diameter. Moisture content in the soil after crop harvest was determined using the same samples through oven-dry methods and expressed as a percentage. Infiltration measurements were taken from four plots treated with CA and four plots treated with conventional system in each replication. This was done using a double-ring infiltrometer with a 30 cm inner diameter and a 60 cm outer diameter.

2.6. Statistical analysis

The system productivity was calculated by using the market price of the respective crop and varieties and converted to the grain yield of the popular variety Radha 4 at 14 % moisture. All the recorded data were subjected to analysis of variance and Duncan's multiple range test (DMRT) for mean comparisons (Gomez and Gomez, 1984). Treatment differences were considered statistically significant at 0.05 levels of significance. Correlation and regression analysis were run between selected parameters. Dependent variables were subjected to analysis of variance using the GenStat 15 edition and MSTAT for strip-split plot design.

3. Results

3.1. Yield and yield components

Maize: During the first year of the experiment, grain yield and total above-ground biomass of maize were not influenced by the establishment method but were significantly higher in the second year ($p < 0.05$). In the second year, the grain yield was 22.7 % higher in CA (3.79 t ha^{-1}) as compared to conventional practice (3.09 t ha^{-1}) (Table 2). Similarly, grain yield, total above-ground biomass, and harvest index were significantly higher for hybrid Rajkumar compared to OPV Rampur Composite in both years, while grains cob^{-1} and sterility percentage were significant only in 2011 (SI Table 1). The grain yield of the hybrid maize was 41 % higher in 2011 and 55 % higher in 2012 (Table 2). Grain yield, grains cob^{-1} and thousand-grain weight all were significantly ($p < 0.01$) increased by higher N rates in both years while increased N rate also increased barrenness and sterility percentage. Higher grain yield was achieved with 180 kg N ha^{-1} in 2011 and 160 kg N ha^{-1} in 2012 compared to lower N rates. However, in the second year, the yield at 160 kg N ha^{-1} was not statistically different from that at 240 kg N ha^{-1}. The interaction effect of variety and N rate on maize grain yield was observed in 2012 (Fig. 2A). Applying 80 kg N ha^{-1} for hybrid resulted in a significantly higher yield than applying double the rate of N for OPV Rampur Composite. Total above-ground biomass in 2011 and HI in 2012 also responded significantly ($p < 0.01$). Some other parameters had few significant interactions (SI Table 1).

Rice: Rice yields were almost similar in both years (4.48 in 2011 and 4.61 t ha^{-1} in 2012). On average, grain yield with CA was higher (7 %) than conventional, but it was significantly ($P < 0.05$) influenced only in the second year (Table 2). Grains panicle^{-1} and thousand-grain weight differed significantly among the varieties in both years, while yield and effective tillers m^{-2} differed between varieties in 2012 only (SI Table 1). Effective tillers m^{-2} and grains panicle^{-1} were higher for the hybrid Loknath-509, while thousand grain weight was higher for the improved Radha-4. Radha-4 had a higher yield by 12 % than Loknath-509 in the first year while Loknath-509 had a higher yield (18 %) than Radha-4 in the second year (Table 2). Nitrogen rates significantly improved ($p < 0.01$) grain yield, total above-ground biomass, and effective tillers m^{-2}. Few interactions were significant for certain plant parameters (SI Table 1). In both years, applications of 120 and 180 kg N ha^{-1} had statistically similar yields but were significantly higher than the lower N rates (Table 2).

Mustard: Though not significant in both years, a slightly higher seed yield was obtained in the conventional practice compared to CA. The seed yield of improved Bikash was higher than that of improved Goldie, but this difference was significant only in 2012. The highest seed yield was achieved with the application of 60 kg N ha^{-1} in 2011 and 90 kg N ha^{-1} in 2012. The application of N at 30, 60, and 90 kg ha^{-1} did not significantly influence seed yield, but it was significantly higher than when no N was applied (Table 2). In 2012, significant interactions between establishment methods and varieties (Fig. 2B) and between varieties and N were observed (Fig. 2C). Bikash had a higher seed yield under the conventional system than under CA while such differences in yield between the two treatments were not seen for Goldie. The effect of N was not significant for Goldie but Bikash responded up to 30 kg N ha^{-1}.

System yield: Though not significant, a ccomparatively higher

Table 2

Maize, rice, and mustard and system yield (t ha^{-1}) under establishment methods, varieties, and nitrogen rates in the maize-rice-mustard system.

Treatments	Maize		Rice		Mustard		System yield	
	2011	2012	2011	2012	2011	2012	2011	2012
Establishment methods								
CA	4.44	3.79	4.59	4.80	0.37	0.38	11.62	11.58
CT	4.45	3.09	4.36	4.42	0.36	0.50	11.35	10.80
LSD	ns	0.51	ns	0.32	ns	ns	ns	ns
Varieties								
V_1	3.68	2.70	4.73	4.22	0.43	0.59	10.82	10.13
V_2	5.20	4.18	4.23	5.00	0.29	0.28	12.15	12.25
LSD	1.26	0.57	ns	0.37	ns	0.20	ns	1.81
N rates								
N_1	3.13^d	1.54^c	3.18^c	3.52^c	0.30^b	0.30^b	8.30^c	7.05^c
N_2	4.18^c	3.40^b	4.47^b	4.48^b	0.38^a	0.46^a	11.23^b	11.08^b
N_3	4.93^b	4.42^a	5.16^a	5.19^a	0.40^a	0.49^a	12.91^a	13.26^a
N_4	5.55^a	4.40^a	5.10^a	5.25^a	0.37^a	0.50^a	13.49^a	13.36^a
LSD	0.43	0.29	0.45	0.31	0.06	0.08	0.62	0.61
CV, %	12.00	8.10	11.40	10.10	18.90	21.80	6.40	6.50
Grand mean	4.48	4.61	4.45	3.44	0.36	0.44	11.48	11.19

Notes: System productivity was calculated by adding the main crop (Radha-4) equivalent yield of maize, rice, and mustard each year. Treatment means followed by a common letter (s) not significantly different among each other based on DMRT at 0.05 level of significance. Abbreviations used: CA, conservation agriculture; CT, Conventional tillage practices; V_1 (Radha-4 rice, Rampur Composite maize, and Bikash mustard); V_2 (Loknath-509 rice, Rajkumar maize, and Goldie mustard); N_1, N_2, N_3, and N_4 denote lowest to highest N rates (Section 2.2 Experimental design and treatments); LSD, least significant differences; CV, coefficient of variation.

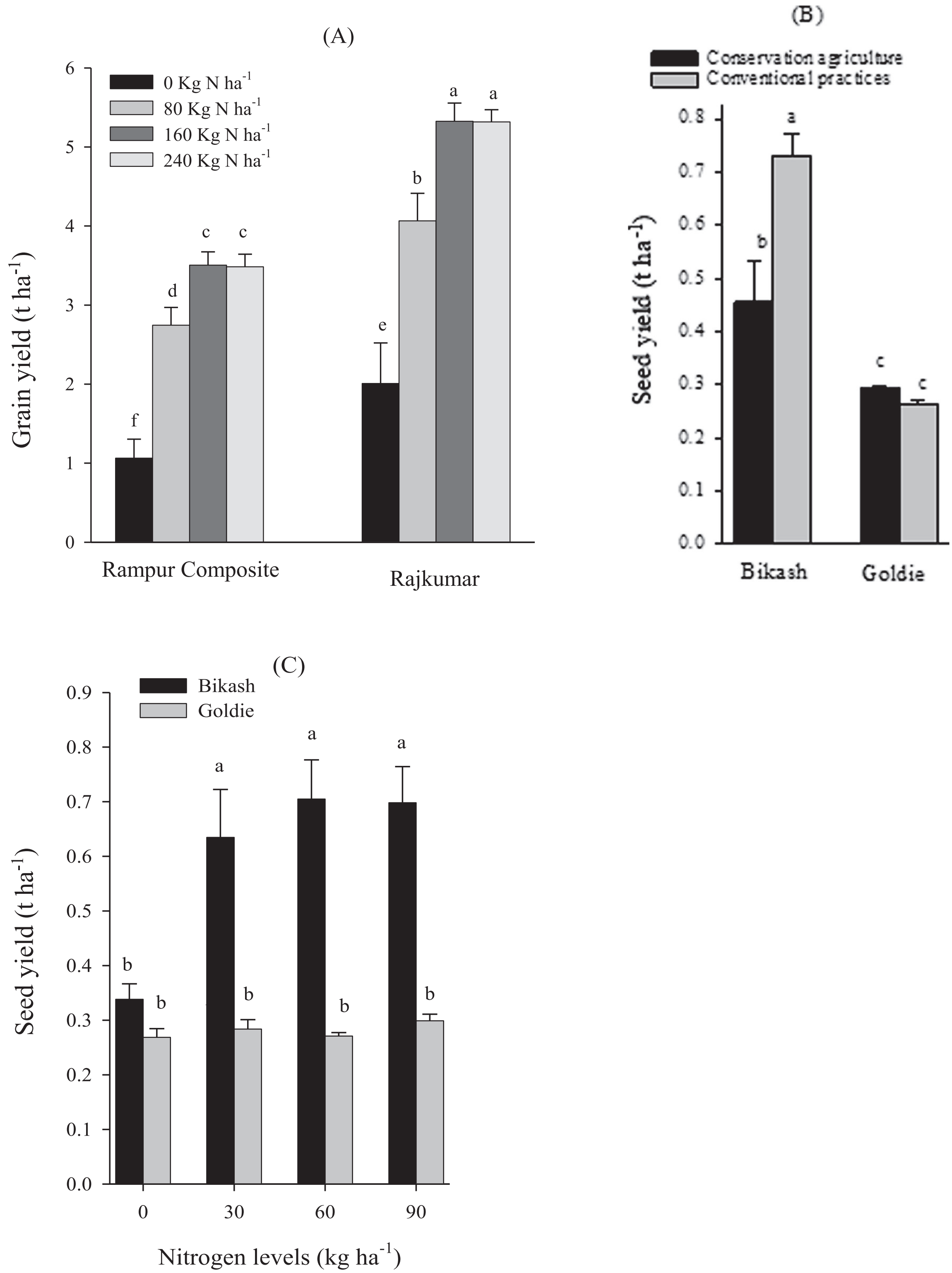

Fig. 2. Grain/seed yield influenced by the interaction of (A) variety and N rate in maize, (B) establishment methods and variety in mustard, and (C) variety and N rate in mustard at Sunawal, Nawalparasi, Nepal. Note: Treatments are followed by a common letter (s) that are not significantly different from each other based on DMRT at 0.05 level of significance.

system yield was obtained under CA (2 % in 2011 and 7 % in 2012) than in conventional practice. Varieties influenced the system yield significantly only in 2012. Rajkumar (maize) – Loknath-509 (rice)– Goldie (mustard) rotation had a higher system yield (12 % in 2011 and 21 % in 2012) than the Rampur Composite (maize) – Radha 4 (rice) – Bikash (mustard) rotation. Nitrogen application also influenced the system yield. Application of 300 and 450 kg N ha^{-1} in 2011 had statistically similar yields but significantly higher than the lower N rates. Similarly, 340 and 510 kg ha^{-1} N applications in 2012 had statistically similar yields but significantly higher than the lower rates (Table 2).

3.2. Nutrient concentration and uptake

Rice: Nitrogen rate significantly ($p < 0.01$) increased N uptake by maize and N, P, and K uptake by rice in both years (SI Table 1). The average straw N concentration of rice was higher in the second year, whereas average P and K concentrations were higher in the first year (SI Table 2). Grain N concentration was higher in the first year, P concentration was higher in the second year, while K concentration was equal in both years (Table 3). Nutrient concentrations were not influenced by the establishment method and variety, except that the grain K concentration was significantly influenced by the establishment method in 2012. Nitrogen rate significantly influenced grain N and straw P concentrations in 2011 and straw N and K concentrations in 2012 (SI Table 2; Table 3), where the higher rate of N resulted in higher contents.

Nitrogen, phosphorus, and potassium uptake were significantly influenced by N levels during both years. Significant differences in varieties were observed in grain K uptake in 2011, where it was significantly higher in the inbred variety Radha 4 (data not sown). In 2012, there was a significant interaction between establishment methods and varieties on available P and K uptake (SI Table 1; SI Fig. 1). The increase in N supply has increased grain, straw, and total uptake of N, P, and K (SI Fig. 2).

Maize: There was a significant difference among establishment methods on N content only in 2012, while varieties did not influence the N concentration (Table 4). Nitrogen levels significantly affected the grain and stover N concentration, and significant interaction effects were almost absent. In 2011, grain N content was highest at 180 kg N ha^{-1} , significantly surpassing N omission but similar to 60 and 120 kg N ha^{-1} applications. In 2012, both stover and grain N concentrations increased significantly with nitrogen application, particularly at 160 and 240 kg N ha^{-1}.

The effect of establishment methods, varieties, and N rates on N uptake in grain and straw and total are presented in SI Tables 1 and 4. Higher stover, grain, and total N uptake was observed under CA than under conventional system, but this difference was only significant in 2012. Rajkumar had more N uptake than the Rampur Composite during both years, however, the effect was mainly non-significant. The highest N uptake was recorded for the highest N levels in both years. In 2011, total N uptake with 180 kg N ha^{-1} application was significantly higher than at lower rates, while in 2012, such significant differences were not observed. Similar trends were observed in grain and stover N uptake.

Table 3
Grain nitrogen, phosphorus, and potassium concentration of rice as influenced by establishment methods, varieties, and nitrogen rates at Sunawal, Nawalparasi, Nepal.

Treatment	2011			2012		
	N (%)	P (%)	K (%)	N (%)	P (%)	K (%)
Establishment methods						
CA	1.13	0.28	0.30	1.07	0.29	0.29^{b}
CT	1.05	0.30	0.30	1.07	0.31	0.31^{a}
LSD	ns	ns	ns	ns	ns	0.01
Varieties						
Radha−4	1.12	0.29	0.32	1.05	0.30	0.30
Loknath−509	1.07	0.29	0.27	1.09	0.30	0.30
LSD	ns	ns	ns	ns	ns	Ns
Nitrogen rates						
0 kg N ha^{-1}	0.94	0.28	0.25	1.01	0.30	0.31
60 kg N ha^{-1}	1.08	0.29	0.30	1.07	0.30	0.31
120 kg N ha^{-1}	1.18	0.29	0.32	1.09	0.29	0.29
180 kg N ha^{-1}	1.17	0.29	0.31	1.12	0.30	0.28
LSD	0.11	ns	ns	ns	ns	Ns
CV, %	12.23	16.43	31.90	12.39	15.67	19.24
Grand mean	1.09	0.29	0.30	1.07	0.30	0.30

Notes: Treatments mean followed by a common letter (s) not significantly different among each other based on DMRT at 0.05 rate of significance. Abbreviation: CA, conservation agriculture; CT, Conventional tillage practices; LSD, least significant differences; CV, coefficient of variation.

3.3. Soil physico-chemical properties

Among the various soil physicochemical properties measured after harvesting of rice after two years of experimentation, only bulk density and organic carbon of topsoil were significantly ($p < 0.05$) influenced by establishment method, while other parameters showed no significant differences (SI Table 6). At 0–7.5 and 7.5–15 cm depths, soil bulk density was significantly lower (by 5.65 and 2.73 %, respectively) under CA compared to conventional practice, while it was similar in the deeper layers (Fig. 3 A). Soil moisture content and soil pH were not significantly different between CA and conventional practice (SI Table 6). In the top soil layer (0–10 cm), soil organic carbon (SOC) was significantly higher under CA than conventional practice, while no significant differences were observed below 10 cm depth. There was a clear stratification of SOC distribution within the soil profile under CA compared to conventional practice (Fig. 3B). The effect of establishment method on total N, available P, and exchangeable K were insignificant (SI Table 6).

The effects of establishment methods on infiltration rate and cumulative infiltration over time are plotted in Fig. 4. The initial infiltration rate was higher under conventional practice, while the base infiltration rate was higher under CA. Similarly, cumulative infiltration during the initial period was slightly higher under conventional system but later higher under CA.

4. Discussion

4.1. Yield and yield components

The adoption of CA practices has shown significant impacts on the yields of major cereals like rice, wheat, and maize in Nepal, where intensive soil tillage without retention of crop residues dominates traditional farming practices (Timsina and Connor, 2001; Timsina et al., 2011). In agreement with past studies (Gathala et al., 2013, 2015, 2016; Saharawat et al., 2010), CA practices in our study have resulted in yield improvements of 7 % for rice and 9 % for maize, though mustard showed a yield reduction of 13 % compared to the conventional system (Table 2). The improved performance of rice and maize under CA can be attributed to several factors. Most importantly, the retention of crop residues and the reduction of tillage led to enhanced soil health. This was evidenced by a decrease in bulk density, an increase in total N, and improved SOC (SI Table 6, Fig. 3). These improvements in soil structure and fertility, coupled with the decomposition of retained residues, made more nutrients available to the crops, thereby contributing to higher yields. Additionally, the retention of residues likely helped in conserving soil moisture, which can alleviate crop water stress in rainfed areas.

In our experiment, the establishment of all crops was good because of sufficient soil moisture content during and after seed sowing. Similarly, there were favorable climatic conditions from crop emergence to maturity. The total rainfall was 1138 mm and 1350 mm in 2011 and 2012, respectively and rainfall during the active vegetative phase was 727 mm and 1060 mm, respectively in the two years. A seed rate of 45 kg ha^{-1} was used for rice, optimized inter-plant competition, resulting in statistically similar yield attributes, such as effective tillers per square meter, number of grains per panicle, and thousand-grain weight, thus resulting in the almost similar or slightly better in terms of yield (SI Table 1). There are contrasting findings in the literature regarding the increase or decrease of rice yield under CA. Pittelkow et al. (2015) and Devkota et al. (2013c) reported lower yields in direct-seeded rice (DSR) under no-till, minimum till, and conventional till systems compared to conventional puddled transplanted rice (PTR). In contrast, Timsina et al. (2010) and Gathala et al. (2013), (2015), (2016) found higher yields. Liu et al. (2015), Bhattacharyya et al. (2006), Ishfaq et al. (2020b), and Devkota et al. (2019) reported statistically similar yields in DSR (no-till, minimum till, and conventional till DSR) compared to PTR.

Table 4
Nitrogen concentration and uptake of maize as influenced by establishment methods, varieties, and N levels at Sunawal, Nawalparasi, Nepal.

Treatments	Grain N concentration (%)		Nutrient uptake (kg ha^{-1})					
			Grain		Stover		Total	
	2011	2012	2011	2012	2011	2012	2011	2012
Establishment methods								
CA	1.24	1.42^{a}	55.64	48.47^{a}	63.19	47.42^{a}	118.83	95.89^{a}
CT	1.27	1.31^{b}	57.62	36.62^{b}	64.80	34.18^{b}	122.42	70.80^{b}
LSD (=0.05)	ns	0.05	ns	6.55	ns	6.32	ns	11.32
Varieties								
Rampur composite	1.26	1.36	47.29	33.36^{b}	58.43	42.56	105.72	75.91
Rajkumar	1.25	1.37	65.97	51.73^{a}	69.56	39.04	135.53	90.77
LSD (=0.05)	ns	ns	ns	6.15	ns	ns	ns	ns
Nitrogen rates								
N_1	1.11^{b}	1.23^{b}	34.62^{c}	17.01^{c}	48.27^{c}	21.28^{b}	82.89^{d}	38.29^{c}
N_2	1.22^{ab}	1.28^{b}	52.01^{b}	38.99^{b}	57.42^{bc}	33.87^{ab}	109.43^{c}	72.86^{b}
N_3	1.34^{a}	1.47^{a}	64.61^{a}	57.32^{a}	67.87^{b}	52.17^{a}	132.49^{b}	109.50^{a}
N_4	1.35^{a}	1.47^{a}	75.27^{a}	56.85^{a}	82.42^{a}	55.88^{a}	157.69^{a}	112.73^{a}
LSD (=0.05)	0.19	0.16	11.38	6.71	12.32	12.68	17.05	18.23
CV, %	18.20	14.20	23.90	18.70	22.80	36.90	16.80	26.00
Grand mean	1.26	1.36	56.63	42.54	64.00	40.80	120.62	83.34

Notes: Treatments mean followed by a common letter (s) within the column are not significantly different among each other based on DMRT at 0.05 level of significance. Abbreviation: CA, conservation agriculture; CT, Conventional tillage practices; N_1, N_2, N_3, and N_4 denote lowest to highest N rates (Section 2.2 Experimental design and treatments); LSD, least significant differences; CV, coefficient of variation.

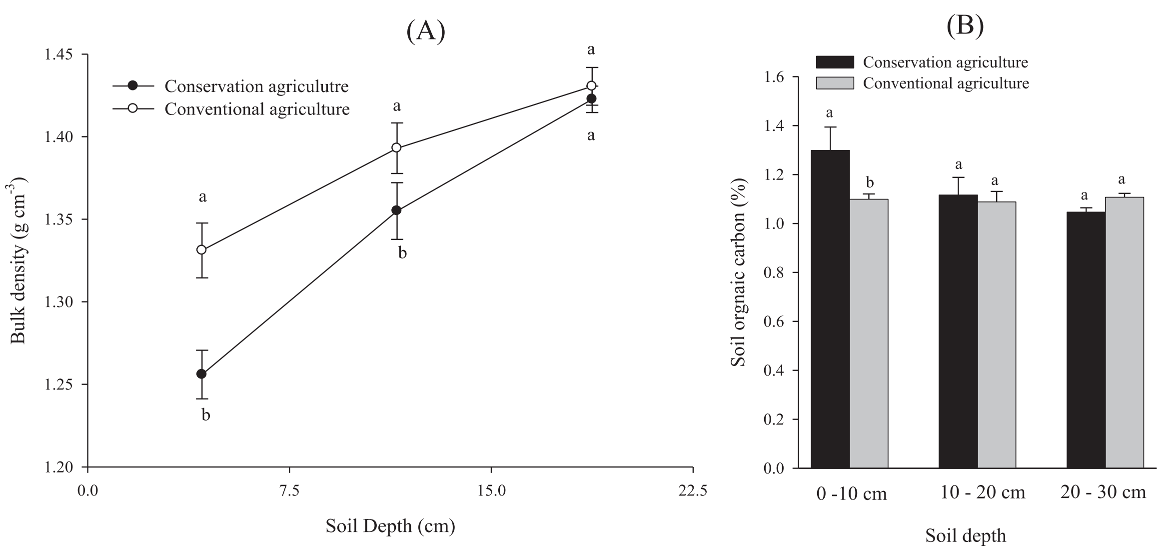

Fig. 3. (A) Bulk density (g cm^{-3}) and (B) soil organic carbon (%) influenced by depth and establishment method after two years of experiments on rice-mustard-maize cropping system at Sunawal, Nawalparasi, Nepal. Note: Treatments mean followed by a common letter (s) within the same depth not significantly different among each other based on DMRT at 0.05 level of significance.

The lower grain yield of DSR under CA was associated with poor crop establishment (Kumar and Ladha, 2011), high weed infestation (Matloob et al., 2014; Kumar and Ladha, 2011), frequent drought stress (Joshi et al., 2013), micronutrient deficiency, nematode infestation (Kumar and Ladha, 2011), and higher sterility percentage (Farooq et al., 2010) due to intra-plant competition. Ishfaq et al. (2020b) also reported a higher number of effective tillers per panicle per square meter in dry DSR.

In the current study, the grain yields of maize under CA and conventional practice were similar in the first year but were higher in the second year. In the CA system, residue retention increased SOC (Fig. 3), conserved soil moisture, and enhanced water infiltration (Fig. 4), enhancing crop growth and improving yield. As in rice, there are contrasting findings in the literature regarding the increase or decrease of maize yield and improved soil physical properties under CA compared to conventional practice. For example, Kiboi et al. (2023), Romero-Perez-grovas et al. (2014), Devkota et al. (2015) reported higher yields under CA compared to conventional tillage. In contrast, Ehsanullah et al. (2015), Pittelkow et al. (2015), Halvorson et al. (2006), Mupangwa et al. (2021), and Guan et al. (2014) observed lower yields in CA while Cambron et al. (2024), Mupangwa et al. (2017), and Gaudin et al. (2015) reported statistically similar yields between CA and conventional tillage. Likewise, Gal et al. (2007), and Tabaglio et al. (2009) also reported higher levels of SOC and Thierfelder and Wall (2009), Abdallah et al. (2021), and Zhang et al. (2007) reported increased infiltration and improved water conservation, which was due to retention of residues in under CA.

In our study, during the initial year, residue retention of two crop cycles did not show any significant effect on maize growth and yield, however, after the residue retention of four crop cycles in the second year, maize growth was better under CA than the conventional system. Maize crop was the first crop in the experiment, sown rice harvested from farmers' fields. Which was sown in February; thus, the applied residues were not decomposed thus the effect of residue application on

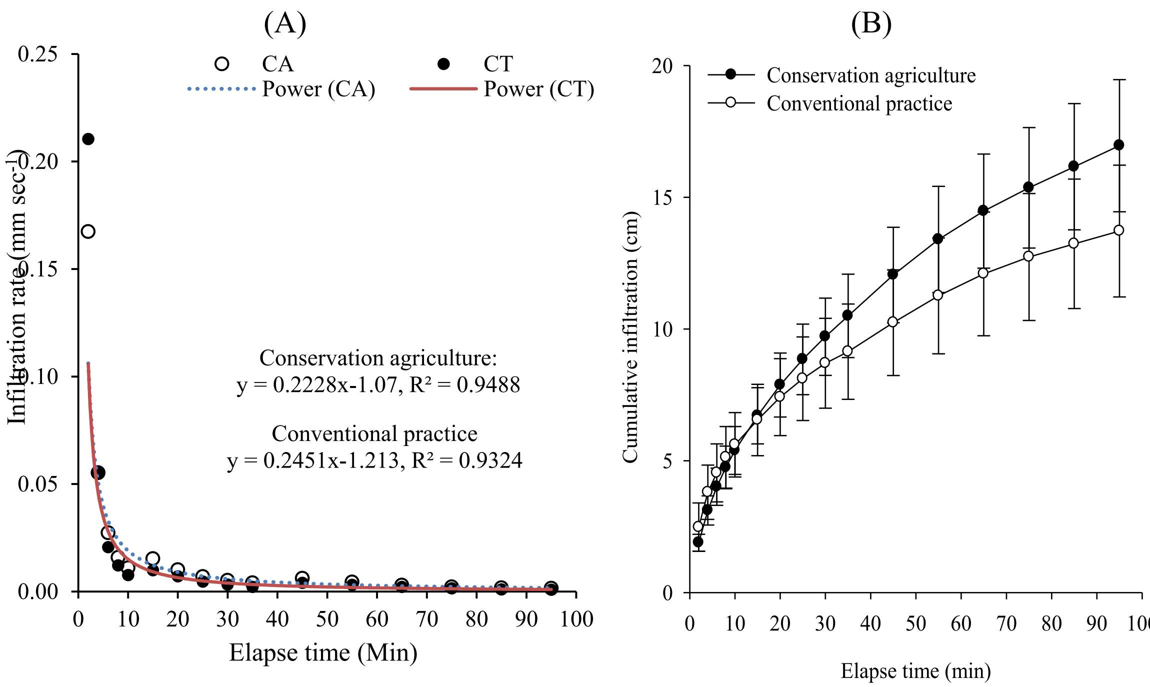

Fig. 4. Effects of establishment methods on (A) infiltration rate (mm sec^{-1}) and (B) cumulative infiltration (cm) over time after rice crop harvest after two years of experiment at Sunawal, Nawalparasi, Nepal.

the CA plots was not effective from the mineralization. But in the second year, the residue applied in the three crops of the first year got mineralized and might supply the nutrients. This is evident from the increased uptake of nutrients in the CA plots. This resulted in a higher number of kernels per cob and thousand kernel weight, along with lower barrenness and sterility (SI Table 1) thus increasing the yield significantly. A significant positive effect of residue retention on rice and maize yields was also observed by Chen et al. (2021), Liu et al. (2005), Huang et al. (2013), and Shafi et al. (2007). Residue retention improved moisture retention probably by reducing evaporation and thus increasing water availability for crop growth and production (Mirzaei et al., 2021). The effect of residues on reducing evaporation and increased water availability was particularly pronounced in the maize crop. Maize grew in the drier spring season, and thus CA had a significant impact on its yield, especially in the second year. Retaining crop residues provides a continuous source of organic matter, serving as a substrate for soil microorganisms. As residues decompose, they stimulate microbial activity, leading to enhanced mineralization and nutrient availability e.g. N and P (SI Fig. 3 A), nutrient uptake, and grain yield. Kirkby et al. (2013) and Cai et al. (2018) also reported residue decomposition might have accelerated mineralization and increased nutrient availability. Govaerts et al. (2007) also observed that the amount of residues applied was correlated with total N and N availability even in no-till soil. Wang (2008) also reported that the total N of the top 30 cm improved by 21.3 % in no-till with straw cover compared to an 11.9 % decrease under conventional tillage compared to the initial value.

The lower yield of mustard in the CA can be attributed to the presence of standing rice residues, which can significantly impact the crop's growth environment during the early stages. These residues create a shading effect, reducing the sunlight that reaches the mustard seedlings. This causes stunted growth and weaker development compared to conventional systems where fields are typically free of such obstructions. Moreover, the standing residues trap moisture, maintaining higher humidity levels, especially during the colder months coinciding with the mustard growing season. The combination of low temperature and high humidity creates an unfavorable microclimate. This damp environment can slow down mustard growth, increase the likelihood of fungal infections, and lead to poor root development. In contrast, in the conventional system, where crop residues are removed, the mustard crop benefits from brighter sunlight and more optimal growing conditions. This results in better photosynthetic efficiency and more vigorous growth, leading to higher yields. Das et al. (2020) also reported that rice residue induced mortality of mustard seedlings at the early seedling stage by causing fungal diseases. In contrast to our findings, Jat et al. (2024) recorded an 11 % higher yield of Indian mustard under CA than the conventional system. To manage residues effectively, planking practices could be used, ensuring proper soil coverage while minimizing interference with the subsequent mustard crop. The rice residue was evenly distributed across the field, preventing it from standing upright and causing shading effects. This approach facilitated residue decomposition while maintaining optimal sunlight exposure for mustard growth. Positioning the residue in this manner, contributed to soil moisture conservation, reduced weed emergence, and enhanced microbial activity without hindering mustard seedling establishment and early growth.

Hybrid rice, hybrid maize, and Nepalese mustard had higher yields than the inbred rice, OPV maize, and Indian mustard (Table 2). Increased grain yields appeared to result from their increased spikelet number and, to some extent, increased grain weight, which enhanced the sink capacity, a finding similar to Philipp et al. (2018). The high harvest index in hybrid maize was due to the large amount of biomass that was accumulated before flowering and translocated to the grains during grain filling. In our experiment, hybrid maize produced a significantly higher yield than the OPV at the same N rate due to superior genetics, improved N use efficiency, and better stress tolerance (Amegbor et al., 2022). Hybrids convert N into biomass more effectively and have stronger root systems for nutrient uptake, leading to higher yields (Timsina et al., 2010). The higher yield of mustard (Bikash variety) compared to the Goldie variety was due to its shorter growth phase, which allowed it to escape exposure to excessively low temperatures in winter. Mustard is particularly sensitive to cold stress, especially during flowering and pod formation. Bikash completed these critical stages before the coldest part of the season, avoiding cold stress and maintaining better growth, which ensured more effective flowering and seed setting and ultimately led to higher yields. In contrast, Goldie's longer growth cycle exposed the crop to prolonged cold, which slowed development. High temperatures in the following spring resulted in smaller seeds and reduced yield.

In our study, increases in yield and yield components of rice and maize were more pronounced when increasing the N rates up to 180 kg ha^{-1}. This suggests that the current recommendation of 130 kg ha^{-1} (MoALD, 2024) might be suboptimal for maximizing crop performance. Subedi et al. (2017) suggested that 125 kg N ha^{-1} is sufficient for improved rice varieties. In contrast, Shah et al. (2023) observed that 180 kg N ha^{-1} is required for hybrid rice, as this dose resulted in significantly higher yield than lower nitrogen levels. Dhital et al. (2022) reported a response to N application rates up to 140 kg ha^{-1} for winter hybrid maize; Gautam et al. (2022) reported N rates response as high as 180 kg ha^{-1} for spring maize, and Adhikari et al. (2021) reported a significant increase with N rates up to 225 kg ha^{-1} in the Terai region of Nepal. The increases in yields with increased N applications were attributed to enhanced crop growth, higher LAI, and increased dry matter accumulation. This, in turn, led to a higher number of grains per panicle or cob, increased thousand-grain weight, and reduced barrenness and sterility, particularly compared to lower N rates or no N application. Adequate N application is necessary for the growth of developing panicle, floret, and 1000-grain weight (Ishfaq et al., 2020b). However, smaller changes or decline in grain yield and its components at higher N rates may be due to the increase in one nutrient, while the availability of other nutrients was affected, making the genetic potential of the crop more important for determining yield (Tilman et al., 2002). Stagnation in grain yield and other yield attributes at high N rates could be due to low sink strength to translocate extra assimilates from the source and increased vegetative growth competing for assimilates available for grain formation and grain filling (Sadras and Richards, 2014). Increased rice yield with increasing N rates in our study was consistent with other studies (Halvorson et al., 2006; Gagnon and Ziadi, 2010).

Our study also showed that higher rice yields under CA and high N levels are influenced by several key factors, including straw dry weight, above-ground biomass, effective tillers per square meter, grains per panicle, and thousand-grain weight, as these factors demonstrate strong positive correlations with yield (SI Table 4). This indicates that CA and higher N levels promote good vegetative growth, efficient partitioning of biomass to grains, and favorable reproductive traits. In contrast, high tiller mortality and sterility percentages in the conventional system and low N levels can negatively impact yield by reducing the number of productive tillers and filled grains, respectively. Likewise, the study showed that maize yield can be significantly influenced by several key traits (SI Table 5). Barrenness percentage showed a strong negative correlation with yield and harvest index, indicating that an increase in non-productive plants reduces yield. Yield is positively correlated with several yield attributes, including the number of cobs per plant, kernel rows per cob, kernels per row, and thousand kernel weight. However, a higher sterility percentage can decrease the number of kernels per cob, ultimately negatively impacting yield.

4.2. Nutrient concentrations and uptake

The effects of establishment methods, varieties, and N levels on nitrogen uptake in grain and straw, and as a total are presented in Table 4. High N uptake in stover, grain, and total biomass under CA compared to the conventional system was significant only in 2012, as the residues decomposition from the three crops in the first year enhanced N availability, making their contribution to N uptake more obvious. Nitrogen uptake varied between CA and the conventional system, showing a slightly lower uptake in 2011 but a higher uptake under CA in 2012. During the first year, N immobilization under CA may have reduced the N uptake, while in the second year, mineralized residues had a pronounced effect on N availability and uptake. Govaerts et al. (2007) observed higher N uptake on residue-applied treatments. Under CA, a slower rate of decomposition may allow for a longer period of N release, thereby supplying N over a longer period during the growing season and minimizing the nitrogen loss (Lupwayi et al., 2004). That resulted in higher N content in plant tissues and N uptake under CA. Under CA, N availability can be influenced by the rate of residue decomposition and soil organic matter dynamics. Studies by Mondal and Chakraborty (2021); Blanco-Canqui and Ruis (2018); Wang et al. (2008), and Jayaraman et al. (2021) indicated that CA can improve N use efficiency due to better soil structure and moisture retention, which enhance microbial activity and N mineralization. In contrast, conventional practices often result in rapid N mineralization but can lead to higher losses through leaching and volatilization (Jakab, 2023; Lal, 2016; Tilman et al., 2002).

In the current study, the application of N fertilizers at different rates significantly impacted nutrient concentrations and uptake in rice and maize. The highest N uptake was recorded with the highest N levels in both years (SI Fig. 2 and Table 4). Optimal N levels vary depending on the crop, variety, and environmental conditions. A study by Song et al. (2024) emphasizes the importance of applying N at levels that match crop demand to maximize N use efficiency and minimize losses. Split applications of fertilizers can further enhance N use efficiency by synchronizing N release with crop uptake patterns. Excessive N application can lead to nutrient imbalances, reduced N use efficiency, and environmental pollution. Research by Shah et al. (2019) shows that over-fertilization with N can cause lodging, increased disease susceptibility, and nitrogen leaching, negatively impacting both crop yield and the environment.

Finally, our study also demonstrated the superiority of hybrids and improved varieties over local varieties on yield uptake. Hybrid and improved varieties have been developed to enhance nutrient uptake efficiency, yield, and resilience to abiotic stresses. Rice and maize hybrids often exhibit higher N uptake efficiency due to their vigorous root systems and enhanced metabolic activities. Studies by Sun et al. (2023) and Ciampitti and Vyn (2012) suggest that hybrid rice and maize varieties can achieve higher yields with lower N inputs compared to traditional varieties, thus improving N use efficiency and reducing environmental impacts.

4.3. Soil physicochemical properties

In the current study, CA significantly reduced the bulk density in the 0–7.5 and 7–15 cm soil layers, with no detectable differences observed below 15 cm (SI Table 6). The decrease in bulk density under CA was likely a result of crop residues being retained, which helped reduce compaction. A significant positive correlation (r = 0.46 *) was observed between SOC of 0–10 cm soil depth and total residue incorporated during two years, which resulted in higher SOC under CA. In the CA treatments, 24.83 t ha^{-1} of residues (dry basis) remained on the surface, while only 0.63 t ha^{-1} was retained in conventional agriculture plots, where it was incorporated into approximately 20 cm of soil. As a result, SOC in the top layer increased. The retention of residues also improved SOC levels (SI Fig. 3 A), which in turn contributed to the reduction in bulk density (SI Fig. 3 C). A significant negative relationship (r = -0.56 **) was also observed between SOC and soil bulk density. No-tillage practices can promote a more stable and porous soil structure, enhancing biotic activity and reducing compaction (Mondal and Chakraborty, 2021; Blanco-Canqui and Ruis, 2018). Lighter residues and SOC promote aggregation, leading to increased root activity on the soil surface and better soil moisture conservation (Husain and Dijkstra, 2023). In addition, the reduced oxidation of soil organic matter under minimal tillage contributes to a slower release of carbon and, consequently, to long-term carbon sequestration (Topa et al., 2021). This ultimately results in lower bulk density, particularly near the soil surface in no-till systems. The impact of tillage on soil bulk density across soil layers under CA observed in the current study has also been observed by Gal et al. (2007). Improvement in bulk density was also due to better soil aggregation because of microbial exudates and fungal hyphae that bind the soil particles together into stable aggregates (Rillig et al., 2015). Such aggregates increase porosity and water infiltration, reduce compaction. The improvement in soil structure thus further facilitates root growth and nutrient uptake, leading to improved crop productivity. Further, moisture content was slightly higher under CA due to crop residues on the soil surface, which helped reduce evaporation rates. This finding aligns with the results of Abdallah et al. (2021).

In our study, comparatively higher soil pH was observed under CA than in conventional system, probably due to the decarboxylation of organic anions formed by the decomposition of residues. Husain and Dijkstra (2023) also observed a significant increase in soil pH from residue application. In the top soil layer (0–10 cm) SOC was significantly higher under CA than conventional system, while no significant differences were observed below 10 cm depth. The increase in SOC in top soil was restricted to the surface due to a lack of tillage and retention of residues on the surface and perhaps due to the lower oxidation of SOC, as also reported by Mondal et al. (2023). Similar to SOC, clear stratification of soil total N was observed under CA as compared to the conventional practice. More N was recorded at 0–10 cm depth under CA, while under conventional system, there was similar total N content in the 0–30 cm depth. In addition, a significant linear relationship was observed between total N and SOC (SI Fig. 3B). Wang et al. (2008) also reported soil total N in the 0–5 cm layer under no-till when straw cover was increased by 81.3 % compared to conventional tillage with straw removal. Likewise, the available P on the surface 0–10 cm was significantly higher (5.82 %) under CA, however in the deeper depths, there were no significant differences (SI Table 6). Available K in 0–10 cm soil depth was slightly higher under CA, while in 10–30 cm depth it was lower than under conventional practice. The topsoil accumulation of P under CA was probably attributed to the limited downward movement of particle-bound P, low mixing of applied P fertilizers, and the upward movement of P from deeper layers through P uptake by roots under no-till, as also reported by Urioste et al. (2006) and Wang et al. (2008). Jayaraman et al. (2021) reported higher K under CA as compared to residue removal under conventional system.

The initial and cumulative infiltration rates were higher under conventional system, while the base infiltration rates were higher for CA (Fig. 4). The lower infiltration in conventional tillage as compared to no-tillage is due to the breakdown of aggregates, increased compaction, and reduction in pore proportion of surface soil. In comparison to conventional tillage, pores in no-tillage are well connected and protected by the residue cover against raindrop impact and other physical intercultural operations (Blanco-Canqui and Lal, 2007). Moreover, aggregates are more stable under no-tillage with residue retention compared to conventional tillage and no-tillage without residue (Li et al., 2007). Abid and Lal (2009) observed significantly higher infiltration in no-tillage than conventional tillage in silt loam. Sharratt et al. (2006) observed cumulative infiltration over one hour was 77 mm for intensive tillage and 91 mm for no-tillage. After 24 years of experiment, residue retention in no-tillage had 3.7 times higher infiltration than in conventional tillage with residue burn (Zhang et al., 2007). Contrastingly, Lipiec et al. (2006) reported conventional till plots had higher infiltration rates throughout the time of water application.

5. Conclusions

The results of this study emphasize the advantages of CA in enhancing soil quality, increasing yields, and improving nutrient uptake in an intensive rainfed rice-based system. High yields were achieved by implementing CA practices like no-tillage and residue retention, which required higher N application rates for high-yielding hybrids, while lower rates were sufficient for medium-yielding varieties. A significant finding of this study was the noticeable enhancement in soil quality characteristics, particularly SOC, in CA, leading to increased yields. Nitrogen rates of up to 120 kg ha^{-1} for rice and 160 kg ha^{-1} for maize significantly improved nutrient uptake and resulted in higher yields, highlighting the importance of N application for optimal crop production. In general, CA in an intensive rice-based farming system can enhance soil physical and chemical properties, maintain satisfactory crop yields, reduce production costs, and promote long-term system sustainability. The research carried out from 2011 to 2013 in this study is expected to contribute knowledge on sustainable agriculture through sustainable intensification with improved soil health, especially from the perspectives of efficient resource use, increasing crop yield, and improvement in soil health. The farming practices adopted during the study period are being promoted by local extension workers and being widely practiced in the region. Efficient extension strategies are being developed for effective transfer of the results from this study. Hence, the findings of this study are largely relevant and expected to contribute significantly to agricultural research by addressing challenges related to crop establishment methods, precision nutrient management, and varietal selection not only in Nepal Terai but largely in the Indo-Gangetic Plain of South Asia with similar climate and cropping systems.

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CRediT authorship contribution statement

Marahatta Santosh: Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Sah Shrawan Kumar:** Validation, Supervision, Methodology, Funding acquisition, Conceptualization. **McDonald Andrew:** Validation, Supervision, Methodology, Funding acquisition, Conceptualization. **Timsina Jagadish:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Devkota Krishna Prasad:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of Competing Interest

We (Santosh Marahatta, Shrawan Kumar Sah, Andrew McDonald, Jagadish Timsina, and Krishna Prasad Devkota) declare no conflicts of interest reported in this paper.

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Abbreviations

Not applicable.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fcr.2025.109825.

Data availability

Data will be made available on request.

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