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Influence of Sub-surface Drip Irrigation on Nitrogen Dynamics and Partitioning in Different Plant Parts under Conservation Agriculture-based Cereal Systems

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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

Intensive cereal-based cropping systems (rice-maize-wheat-mungbean) in North-West India face challenges from inefficient flood irrigation, leading to nitrogen (N) losses via leaching, volatilization and denitrification, which reduce nitrogen use efficiency (NUE). Conservation agriculture (CA) practices like zero tillage and residue retention, combined with sub-surface drip irrigation (SSDI), offer potential to optimize N dynamics by targeting delivery to the root zone. For this study ongoing experiment of CIMMYT (International Maize and Wheat Improvement Centre) – ICAR-CSSRI (Indian Council of Agricultural Research-Central Soil Salinity Research Institute) strategic research platform, located at ICAR-CSSRI, Karnal with geographic coordinates of 29◦42″ 20.7′ N toward latitude, 76◦57″19.79′ E toward longitude and at an elevation of 243 m above mean sea level, Haryana, India was investigated. The objective of this study was evaluate impact of sub-surface drip irrigation (SSDI) versus flood irrigation on soil Nitrogen (NH_4^+-N and NO_3^--N) distribution under six cropping scenarios (Sc): Sc1—conventional puddled transplanted rice (TPR) followed by conventional tilled (CT) wheat with residue removal; Sc2—TPR followed by zero-till (ZT) wheat and ZT-mungbean with partial residue retention; Sc3—direct-seeded rice (DSR) followed by ZT-wheat and ZT-mungbean with full residue retention; Sc4—ZT-maize replacing DSR, followed by ZT-wheat and ZT-mungbean; Sc5— direct-seeded rice (DSR) followed by ZT-wheat and ZT-mungbean with full residue retention integrated with sub-surface drip irrigation (SSDI) and Sc6— ZT-maize replacing DSR, followed by ZT-wheat and ZT-mungbean , respectively and across depths (0-5, 5-15, 15-30, 30-50, 50-75, 75-100 cm). SSDI maintained higher soil moisture (25-35%) and ammonical and nitrate nitrogen (NH_4^+/NO_3^--N) concentrations The CA practices increased ammonium (NH_4^+-N) and nitrate (NO_3^--N) concentrations at surface soil depths. In CA-based rice and maize systems, SSDI showed higher NH_4^+/NO_3^--N at 15-30 cm during the first observation compared to flood irrigation minimizing deep leaching. However, under wheat, surface soils exhibited elevated NH_4^+/ NO_3^--N under both irrigation systems. Wheat leaves showed higher nitrogen concentration under SSDI compared to flood irrigation, while stems exhibited greater N under flood systems. Roots displayed significantly higher N concentration in the rice-wheat-mungbean + SSDI than in the maize-wheat-mungbean + SSDI system. Overall, maize-wheat-mungbean system under SSDI performed better in terms of NUE and system productivity.

Keywords: Conservation agriculture; nitrogen dynamics; sub-surface drip irrigation; Cereal systems; nitrogen partitioning.

1. Introduction

The crisis of quality water for irrigation is widely recognized as one of the foremost environmental threats, severely impacting both agricultural sustainability and food security (Zhang *et al*., 2024). Cereal-based cropping systems, which dominate many regions in Asia, are particularly vulnerable to water scarcity and low NUE due to persistent intensive farming practices (Jat *et al*., 2025 Chivenge et al., 2021). Furthermore, climate change has compounded these pressures, increasing the frequency of droughts, extreme rainfall and placing additional stress on water and nutrient management strategies (Ni *et al*., 2023; Zhang *et al*., 2024). Nitrogen is a critical macronutrient for plant growth and a major determinant of agricultural productivity. However, the reliance on synthetic N fertilizers has been accompanied by substantial economic costs and environmental hazards, including nitrate leaching, groundwater contamination and nitrous oxide emissions (Mirzaee & Nafchi, 2025). Balancing optimum crop yields with reductions in N-induced environmental damage remains a major research priority (Liu *et al*., 2010). Sustainable nutrient management approaches, such as the return of crop residues, have demonstrated improvements in soil organic matter and N cycling, with consequent benefits for soil health and productivity (Jat *et al*., 2020; Parihar *et al*., 2018). Recent technological advancements, particularly sub-surface drip irrigation (SSDI) with fertigation, have greatly enhanced the efficiency of both water and N applied to crops (Sidhu *et al*., 2019). By applying water and nutrients directly to the root zone at controlled intervals, SSDI systems reduce evaporative and percolation losses, improve soil moisture retention and offer a more synchronized supply of N to meet crop demand (Dinnes *et al*., 2002). These strategies have been shown to reduce evapotranspiration and nitrate leaching in maize-wheat systems under conservation agriculture while supporting higher yield and resource use efficiency (Gupta *et al*., 2023; Sidhu *et al*., 2019; Kakraliya et al., 2024).

Adoption of conservation agriculture (CA) defined by reduced tillage, retention of crop residues and diversified cropping has emerged as a leading paradigm for improving long-term soil moisture conservation, nutrient cycling and system resilience (Jat *et al*., 2020; Jat *et al*., 2025). Studies demonstrate that CA promotes soil organic carbon sequestration, enhances aggregation and improves infiltration capacity, thereby raising both water and N use efficiencies over conventional systems (Veeranna *et al*., 2001; Sidhu *et al*., 2019; Parihar *et al*., 2018). Long-term CA has also been shown to stabilize yields and buffer cereal production against climatic variability by moderating soil temperature and moisture extremes (Ni *et al*., 2023; Shivashankar *et al*.,1998).

Despite these advantages, the field-level understanding of the interactions between soil hydrology, mineral N dynamics and crop performance under combined CA and advanced irrigation practices remains incomplete (Parihar *et al*., 2018; Sidhu *et al*., 2019). Quantitative evaluations of these processes are vital for developing adaptive management strategies that reduce agriculture's environmental footprint while supporting productivity under both current and future climate conditions (Mirzaee & Nafchi, 2025; Ni *et al*., 2023). Improving N use efficiency in particular is seen as central to reducing greenhouse gas emissions and enhancing the sustainability of cereal-dominated landscapes (Umair *et al*., 2019; Parihar et al., 2018; Patra et al., 2026).

Insufficient investigations persist regarding the mechanistic responses of soil properties, organic carbon fractions, water movement and N partitioning among crop components under different management scenarios, especially in relation to split N applications through SSDI versus conventional irrigation (Gupta *et al*., 2023; Sidhu *et al*., 2019). Addressing these uncertainties is essential for generating site-specific recommendations and for guiding regional policy towards climate-smart, resource-efficient agriculture (Jat *et al*., 2025; Jat *et al*., 2020). Therefore, the present study was undertaken to assess the effects of long-term CA practices on soil moisture and N dynamics under split N fertigation by SSDI compared to conventional flood irrigation.

2. Materials and Methods

A long-term field experiment was established in the *Kharif* season of 2009 at the CIMMYT (International Maize and Wheat Improvement Centre) – ICAR-CSSRI (Indian Council of Agricultural Research-Central Soil Salinity Research Institute) strategic research platform, located at ICAR-CSSRI, Karnal with geographic coordinates of 29°42″ 20.7′ N toward latitude, 76°57″19.79′ E toward longitude and at an elevation of 243 m above mean sea level, Haryana, India. The region has a semi-arid climate, with hot and dry spell in April to June to wet summer spell in July to September and a cool and dry winter spell in October to march. The area receives average rainfall of 670 mm, 75-80% of which occurred during monsoon season. The mean maximum temperature was 31.68 °C in the month of June, whereas minimum temperature was 11.62 °C in coldest month of January. The soil was classified as Typic Natrustalf as per the USDA soil taxonomy. Initially (2009), the soil of the experimental field was loam in texture (Clay-19.89%; Silt-46.07 %; Sand-34.03%), low in total carbon (0.56 %) with slightly alkaline pH (8).

In this experiment treatments are refered as Scenarios which were designed to address various drivers of current as well as future agricultural production system in this region (Table 1). Initially the experiment was started with four scenarios (Sc) during 2009–10 under CSISA (Cereal Systems Initiative for South Asia) project, viz. (Sc1)- Transplanted puddled rice + conventional tilled wheat (TPR-RW), farmer's practice, (Sc2)-Transplanted puddled rice – Zero tilled wheat- Zero till mungbean (TPR-ZTDSR), (Sc3)-Zero tilled direct seeded rice–Zero tilled wheat-mung bean (ZTWMb) and (Sc4)-Zero tilled maize – Zero tilled wheat-mung bean (ZTM-ZTWMb). Later in 2016, more treatments were included in which sub-surface drip irrigation (SSDI) was imposed over Sc3 and Sc4 in half of the plot (1000 m^2) and named as (Sc5)- ZTDSR-ZTWMb + SSDI and (Sc6) ZTM-ZTWMb + SSDI, respectively. In Sc1 and Sc2, transplanted puddled rice was grown. In Sc1, wheat was sown by conventional broadcasting method after preparing the field by passing two harrowing and two cultivator operations. In Sc1, no residues of rice and wheat crop are retained. In CA based scenarios (Sc3, Sc4, Sc5 and Sc6), zero tillage (ZT) rice (direct seeded rice; DSR), wheat, mungbean and maize were planted by '*Happy seeder*' machine. Full residues of rice and mungbean (100%) and 30% of wheat residues (anchored wheat stubbles of 20–25 cm height) were kept in Sc2, Sc3 and Sc5 after crop harvest. In both Sc4 and Sc6, partial (65%) residues of maize, 30% residues of wheat and 100% residues of mungbean were retained in field. The row-to-row distance was maintained at 22.5 cm for ZT-rice & wheat and mung bean and 67.5 cm for ZT-maize. Both rice and maize were sown during June before onset of monsoon season, wheat was sown in between last week of October to first week of November and mungbean was cultivated in between April to mid-June of every year. Recommended doses of fertilizers (150–60-60 kg ha^{-1} of N-P_2O_5-K_2O for both rice and wheat and 175:60:60 kg ha^{-1} of N-P_2O_5-K_2O for maize) were applied in all the CA based scenarios (Sc2–Sc4) except Sc1. In Sc5 and Sc6, 25% less nitrogenous fertilizers were applied for rice, wheat and maize crops, respectively.

Table 1. Treatment details of conservation agriculture management scenarios under cereal based cropping systems

Scenarios	Crop Rotations	Tillage	Crop Establishment Method	Residue Management	Nutrient Management (NPK, kg/ ha)	Water management
Sc1	Rice-Wheat-Fallow	CT-CT	Rice: Transplanting Wheat: Broadcasting	All residue removed	Rice: 175+58+0 Wheat: 150+58+0	Flood irrigation
Sc2	Rice-Wheat-Mungbean	CT-ZT-ZT	Rice: Transplanting Wheat: Drill seeding Mungbean:Drill/relay	Full (100%) rice and Mungbean; anchored wheat residue retained on soil surface	Rice:151+58+60 Wheat:151+64+32 Mungbean: 0+0+0	Flood irrigation based on soil matric potential
Sc3	Rice-Wheat-Mungbean	ZT-ZT-ZT	Rice: Drill seeding Wheat: Drill seeding Mungbean:Drill/relay	Full (100%) rice and Mungbean; anchored wheat residue retained on soil surface	Rice: 162+64+62 Wheat: 151+64+32 Mungbean: 0+0+0	Flood Irrigation based on soil matric potential
Sc4	Maize-Wheat-mungbean	ZT-ZT-ZT	Maize: Drill seeding Wheat: Drill seeding Mungbean:Drill/relay	Maize 65% and full mungbean:anchored wheat residue retained on soil surface	Maize: 174+64+62 Wheat: 151+64+32 Mungbean: 0+0+0	Flood irrigation based on soil matric potential
Sc5	Rice-Wheat-Mungbean	ZT-ZT-ZT	Rice: Drill seeding Wheat: Drill seeding Mungbean:Drill/relay	Full (100%) rice and Mungbean; anchored wheat residue retained on soil surface	Rice: 162+64+62 Wheat: 151+64+32 Mungbean: 0+0+0	Sub surface drip irrigation based on soil matric potential
Sc6	Maize-Wheat-Mungbean	ZT-ZT-ZT	Maize: Drill seeding Wheat: Drill seeding Mungbean:Drill/relay	Maize 65% and full mungbean:anchored wheat residue retained on soil surface	Maize:139+64+62 Wheat: 21+64+32 Mungbean: 0+0+0	Sub Surface Drip Irrigation based on Soil matric potential

The soil samples were collected 1st, 3rd and 5th day after fertigation (DAF) and soil samples were collected after each fertigation from 0-5, 5-15, 15-30, 30-50, 50-75, 75-100 cm depth by digging a profile with spade. Gravimetric water content measured by taking on site fresh weight of soil sample and later on oven dry (105°C) weight was taken for the determination of moisture content. Then the samples were analyzed for ammoniacal and nitrate nitrogen content using kjeldahl distillation method (Jackson, 1973) and nitrogen partitioning in different plant parts during critical crop growth stages was determined using CHNS analyzer (EuroEA Elemental Analyser).

The data were analysed using randomized block design (RBD). Statistical analysis was performed by DOS-based SPSS version 17.0. The SPSS procedure was used for analysis of variance (ANOVA) to determine the statistical significance of treatments as well as of cropping systems. Two factor factorial ANOVA was used to determine the existence of interaction effect between treatments and cropping systems.

3. Results

3.1 Soil moisture Content, Ammonium (NH_4^+) and Nitrate (NO_3^-) Concentrations as Influenced by DSR under Rice-wheat-mungbean System (Sc5)

Soil moisture content after each fertigation at 1st, 3rd and 5th day after fertigation (DAF) is showed in Table 2. After each fertigation highest moisture was recorded at 0-5 cm soil depth at 1st DAF whereas it decreases with depth toward 3rd and 5th DAF. Lowest soil moisture content was recorded at 75-100 cm soil depth after 5th DAF and similar trend was observed after each fertigation. Lowest and highest soil moisture reported were 0.02 g g^{-1} and 0.39 g g^{-1}, respectively.

Table 2. Effect on soil moisture content, ammonium and nitrate concentration as influenced by SSDI in DSR under rice-wheat-mungbean system (Sc5)

	Sc5	Moisture content (g g^{-1})			NH_4^+ (ppm)			NO_3^- (ppm)		
	Depth	**1st DAF**	**3rd DAF**	**5th DAF**	**1st DAF**	**3rd DAF**	**5th DAF**	**1st DAF**	**3rd DAF**	**5th DAF**
1st Fertigation	0-5	0.39 Aa	0.30 Ba	0.14 Ca	21.30 Ab	17.55 Bb	14.95 Ca	22.98 Ac	22.64 Aa	18.98 Ba
	5-15	0.25 Ab	0.20 Ab	0.04 Bb	22.19 Aab	18.29 Bb	11.62 Cb	29.01 Aab	24.57 Ba	16.85 Ca
	15-30	0.20 Abc	0.19 Ab	0.05 Bb	24.59 Aa	21.18 Ba	12.19 Cb	30.31 Aa	23.47 Ba	17.99 Ca
	30-50	0.20 Abc	0.19 Ab	0.06 Bb	24.02 Aa	18.31 Bb	11.60 Cb	27.45 Ab	22.32 Ba	19.14 Ba
	50-75	0.18 Ac	0.19 Ab	0.05 Ab	13.75 Ac	10.87 ABc	8.70 Bc	18.33 Ad	15.45 Bb	11.60 Cb
	75-100	0.19 Ac	0.18 Ab	0.05 Bb	9.16 Ad	4.58 Bd	4.65 Bd	15.46 Ae	10.31 Bc	8.71 Bc
2nd Fertigation	0-5	0.29 Aa	0.26 Aa	0.13 Ba	23.22 Aa	21.03 Aa	20.73 Aa	23.79 Abc	22.74 Aab	23.03 Aa
	5-15	0.19 Ab	0.19 Ab	0.03 Bb	24.03 Aa	16.60 Bb	16.87 Bb	25.18 Aab	24.61 ABa	20.94 Ba
	15-30	0.18 Abc	0.17 Ab	0.04 Bb	25.21 Aa	18.35 Bb	16.27 Cb	28.08 Aa	19.50 Bbc	18.60 Bb
	30-50	0.18 Abc	0.18 Ab	0.06 Bb	17.75 Ab	16.61 Ab	13.92 Bc	20.62 Ac	17.76 ABc	15.66 Bc
	50-75	0.17 Ac	0.17 Ab	0.04 Bb	10.32 Ac	11.47 Ac	9.87 Ad	14.91 Ad	20.06 Abc	15.10 Ac
	75-100	0.17 Ac	0.17 Ab	0.05 Bb	8.60 Ac	8.03 Ad	9.29 Ad	8.60 Be	9.75 ABd	11.61 Ad
3rd Fertigation	0-5	0.36 Aa	0.32 Aa	0.13 Ba	26.99 Aa	28.80 Aa	27.06 Aa	30.36 Ba	34.45 Aa	29.94 Ba
	5-15	0.26 Ab	0.20 Abc	0.05 Bb	27.27 Aa	24.58 Ab	19.15 Cb	30.11 Aa	22.86 Bb	24.38 Bb
	15-30	0.23 Ab	0.21 Ab	0.04 Bb	23.94 Ab	21.70 Ac	16.85 Bb	29.07 Aa	24.56 Bb	18.01 Cc
	30-50	0.19 Ac	0.20 Abc	0.05 Bb	23.46 Ab	18.29 Bd	12.19 Cc	29.76 Aa	22.87 Bb	12.77 Cd
	50-75	0.18 Ac	0.18 Abc	0.06 Bb	17.76 Ac	14.89 Be	9.86 Cc	22.91 Ab	17.76 Bc	11.02 Cde
	75-100	0.18 Ac	0.17 Ac	0.04 Bb	11.46 Ad	10.32 Af	5.23 Bd	12.60 Ac	10.89 ABd	9.30 Be
4th Fertigation	0-5	0.30 Aa	0.26 Aa	0.27 Aa	21.50 Ab	17.62 Ba	22.14 Aa	24.33 Aa	23.86 Aa	23.27 Aab
	5-15	0.20 Ab	0.20 Ab	0.21 Ab	21.15 Ab	17.72 Ba	22.84 Aa	23.44 Aa	18.29 Bbc	24.56 Aa
	15-30	0.19 Ab	0.17 Abc	0.18 Ab	23.46 Aa	16.05 Ca	19.48 Bb	22.32 Aab	17.77 Bcd	21.77 Ab
	30-50	0.20 Ab	0.15 Bc	0.20 Ab	17.72 Ac	17.81 Aa	16.58 Ac	20.58 Ab	20.69 Ab	22.29 Aab

	Sc5	**Moisture content (g g^{-1})**			**NH_4^+ (ppm)**			**NO_3^- (ppm)**		
	Depth	**1st DAF**	**3rd DAF**	**5th DAF**	**1st DAF**	**3rd DAF**	**5th DAF**	**1st DAF**	**3rd DAF**	**5th DAF**
	50-75	0.18 Ab	0.16 Ac	0.17 Ab	9.74 Bd	16.07 Aa	14.34 Ac	12.60 Bc	17.80 Acd	17.78 Ac
	75-100	0.17 Ab	0.14 Ac	0.17 Ab	7.46 Be	11.50 Ab	6.88 Bd	10.90 Bc	15.53 Ad	10.32 Bd
5th Fertigation	0-5	0.31 Aa	0.27 Ba	0.11 Ca	25.44 Aa	24.97 Aa	23.66 Aa	28.83 Aa	28.95 Aa	23.08 Ba
	5-15	0.24 Ab	0.22 Ab	0.04 Cb	24.48 Aa	22.82 Ab	22.66 Aa	23.91 Ab	23.96 Ab	24.40 Aa
	15-30	0.21 Abc	0.19 Abc	0.06 Cb	24.56 Aa	18.31 Bc	13.92 Cb	30.84 Aa	22.89 Bbc	17.97 Cb
	30-50	0.22 Abcd	0.19 Abc	0.05 Bb	21.11 Ab	17.17 Bc	11.61 Cbc	22.82 Ab	20.60 Ac	11.61 Cd
	50-75	0.20 Acd	0.17 Ac	0.04 Bb	17.72 Ac	10.89 Bd	11.04 Bc	18.86 Ac	15.48 Ad	17.42 Ab
	75-100	0.18 Ad	0.16 Ac	0.04 Bb	16.04 Ac	6.31 Ce	9.88 Bc	18.90 Ac	9.19 Be	12.20 Bc
6th Fertigation	0-5	0.30 Aa	0.23 Ba	0.12 Ca	22.63 Aa	21.66 Aa	17.87 Bb	25.47 Aa	23.37 ABa	20.75 Bb
	5-15	0.20 Ab	0.18 Ab	0.02 Bc	18.29 Bb	19.47 Bab	22.12 Aa	20.58 Bb	22.91 ABa	23.87 Aa
	15-30	0.19 Ab	0.16 Ab	0.03 Bbc	17.74 Bb	17.79 Bbc	22.68 Aa	18.31 Bbc	22.39 Aa	25.01 Aa
	30-50	0.17 Ab	0.17 Ab	0.05 Bb	11.47 Cc	17.78 Bbc	20.90 Aa	20.07 ABb	18.35 Bb	23.22 Aab
	50-75	0.16 Ab	0.16 Ab	0.03 Bbc	10.91 Ccd	15.50 Ac	14.54 Ac	13.78 Bd	18.94 Ab	17.45 Ac
	75-100	0.16 Ab	0.16 Ab	0.04 Bbc	9.18 Ad	5.17 Bd	8.14 ABd	14.93 Acd	8.61 Bc	8.13 Bd
7th Fertigation	0-5	0.30 Aa	0.24 Ba	0.15 Ca	27.16 Aa	23.91 Ba	17.81 Ca	29.99 Aa	29.60 Aa	17.24 Ba
	5-15	0.21 Ab	0.20 Ab	0.05 Bb	25.13 Aab	20.58 Bb	11.61 Cb	23.98 Ab	24.58 Abc	17.99 Ba
	15-30	0.20 Ab	0.18 Ab	0.06 Bb	22.87 Ab	21.77 Aab	9.86 Bbc	23.44 Ab	25.20 Ab	12.76 Bb
	30-50	0.19 Abc	0.17 Ab	0.04 Bb	18.31 Ac	17.78 Ac	9.30 Bbc	17.17 Bc	22.36 Acd	12.20 Cb
	50-75	0.16 Ac	0.16 Ab	0.04 Bb	15.50 Ad	17.22 Ac	8.71 Bbc	17.79 Bc	20.66 Ad	7.55 Cc
	75-100	0.16 Ac	0.16 Ab	0.04 Bb	8.61 Ae	10.33 Ad	7.55 Ac	9.18 Ad	10.91 Ae	8.71 Ac
8th Fertigation	0-5	0.33 Aa	0.30 Aa	0.12 Ba	20.31 Aab	18.12 Aa	20.75 Aa	22.00 Ab	22.64 Aa	23.05 Aa
	5-15	0.27 Ab	0.21 Bb	0.08 Cb	22.13 Aa	17.70 Ba	18.52 Ba	22.14 Ab	22.27 Aa	24.30 Aa
	15-30	0.22 Ac	0.20 Ab	0.06 Bbc	22.25 Aa	17.15 Ba	14.49 Bb	25.10 Aa	17.72 Bb	17.97 Bb
	30-50	0.20 Acd	0.19 Abc	0.05 Bbc	17.15 Abc	10.30 Bb	8.71 Bc	23.44 Aab	16.02 Bbc	15.09 Bc
	50-75	0.18 Acd	0.16 Ac	0.05 Bbc	16.62 Ac	10.33 Bb	4.06 Cd	18.33 Ac	13.78 Bc	13.93 Bc
	75-100	0.16 Ad	0.16 Ac	0.04 Bc	9.18 Ad	5.17 Bc	5.81 Bd	10.91 Ad	10.33 Ad	11.04 Ad

Significant variation in NH_4^+ and NO_3^- concentration was observed both in soil depths and days after fertigation (DAF) in SSDI based wheat under rice-wheat-mung bean systems (Sc5). In first fertigation and one day after first fertigation, highest NH_4^+ concentration (24.59 ppm) was observed at 15-30 cm soil depth whereas, at 75-100 cm soil depth, lowest NH_4^+ (9.16 ppm) was observed. At 3rd day after fertigation, similar trend was observed, highest NH_4^+ concentration (21.18 ppm) was observed at 15-30 cm soil depth. Below 30 cm soil depth, NH_4^+ concentration decreased along depth, lowest was associated with 75-100 cm soil depth irrespective of days after fertigation. At 5th DAF, significantly lowest NH_4^+ concentration was observed in all the soil depths as compared to 1st and 3rd DAF, highest and lowest NH_4^+ was associated with 0-5 cm (14.95 ppm) and 75-100 cm (4.65 ppm) soil depth, respectively. Highest NO_3^- concentration was observed at 15-30 cm soil depth (30.31ppm) followed by 5-15 cm (29.01 ppm) and 30-50 cm soil depth (27.45 ppm) at one day after fertigation. At 3rd DAF, similar NO_3^--N concentration was observed upto 50 cm soil depth below that significant decline was observed. Similar trend was observed at 5th DAF. Along depths, significant decline in NO_3^--N concentration was observed.

In 2nd fertigation, similar trend of decrease in concentration of $NH_4^+$and NO_3^- along depth and days after fertigation was observed. Highest concentration of NH_4^+ in first day after fertigation was observed at 15-30 cm soil depth (25.21 ppm) followed by 5-15 cm (24.03 ppm) and 0-5 cm (23.22 ppm) soil depth. Below 15-30 cm soil depth, NH_4^+ concentration decreased significantly from 17.75 ppm to 9.29 ppm at 15-30 cm soil depth of 1st DAF and 75-100 cm soil depth of 5th DAF, respectively. Overall highest NO_3^- concentration was observed at 15-30 cm soil depth (28.08 ppm) followed by 5-15 cm (25.18 ppm) on 1st DAF and 5-15 cm soil depth (24.61 ppm) after 3rd DAF.

In 3rd fertigation, highest NH_4^+ concentration was recorded at 0-5 cm soil depth (28.80 ppm) during 3rd DAF followed by 5-15 cm (27.27 ppm) during 1st DAF and lowest at 75-100 cm soil depth (5.23 ppm) during 5th DAF. NO_3^- concentration was found to be highest at surface soil (0-5 cm ppm) in 1st (30.36 ppm), 3rd (34.45 ppm) and 5th (29.94 ppm) DAF and found to be decreased along depth whereas, lowest NO_3^- concentration was observed at 75-100 cm soil depth (9.30 ppm) during 5th DAF.

In 4th fertigation, highest NH_4^+ concentration was recorded at 15-30 cm (23.46) in 1st DAF followed by 5-15 cm (22.84 ppm) and 0-5 cm soil depth (22.14 ppm) in 5th DAF, respectively. Lowest NH_4^+ concentration was recorded at 75-100 cm (7.46 ppm) in 1st DAF followed by 6.88 and 11.50 ppm at same depth in 5th and 3rd DAF, respectively. Highest NO_3^--N concentration was observed at 5th DAF at 5-15 cm soil depth (24.56 ppm) followed by 0-5 cm soil depth (24.33) and (23.86 ppm) in 1st and 3rd DAF, respectively. Lowest NO_3^- concentration was observed at 75-100 cm soil depth in 5th (10.32) and 1st (10.90 ppm) DAF.

In 5th fertigation, highest NH_4^+ concentration was recorded at surface soil (0-5 cm) in both 1st (25.44 ppm) and 3rd (24.97 ppm) DAF followed by 5-15cm depth (24.48 ppm) in 1st DAF. Lowest NH_4^+concentration was recorded at 75-100 cm soil depth in both 3rd (6.31 ppm) and 5th (9.88 ppm) DAF. NO_3^- concentration was highest at 15-30 cm (30.84 ppm) soil depth in 1st DAF, followed by 0-5 cm (28.95 ppm) in 3rd DAF, respectively. Lowest NO_3^- concentration was observed at 75-100 cm soil depth in 3rd (9.19 ppm) DAF followed by 5th DAF (12.20 ppm), respectively.

In 6th fertigation, soil depth of 15-30 cm recorded highest NH_4^+ concentration (22.68 ppm) in 5th DAF followed by 0-5 cm in 1st (22.63 ppm) and 5th (21.66 ppm) DAF. Lowest NH_4^+ was recorded at 75-100 cm soil depth in 3rd (5.17 ppm) and 5th (8.14 ppm) DAF. NO_3^- was highest at 0-5 cm soil depth (25.47 ppm) in 1st DAF followed by 15-30 cm (25.01 ppm) and 5-15 cm depth (23.87 ppm) in 5th DAF whereas, lowest NO_3^- was recorded at 75-100 cm soil depth in 5th (8.13 ppm) and 3rd (8.61 ppm) DAF, respectively.

In 7th fertigation, highest NH_4^+ concentration was recorded at 0-5 cm soil depth followed by 5-15 cm (27.16 ppm) in 1st DAF followed by 23.91 ppm at 0-5 cm soil depth in 3rd DAF. Lowest NH_4^+ was recorded at 75-100 cm soil depth (7.55 ppm) in 5th DAF and 8.61 ppm in 1st DAF. Highest NO_3^- concentration was recorded at 0-5 cm soil depth in 1st (29.99 ppm) and 5th (29.60 ppm) DAF followed by 15-30 cm soil depth (25.20 ppm) in 15-30 cm soil depth. Lowest NO_3^-content was recorded at 50-75 cm (7.55 ppm) and 75-100 cm soil depth (8.71 ppm) in 5th DAF, respectively.

In 8th fertigation, highest NH_4^+concentration was recorded at 15-30 cm (22.25 ppm) and 5-15 cm soil depth (22.13 ppm) in 1st DAF followed by 20.75 ppm at 0-5 cm soil depth in 5th DAF, respectively. Lowest NH_4^+ concentration was recorded at 50-75 cm soil depth in 5th (4.06 ppm) DAF followed by 75-100 cm soil depth in 3rd (5.17 ppm) and 5th (5.81 ppm) DAF, respectively.

3.2 Soil Moisture Content, Ammonium (NH_4^+) and Nitrate (NO_3^-) as Influenced by Flood Irrigation in DSR under Rice-wheat-mungbean System (Sc3)

Soil moisture content after each irrigation at 1st, 3rd and 5th day after irrigation (DAI) is showed in Table 3. After each irrigation, highest moisture was recorded at 0-5 cm soil depth at 1st DAI whereas it decreased with depth toward 3rd and 5th DAI. Range of soil moisture content after 1st irrigation was between 0.19 g g^{-1} and 0.51 g g^{-1}. Soil moisture content after 2nd irrigation varied between 0.19 g g^{-1} to 0.50 g g^{-1}. Similarly, after 3rd irrigation soil moisture content ranged from 0.19 g $g^{-1}$to 0.53 g g^{-1}.

In 1st irrigation, highest NH_4^+ concentration was recorded at 0-5 cm soil depth (27.12 ppm) followed by 5-15 cm depth (23.50 ppm) in 1st day after irrigation (DAI) and 3rd (23.06 ppm) days after irrigation (DAI), respectively. Lowest NH_4^+ was recorded at 75-100 cm soil depth in 3rd (4.00 ppm) and 5th (5.15 ppm) DAI, respectively. NO_3^- was highest at 0-5 cm (33.20 ppm) followed by 5-15 cm soil depth (30.21 ppm) in 1st DAI and 0-5 cm soil depth (29.43 ppm) in 5th DAI, respectively. Lowest NO_3^- was recorded at 75-100 cm soil depth in 1st (8.36 ppm), 3rd (8.57 ppm) and 5th (10.40 ppm) DAI.

In 2nd irrigation, NH_4^+ concentration was highest at 0-5 cm (28.26 ppm) in 5th DAI followed by 1st DAI (28.26 ppm) and 27.97 ppm in 5th DAI. Lowest NH_4^+ was recorded at 75-100 cm soil depth in 1st (6.71 ppm), 3rd (8.57 ppm) and 5th (9.15 ppm) DAI, respectively. Higher NO_3^- concentration was observed at 5th DAI as compared to 1st and 3rd DAI, irrespective of soil depth. Highest NO_3^- concentration was found at 0-5 cm (34.04 ppm) followed by 5-15 cm (29.11 ppm) and 15-30 cm soil depth (28.05 ppm) in 5th DAI. Lowest NO_3^- was recorded at 75-100 cm soil depth in 5th (9.72 ppm), 3rd (9.72 ppm) and 1st (11.18 ppm) DAI, respectively.

Table 3. Effect on soil moisture content, ammonium and nitrate concentration as influenced by flood irrigation in DSR under rice-wheat-mungbean system (Sc3)

	Sc3	Moisture content ($g\ g^{-1}$)			NH_4^+ (ppm)			NO_3^- (ppm)		
	Depth	**1st DAI**	**3rd DAI**	**5th DAI**	**1st DAI**	**3rd DAI**	**5th DAI**	**1st DAI**	**3rd DAI**	**5th DAI**
1st Irrigation	0-5	0.51 Aa	0.36 Ba	0.30 Ba	27.12 Aa	23.06 Ba	22.08 Ba	33.20 Aa	27.00 Ba	29.43 Ba
	5-15	0.41 Aab	0.22 Bb	0.20 Bb	23.50 Ab	20.53 Ab	20.57 Aa	30.21 Ab	29.08 Aa	25.72 Bb
	15-30	0.33 Ab	0.20 Bb	0.19 Bc	18.60 Ac	16.58 ABc	13.74 Bb	21.99 Ac	24.01 Ab	22.33 Ac
	30-50	0.34 Ab	0.21 Bb	0.20 Bbc	17.47 Ac	13.71 Bd	10.87 Cc	16.34 Ad	15.43 Ac	17.73 Ad
	50-75	0.38 Ab	0.21 Bb	0.20 Bbc	16.27 Ac	9.71 Be	8.01 Bd	11.78 Be	10.85 Bd	16.58 Ad
	75-100	0.43 Ab	0.21 Bb	0.20 Bb	9.48 Ad	4.00 Bf	5.15 Be	8.36 Ae	8.57 Ad	10.40 Ae
2nd Irrigation	0-5	0.50 Aa	0.35 Ba	0.27 Ca	28.26 Aa	23.64 Ba	30.07 Aa	23.83 Ba	24.20 Ba	34.04 Aa
	5-15	0.45 Ab	0.26 Bb	0.21 Bb	23.41 Bb	24.43 Ba	27.97 Ab	23.41 Ba	23.30 Ba	29.11 Ab
	15-30	0.35 Ae	0.22 Bc	0.19 Bb	18.02 Bc	22.25 Aa	24.62 Ac	21.96 Ba	22.25 Ba	28.05 Ab
	30-50	0.37 Ade	0.23 Bbc	0.19 Bb	16.30 Ac	17.10 Ab	17.74 Ad	17.42 Bb	17.67 Bb	22.31 Ac
	50-75	0.38 Ad	0.23 Bbc	0.19 Cb	13.46 Bd	13.68 ABc	16.60 Ad	15.15 Ab	11.40 Bc	15.45 Ad
	75-100	0.41 Ac	0.20 Bc	0.19 Bb	6.71 Ae	8.57 Ad	9.15 Ae	11.18 Ac	9.72 Ac	9.72 Ae
3rd Irrigation	0-5	0.53 Aa	0.37 Ba	0.31 Ca	24.86 Aa	23.60 ABa	20.35 Ba	30.38 Aa	21.91 Ba	20.91 Ba
	5-15	0.42 Ab	0.23 Bb	0.19 Bb	24.04 Aa	20.53 ABb	17.73 Ba	22.36 Ab	17.68 Bab	20.59 ABa
	15-30	0.32 Ac	0.22 Bb	0.20 Bb	20.89 Ab	19.40 Abc	13.72 Bb	22.59 Ab	15.41 Babc	17.72 Bb
	30-50	0.35 Ac	0.21 Bb	0.20 Bb	15.19 Ac	17.70 Ac	12.01 Bb	17.45 Ac	18.83 Aab	10.87 Ac
	50-75	0.36 Ac	0.20 Bb	0.19 Bb	13.50 Ac	13.73 Ad	8.58 Bc	16.31 Ac	8.58 Bbc	6.86 Bd
	75-100	0.44 Ab	0.21 Bb	0.19 Bb	8.92 Ad	8.57 Ae	4.01 Bd	10.59 Ad	5.71 Bc	6.87 Bd

In 3rd irrigation, highest NH_4^+ concentration was recorded at 0-5 cm (24.86 ppm) and 5-15 cm soil depth (24.04 ppm) in 1st DAI followed by 0-5 cm soil depth (23.60 ppm) in 3rd DAI, respectively. NH_4^+ concentration was lowest at 75-100 cm soil depth (4.01 ppm) in 5th DAI followed by 3rd (8.57 ppm) and 50-75 cm soil depth (8.58 ppm) in 5th DAI, respectively. Highest NO_3^- concentration was recorded in 1st DAI as compared to 3rd and 5th DAI, irrespective of soil depth. Highest concentration of NO_3^- was observed at 0-5 cm (30.38 ppm) followed by 5-15 cm (22.36 ppm) and 15-30 cm soil depth (22.59 ppm) in 1st DAI, respectively whereas, lowest NO_3^- concentration was observed in 3rd (5.71 ppm) and 5th (6.87 ppm) DAI at 75-100 cm soil depth, respectively.

3.3 Soil Moisture Content, Ammonium (NH_4^+) and Nitrate (NO_3^-) as Influenced by SSDI under Maize-wheat-mungbean System (Sc6)

Soil moisture content after each fertigation at 1st, 3rd and 5th day after fertigation (DAF) is showed in Table 4. After each irrigation, highest moisture was recorded at 0-5 cm soil depth at 1st DAF whereas it decreased with depth toward 3rd and 5th DAF. After 1stfertigation, highest soil moisture was observed at 0-5 cm (0.36 $g\ g^{-1}$) whereas lowest soil moisture was recorded at 75-100 cm soil depth at 5th DAF. After 2nd fertigation, highest soil moisture was recorded at 0-5 cm soil depth (0.35 $g\ g^{-1}$) whereas lowest soil moisture (0.14 $g\ g^{-1}$) was recorded at 75-100 cm soil depth at 5th DAF. After 3rd fertigation highest soil moisture was recorded at 0.31 $g\ g^{-1}$ and lowest was recorded at 0.15 $g\ g^{-1}$ at 75-100 cm soil depth at 5th DAF. After 4th fertigation, highest soil moisture was recorded at 0-5 cm soil depth at 1st DAF (0.37 $g\ g^{-1}$) and lowest was recorded at 0.11 $g\ g^{-1}$ at 75-100 cm soil depth at 5th DAF.

In 1st fertigation, concentration of NH_4^+ was highest at 5-15 cm soil depth (30.66 ppm) and 15-30 cm soil depth (29.64 ppm) in 1st DAF followed by 15-30 cm (22.88 ppm) in 3rd DAF, respectively. Lowest NH_4^+ concentration was recorded at 75-100 cm soil depth in 3rd (4.59 ppm), 5th (4.61 ppm) and 1st (8.02 ppm) DAF. Highest concentration of NO_3^- was recorded at 15-30 cm soil depth (34.19 ppm) followed by 3rd DAF (30.89 ppm) at same depth. Lowest NO_3^- concentration was observed at 75-100 cm soil depth in 1st (9.17 ppm) followed by 5th (6.92 ppm) DAF.

Table 4. Effect on soil moisture content, ammonium and nitrate concentration as influenced by SSDI under maize under maize-wheat-mungbean system (Sc6)

	Sc6	Moisture content ($g\ g^{-1}$)			NH_4^+ (ppm)			NO_3^- (ppm)		
	Depth	**1st DAF**	**3rd DAF**	**5th DAF**	**1st DAF**	**3rd DAF**	**5th DAF**	**1st DAF**	**3rd DAF**	**5th DAF**
1st Fertigation	0-5	0.36 Aa	0.30 Ba	0.19 Ca	21.38 Ab	19.23 Aab	14.87 Ba	29.25 Aa	21.49 Bb	20.59 Babc
	5-15	0.27 Ab	0.20 Bb	0.18 Bab	30.66 Aa	19.43 Bab	18.32 Ba	30.66 Aa	20.57 Bb	24.05 ABa
	15-30	0.23 Ac	0.19 Bb	0.17 Bb	29.64 Aa	22.88 Ba	18.34 Ca	34.19 Aa	30.89 Aa	21.78 Bab
	30-50	0.19 Ad	0.20 Ab	0.16 Bc	19.45 Ab	18.30 ABb	14.93 Ba	21.75 Ab	21.73 Ab	17.23 Abc
	50-75	0.18 Ad	0.18 Abc	0.13 Bd	11.46 Ac	10.31 Ac	8.06 Ab	17.19 Ab	16.04 Ac	14.97 Ac
	75-100	0.18 Ad	0.16 Bc	0.11 Ce	8.02 Ac	4.59 Ad	4.61 Ab	9.17 Ac	11.48 Ad	6.92 Ad
2nd Fertigation	0-5	0.35 Aa	0.32 Ba	0.22 Ca	30.39 Aa	21.46 Ba	14.84 Cb	30.38 Aa	31.63 Aa	19.40 Bc
	5-15	0.32 Ab	0.24 Bb	0.19 Cb	23.71 Ab	21.64 ABa	18.32 Bab	33.87 Aa	30.76 ABa	25.19 Bb
	15-30	0.27 Ac	0.21 Bc	0.17 Cc	20.44 Ab	18.28 Aab	22.94 Aa	23.84 Bb	22.85 Bb	32.12 Aa
	30-50	0.21 Ad	0.18 Bd	0.16 Cc	20.56 Ab	14.89 Ab	14.92 Ab	20.56 Abc	21.76 Ab	17.22 Ac
	50-75	0.18 Ae	0.17 Ad	0.14 Bd	14.89 Ac	8.02 Bc	6.90 Bc	17.18 Ac	10.32 Ac	10.35 Ad
	75-100	0.16 Af	0.17 Ad	0.14 Bd	9.18 Ad	4.59 Bc	4.60 Bc	18.36 Abc	8.03 Bc	8.06 Bd
3rd Fertigation	0-5	0.28 Aa	0.31 Aa	0.21 Ba	21.53 Aa	18.10 Aa	19.42 Aab	31.73 Aa	21.49 Bb	21.70 Ba
	5-15	0.24 Ab	0.26 Ab	0.18 Bb	20.49 Aa	20.45 Aa	21.76 Aa	20.49 Bb	30.68 Aa	27.49 Aa
	15-30	0.19 Abc	0.21 Ac	0.18 Ab	24.03 Aa	17.13 Ba	19.47 ABab	30.90 Aa	22.85 Bb	24.05 Ba
	30-50	0.19 Ac	0.18 Acd	0.17 Ab	21.73 Aa	9.16 Cb	16.05 Bb	34.32 Aa	9.16 Cc	20.63 Ba
	50-75	0.21 Ac	0.18 Bcd	0.17 Bbc	14.85 Ab	8.02 Bb	5.74 Bc	19.42 Ab	20.61 Ab	16.07 Aa
	75-100	0.20 Ac	0.17 Ad	0.15 Bc	8.00 Ac	6.88 Ab	4.59 Ac	17.14 Ab	10.33 Bc	4.60 Bb
4th Fertigation	0-5	0.37 Aa	0.31 Ba	0.19 Ca	23.60 Ab	21.47 Aa	16.02 Bb	30.35 Aa	27.12 ABa	21.74 Ba
	5-15	0.31 Ab	0.22 Bb	0.17 Cb	21.49 Abc	18.25 Aab	18.34 Aab	23.75 Ab	21.68 Ab	20.63 Aa
	15-30	0.25 Ac	0.19 Bc	0.16 Cbc	29.58 Aa	13.74 Cb	21.80 Ba	34.12 Aa	19.46 Bb	22.95 Ba
	30-50	0.21 Ad	0.18 Bcd	0.16 Cc	21.71 Abc	17.18 Aab	17.22 Ab	23.99 Ab	22.91 Ab	19.52 Aa
	50-75	0.18 Ae	0.17 Ad	0.14 Bd	17.18 Ac	9.17 Bc	8.05 Bc	21.76 Ab	8.03 Bc	8.06 Bb
	75-100	0.17 Ae	0.17 Ad	0.11 Be	8.03 Ad	4.59 Ad	5.77 Ac	4.59 Ac	4.59 Ac	4.61 Ab

In 2nd fertigation, highest concentration of NH_4^+ was recorded at 0-5 cm (30.39 ppm) and 5-15 cm soil depth (23.71 ppm) in 1st DAF followed by 5-15 cm soil depth (21.64 ppm) at 3rd DAF, respectively. Lowest $NH_4^+$was observed at 75-100 cm soil depth in 3rd (4.59 ppm) and 5th (4.60 ppm) DAF, respectively. Highest NO_3^- concentration was recorded at 15-30 cm soil depth (33.87 ppm) in 1st DAF followed by 0-5 cm (31.63 ppm) and 5-15 cm soil depth (30.76 ppm) in 3rd DAF, respectively. Lowest NO_3^- concentration was recorded at 75-100 cm soil depth in 3rd (8.03 ppm) and 5th (8.06 ppm) DAF, respectively.

In 3rd fertigation, highest NH_4^+ was recorded at 15-30 cm soil depth (24.03 ppm) in 1st DAF followed by 5-15 cm soil depth (21.76 ppm) in 5th DAF, respectively. Lowest concentration of $NH_4^+$was recorded at 75-100 cm soil depth (4.59) at 5th DAF followed 3rd DAF.NO_3^- concentration was highest at 30-50 cm soil depth (34.32 ppm) followed by 0-5 cm (31.73 ppm) in 1st DAF and 5-15 cm soil depth (30.68 ppm) in 3rd DAF, respectively. Lowest NO_3^- concentration was recorded at 75-100 cm soil depth (4.60 ppm) in 5th DAF followed by 10.33 ppm in 3rd DAF at same soil depth.

In 4th fertigation, highest NH_4^+ concentration was observed at 15-30 cm (29.58 ppm) followed by 0-5 cm (23.60 ppm) and 30-50 cm soil depth (21.71 ppm) in 1st DAF whereas, lowest NH_4^+ concentration was observed in 3rd (4.59 ppm) and 5th (5.77 ppm) DAF at 75-100 cm soil depth, respectively. Highest NO_3^- concentration was observed at 15-30 cm (34.12 ppm) and 0-5 cm (30.35 ppm) soil depth followed by 0-5 cm soil depth (27.12 ppm) in 1st and 3rd DAF, respectively. Lowest NO_3^- concentration was recorded in 1st (4.59 ppm), 3rd (4.59 ppm) and 5th (4.61 ppm) DAF, respectively at 75-100 cm soil depth.

3.4 Soil Moisture Content, Ammonium (NH_4^+) and Nitrate (NO_3^-) as Influenced by Flood Irrigation under Maize-wheat-mungbean System (Sc4)

Soil moisture content after each irrigation at 1st, 3rd and 5th day after irrigation (DAI) is showed in Table 5. After each irrigation highest soil moisture was recorded at 0-5 cm (0.52, 0.53 and 0.51 g g^{-1}) at 1st DAI at 1st, 2nd and 3rd irrigation, respectively and lowest was recorded at 5th DAI (0.18, 0.12 and 0.14 g g^{-1}) at 30-50, 75-100 and 15-30 cm soil depth after 1st, 2nd and 3rd irrigation, respectively.

Table 5. Effect on soil moisture content, ammonium and nitrate concentration as influenced by flood irrigation in maize under maize-wheat-mungbean system (Sc4)

	Sc4	Moisture content (g g^{-1})			NH_4^+ (ppm)			NO_3^- (ppm)		
	Depth	**1st DAI**	**3rd DAI**	**5th DAI**	**1st DAI**	**3rd DAI**	**5th DAI**	**1st DAI**	**3rd DAI**	**5th DAI**
1st Irrigation	0-5	0.52 Aa	0.31 Ba	0.28 Ca	23.22 Aa	21.48 Aa	18.15 Aab	30.97 Aa	22.61 Ba	22.69 Ba
	5-15	0.43 Ab	0.25 Bb	0.22 Cb	22.33 Aa	19.34 Aab	19.40 Aa	30.15 Aa	21.62 Ba	22.83 Ba
	15-30	0.37 Ac	0.21 Bbc	0.20 Bbc	19.09 Aa	15.99 ABb	14.86 Bb	17.97 Ab	18.28 Aa	19.43 Aa
	30-50	0.32 Ad	0.23 Bcd	0.18 Ccd	13.55 Ab	7.98 ABc	6.87 Bc	21.46 Ab	13.68 Bb	19.47 Aa
	50-75	0.33 Ad	0.22 Bde	0.20 Cd	5.64 Ac	5.71 Ac	6.18 Ac	9.03 Ab	10.27 Abc	8.01 Ab
	75-100	0.31 Ad	0.20 Be	0.19 Bd	4.52 Ac	4.57 Ac	5.72 Ac	7.91 Ab	8.01 Ac	5.72 Ab
2nd Irrigation	0-5	0.53 Aa	0.28 Ba	0.25 Ca	30.93 Aa	34.03 Aa	30.70 Aa	24.34 Aa	36.30 Aa	35.25 Aa
	5-15	0.46 Ab	0.21 Bb	0.19 Bb	22.25 Bb	31.99 Aa	22.90 Bb	26.70 Ba	33.13 Aa	32.06 Aa
	15-30	0.36 Ac	0.17 Bc	0.16 Bc	22.50 ABb	25.24 Ab	19.51 Bb	32.62 Aa	34.42 Aa	24.11 Bb
	30-50	0.30 Ad	0.15 Bd	0.15 Bcd	16.97 Ac	18.16 Ac	8.05 Bc	20.37 Aab	22.99 Ab	17.24 Ac
	50-75	0.28 Ad	0.14 Bde	0.13 Bde	5.67 Bd	13.81 Ac	5.76 Bc	7.94 Bbc	18.41 Ac	9.21 Bd
	75-100	0.27 Ad	0.13 Be	0.12 Be	4.54 Ad	4.61 Ad	4.61 Ac	5.67 Ac	10.36 Ad	8.07 Ad
3rd Irrigation	0-5	0.51 Aa	0.27 Ba	0.24 Ca	33.22 Aa	34.05 Aa	30.73 Aa	39.86 Aa	35.18 Aa	35.28 Aa
	5-15	0.45 Ab	0.20 Bb	0.18 Bb	30.10 Aa	26.30 ABb	20.63 Bb	36.78 Aab	30.87 Aa	30.93 Ab
	15-30	0.32 Ac	0.18 Bb	0.14 Cbc	27.11 Aa	17.18 Bc	18.40 Bbc	32.74 Ab	21.76 Bb	23.00 Bc
	30-50	0.30 Ac	0.15 Bc	0.16 Bbc	14.72 Ab	13.79 Ac	14.92 Ac	21.51 Ac	18.38 Ab	19.51 Ac
	50-75	0.30 Ac	0.15 Bc	0.16 Bbc	6.79 Ac	6.90 Ad	5.74 Ad	16.97 Ac	6.90 Bc	9.19 Bd
	75-100	0.31 Ac	0.16 Bc	0.17 Bc	5.65 Ac	4.59 Ad	5.74 Ad	7.91 Ad	5.74 Ac	8.03 Ad

In 1st irrigation, highest NH_4^+ concentration was recorded at 0-5 cm soil depth (23.22 ppm) and 5-15 cm soil depth (22.33 ppm) in 1st DAI, followed by 0-5 cm soil depth (21.48 ppm) in 3rd DAI, respectively. Lowest NH_4^+ concentration was observed in 1st (4.52 ppm) and 3rd DAI (4.57 ppm) at 75-100 cm soil depth. Highest NO_3^- concentration was recorded at 0-5 cm soil depth (30.97 ppm) followed by 5-15 cm soil depth (30.15 ppm) in 1st DAI followed by 0-5 cm (22.69 ppm) in 5th DAI, respectively. Lowest NO_3^- concentration was observed at 5th (5.72 ppm), 1st (7.91 ppm) and 3rd (8.01 ppm) DAI at 75-100 cm soil depth, respectively.

In 2nd irrigation, highest NH_4^+ concentration was observed at 0-5 cm soil depth (34.03 ppm) followed by 5-15 cm (31.99 ppm) in 3rd DAI and 0-5 cm soil depth (30.93 ppm) in 1st DAI, respectively. Lowest NH_4^+ concentration was recorded in 1st (4.54 ppm) and 3rd (4.61 ppm) DAI, respectively. Highest NO_3^- concentration was observed in 0-5 cm (36.30 ppm) in 3rd DAI followed by 0-5 cm

(35.25 ppm) in 5th and 15-30 cm (34.42 ppm) in 3rd DAI whereas, lowest NO_3^- concentration was recorded at 1st (5.67 ppm) followed by 5th (8.07 ppm) DAI.

In 3rd irrigation, highest NH_4^+ concentration was observed in 3rd (34.05 ppm) followed by 1st (33.22 ppm) and 5th (30.73 ppm) DAI at 0-5 cm soil depth, respectively. Similarly, lowest NH_4^+ concentration was recorded in 3rd (4.59 ppm) followed by 1st (5.65 ppm) and 5th (5.74 ppm) DAI at 75-100 cm soil depth, respectively. NO_3^- concentration was highest at 0-5 cm (39.86 ppm) in 1st DAI followed by 0-5 cm (35.28 ppm) in 5th DAI and 5-15 cm (36.78 ppm) in 1st DAI, respectively. Lowest NO_3^- concentration was recorded at 75-100 cm soil depth (5.74 ppm) followed by 50-75 cm soil depth (6.90 ppm) in 3rd DAI.

3.5 Variation in Nitrogen Partitioning Different Plant Parts at Critical Crop Growth Stages under Different CA Practices

Significant variation in plant N concentration was observed (Table 6). In rice 2019, during panicle initiation stage, higher N content was observed in rice leaves of SSDI system (Sc5, 5.22%) compared to flood system (Sc3, 5.05%). During flowering stage, leaf N content was higher under flood system (Sc3, 3.85%) compared to SSDI system (Sc5, 2.78 %). In stem higher N was found in Sc5 (3.34%) compared to Sc3 (2.86 %) during tillering stage. During panicle initiation stage, N content was higher in rice stem of Sc3 (3%) over Sc5 (2.84% N). During tillering and flowering stage, higher N content in root was observed in Sc5 (3.7 %) compared to Sc3 (2.8 & 3.04%), respectively. whereas high root N was observed in Sc3 (3.18 %) compared to Sc5 (2.19 %) during panicle initiation stage.

Table 6. Nitrogen partitioning in different plant parts at critical crop growth stages under different CA practices

			Total N %		
Crop	**Crop stage**	**Scenario**	**Leaf**	**Stem**	**Root**
RICE (2019)	Tillering	Sc3	5.091	2.856	2.811
		Sc5	5.002	3.340	3.016
	Panicle	Sc3	5.047	3.008	3.176
		Sc5	5.218	2.840	2.189
	Flowering	Sc3	3.85	2.255	3.041
		Sc5	2.777	2.222	3.738
Maize (2019)	Tasseling	Sc4	4.931	3.567	3.281
		Sc6	4.607	3.304	3.826
	Silking	Sc4	3.855	3.22	2.736
		Sc6	4.293	3.135	2.699
	Dough	Sc4	3.757	2.587	2.502
		Sc6	3.946	2.911	2.919
Wheat (2019-20)	CRI	Sc4	2.041	-	2.72
		Sc6	2.148	-	2.548
		Sc3	2.176	-	2.251
		Sc5	2.205	-	2.348
	Tillering	Sc4	2.869	5.274	3.484
		Sc6	3.418	5.102	3.105
		Sc3	2.872	4.616	3.194
		Sc5	4.248	4.4	3.664
	Booting	Sc4	4.261	3.112	3.562
		Sc6	4.744	2.863	2.689
		Sc3	3.715	4.751	3.666
		Sc5	3.946	3.195	3.746

In maize 2019, highest N concentration in leaves was observed in SSDI (Sc6, 4.29%) at silking stage whereas, lowest was observed in flood system (Sc4, 3.6%) at dough stage. In stem, higher N was found in Sc4 (3.57%) at tasseling stage whereas, lowest in Sc4 (2.59%) at dough stage. Highest N concentration in root was recorded in SSDI system Sc6 (3.83 %) during tasseling stage whereas, lowest concentration was observed during dough stage under SSDI system (Sc4, 2.502).

In Wheat 2019-2020, highest N concentration in leaves was observed during booting stage under flood system (Sc4, 4.26%) and lowest in flood system (Sc4, 2.04%) at crown root initiation (CRI) stage. Flood based irrigation system (Sc4) recorded highest N concentration (5.27%) in stem whereas, lowest was observed in SSDI system (Sc6, 2.86%). In root, highest N concentration was observed in SSDI system (Sc5, 3.74%) during booting stage and lowest during CRI stage (2.25%) under flood system (Sc2). An interesting observation was found that, rice-based scenarios recorded higher N concentration in leaf as compared to maize-based scenarios whereas in stem and root trend was reversed.

3.6 Crop Yield under Different CA Practices

3.6.1 Crop Yield

Highest grain yield of rice during 2019 (Table 7) was recorded in Sc2 (7.28 t ha^{-1}) which is 7.37% higher over Sc1 (6.78 t ha^{-1}), 14.65% higher over Sc3 (6.35 t ha^{-1}) and 12.35% higher over Sc5 (6.48 t ha^{-1}) whereas, maize yield was highest in Sc6 (9.08 t ha^{-1}) where SSDI was applied which was 4.13% higher as compared to Sc4 (8.72 t ha^{-1}).

Table 7. Effect of CA based management practices on rice, maize, wheat and mungbean grain yield (t/ha) under different scenarios during year 2019-20

Scenarios	Yield (t ha^{-1})		
	Rice/Maize (2019)	Mungbean (2019)	Wheat (2019-20)
Sc1	6.78	0.00	4.58
Sc2	7.28	0.67	5.37
Sc3	6.35	0.00	5.59
Sc4	8.72	0.00	5.76
Sc5	6.48	0.45	5.69
Sc6	9.08	0.69	5.94

Grain yield of wheat was recorded highest in Sc6 (5.94 t ha^{-1}) which was 29.69% higher over Sc1 (4.58), 10.61% higher over Sc2 (5.37 t ha^{-1}), 6.26% higher over Sc3 (5.59 t ha^{-1}) and 4.39% higher over Sc5 (5.69 t ha^{-1}). Highest yield of mungbean was observed in Sc6 (0.69 t ha^{-1}) followed by Sc2 (0.67 t ha^{-1}) and Sc5 (0.45 t ha^{-1}).

4. Discussion

Nitrate (NO_3^-) and ammonium (NH_4^+) concentration were found to be higher under Sc4 and Sc5 at 15-30 cm soil depth on 1st day after fertigation (DAF) which may be due to the predominance of these ions during fertigation from sub-surface drip lines at 20 cm depth below the soil surface. Whereas (NO_3^-) and (NH_4^+) were observed higher at surface soil (0-5 cm) at 5th DAF which might be due to the capillary rise of irrigation water and further decomposition and mineralisation of organic matter present on the soil surface. In case of flood irrigated Sc3 and Sc4, higher concentration of NO_3^- and NH_4^+ was observed on surface soil (0-5 cm) and concentration declined along depth which might be due to the surface application of urea which slowly moved down with irrigation water (Datta & Saha, 2017). In rice, under tillering and flowering stage, higher N in root might be due to higher N uptake in drip fertigation system compared to flood irrigation as evidenced from higher N availability in former method of irrigation. Higher wheat root N under drip irrigationbased rice-wheat-mungbean system (Sc5) over wheat grown under drip irrigationbased maize-wheat-mungbean system (Sc6) irrespective of crop growth stages might be due to better soil-water-plant continuum under the former situation leading to higher N availability and uptake. More studies are required on this aspect to have a robust understanding on water and N relations under flood and drip irrigated cereal systems (Kumar *et al*., 2018; Hess *et al*., 2020; Parihar *et al*., 2018).

Alam *et al*., (2020) observed that the N recycled by high residue retention level was 6.1 kg higher than N recycled by low residue in monsoon rice season. The effects of both the minimum soil disturbance, including the non–puddled rice seedling establishment practices and the increasing residue retention in the rice–based triple cropping CA systems can be linked to the changes in total N and decomposition (Haque *et al*., 2016: Alam *et al*., 2016). Due to limited contact between soil microorganisms and the barely disturbed surface soil, total N enrichment in soil is attributed to slower breakdown of waste maintained or anchored between rows (Islam *et al*, 2016; Dikgwatlhe *et al*., 2014; Xue *et al*., 2015). Several research findings have found that overall gross N mineralization rates in long-term fertiliser studies are positively associated with SOC and TN concentrations (Booth *et al*., 2005; Wang *et al*., 2015).

5. Conclusion

The integration of conservation agriculture with SSDI-fertigation improved root-zone moisture and mineral N availability and altered plant N partitioning compared with flood irrigation. SSDI promoted the concentration of NH_4^+-N and NO_3^--N within the root zone. The rice–wheat–mungbean system under SSDI (Sc5) showed greater root N concentration, particularly in wheat, whereas the maize–wheat–mungbean system under SSDI (Sc6) achieved the highest maize, wheat and mungbean yields despite a 25% reduction in N fertilizer input. These results indicate that SSDI-based conservation agriculture can contribute to improved N management and productive intensification in cereal-based systems, particularly in water and nutrient deficient areas. Nevertheless, direct quantification of NUE and comprehensive N-balance studies are required to confirm the magnitude of N-use-efficiency gains and the long-term environmental benefits of these systems.

6. Limitations

This study was conducted at a single long-term experimental site in Karnal, Haryana, which may limit the generalisability of the findings to other soil and climatic conditions. Soil moisture and mineral nitrogen were assessed at selected depths and only on the 1st, 3rd and 5th days after irrigation or fertigation, limiting the temporal resolution of nitrogen movement. Future multi-location studies with more frequent sampling and comprehensive nitrogen-balance measurements would strengthen the assessment of long-term SSDI-based conservation agriculture 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 they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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