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RESEARCH ARTICLE

Impact of drip fertigation on maize growth and productivity under conservation agriculture practices in the eastern Indo-Gangetic plains of India

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Abstract

A two-season field experiment (2022-23 and 2023-24) was conducted at the International Rice Research Institute – South Asia regional Centre, Varanasi, India to evaluate the performance of rabi maize in a five-year long term conservation agriculture-based rice-maize system under surface and subsurface drip fertigation. The experiment was followed a randomized complete block design with nine treatment combinations and three replications. The treatment, zero till maize – direct seeded rice system under subsurface drip fertigation and 100 % recommended nitrogen (ZTM-DSR-SSD-100N) exhibited the highest plant height (213.7 cm), dry matter accumulation (316.0 g plant^{-1}) and leaf area index (LAI) (6.74 at 90 DAS), outperforming other treatments by 13.9 %, 35 % and 21 %, respectively, over the lowest-performing CTM-PTR-100N. Yield attributes followed a similar trend, with ZTM-DSR-SSD-100N recording the highest cobs per hectare (72.18), cob length (19.77 cm) and grains per cob (559.94), with 27.6 % higher grain yield (7.43 t ha^{-1}) over least-performing treatment, ZTM-PTR-75N. Enhanced resource efficiency under SSD ensured precise water and nutrient delivery, promoting superior canopy and cob development. Conversely, conventional puddled systems exhibited reduced yields due to waterlogging and inefficient nutrient use. This study highlights the superiority of SSD over traditional methods, showcasing its potential to improve maize productivity and resource-use efficiency under CA-based systems. These findings emphasize the importance of advanced irrigation and nitrogen management strategies for sustainable intensification in the eastern Indo-Gangetic plains.

Keywords: conservation agriculture; drip fertigation; rabi maize; resource optimisation; rice-maize system

Introduction

Cereal-based cropping systems play a crucial role in ensuring food and nutritional security in South Asia (1). In India, the rice-maize (RM) system has gained prominence as an alternative to the traditional rice-wheat system, primarily in the eastern Indo-Gangetic Plains (IGPs), where maize has been identified as a high-yielding, profitable and climate-resilient crop, due to short growing period, efficient water use and wider adaptability to different agro-climatic conditions (2). However, traditional RM practices face significant challenges, including excessive fertiliser use and inefficient irrigation practices, suboptimal crop productivity and deteriorating soil health, all of which threaten the long-term sustainability of the system (3). Also, these systems rely heavily on intensive tillage and flood irrigation, which not only deplete water resources but also lead to soil compaction, reduced root growth and inefficient nutrient uptake (4). Additionally, maize, as a high-nutrient-demanding crop, often suffers from imbalanced fertilization and poor water management, resulting in suboptimal yields. These challenges are exacerbated in the eastern IGP, where smallholder farmers dominate and resource constraints limit the adoption of modern agricultural technologies (4). Hence, there is an urgent need to adopt sustainable and resource-efficient alternatives to enhance maize productivity and system resilience. The intense puddling for rice and repeated tillage operations for maize disrupts soil structure, leading to subsoil compaction and poor drainage, which negatively impact the subsequent maize crop (5). The alternating water regimes between the two crops further contribute to soil degradation and hinder sustainable productivity. Direct-Seeded Rice (DSR) has emerged as a sustainable alternative to PTR, offering reduced water use, improved soil structure and wider sowing window for succeeding crop, which are critical for enhancing the maize productivity (6). Maize, being a C4 plant is highly sensitive to water and nutrient stress, particularly during its critical growth stages such as tasselling and grain filling. Inadequate irrigation and imbalanced nutrient application often result in poor kernel development and reduced grain yields (7). Furthermore, the removal of crop residues for alternative uses, such as fodder or fuel, deprives the soil of organic matter, further diminishing its fertility and water-holding capacity (8).

Conservation Agriculture (CA) offers a promising framework for addressing the challenges associated with the RM system. By integrating principles such as minimal soil disturbance, crop residue retention and crop diversification, CA enhances soil health, water use efficiency and overall system productivity (7, 8). However, widespread adoption of CA is often limited by constraints such as lack of appropriate machinery, initial high costs, limited awareness and resistance to changing traditional farming practices (8). Further, integrating drip fertigation along with CA, has shown significant potential in improving maize performance under the RM system (9). Drip fertigation, whether surface or subsurface, optimizes resource use by minimizing water losses due to evaporation and deep percolation. This method not only ensures uniform water distribution but also facilitates the timely and targeted application of nutrients, reducing losses and enhancing nutrient uptake (10). Additionally, by delivering water directly to the root zone, drip irrigation limits moisture availability in inter-row zone, thereby reducing weed proliferation (11, 12). Studies have shown that drip fertigation can significantly improve maize grain yields, water productivity and nutrient use efficiency compared to traditional flood irrigation and broadcast fertilization (13). Moreover, subsurface drip fertigation further reduces evaporation losses and promotes deeper root growth, making maize more resilient to water stress (14). Residue retention, complements drip fertigation by improving soil organic matter content, enhancing water infiltration and reducing surface runoff (13, 14). The incorporation of rice residues into the system creates a favorable microenvironment for maize growth by moderating soil temperature, conserving soil moisture and providing a slow release of nutrients (15, 16). This practice also reduces weed pressure and minimizes the need for herbicides, contributing to a more sustainable production system.

The integration of drip fertigation and CA practices, along with DSR as a key component in RM system leads to improved maize growth, higher grain yields and better resource-use efficiency, making it a viable pathway to address the sustainability challenges in the IGPs (14, 16). Despite the demonstrated benefits of CA, drip fertigation and DSR, limited studies have explored their combined impact on maize performance within the RM system, particularly in smallholder-dominated regions like the eastern IGPs. Hence, to address this key challenge, the present study aims to evaluate the growth and productivity of maize under different crop establishment techniques, irrigation methods and nitrogen application levels within a long-term CA-based RM rotation.

Materials and Methods

Experimental site

The field experiment was conducted at the IRRI-South Asia Regional Centre (ISARC), Varanasi (25.31° N, 82.97° E), located in the eastern IGPs of India, a region where RM systems are increasingly adopted due to their high productivity potential and strategic importance for regional food security. The experimental site falls in a humid subtropical climate with mean monthly temperatures ranging from 13.4 °C in January and 32.7 °C in June. The average annual rainfall was 1100 mm, with approximately 9.7 hours of sunshine per day. The daily mean weather pattern during the crop growing seasons of 2022-23 and 2023-24 have been presented in Fig. 1. The soil at the site is silty loam in texture with a pH of 7.8 and organic carbon content ranging from 0.52 % to 0.64 % (17). Available nitrogen, phosphorous and potassium were found to be 182 kg ha^{-1}, 22 kg ha^{-1}, 161 kg ha^{-1}, respectively. Available nitrogen was determined by using Alkaline $KMnO_4$ method (18), phosphorous by Olsen's method (19) and potassium through flame photometry following ammonium acetate extraction (20).

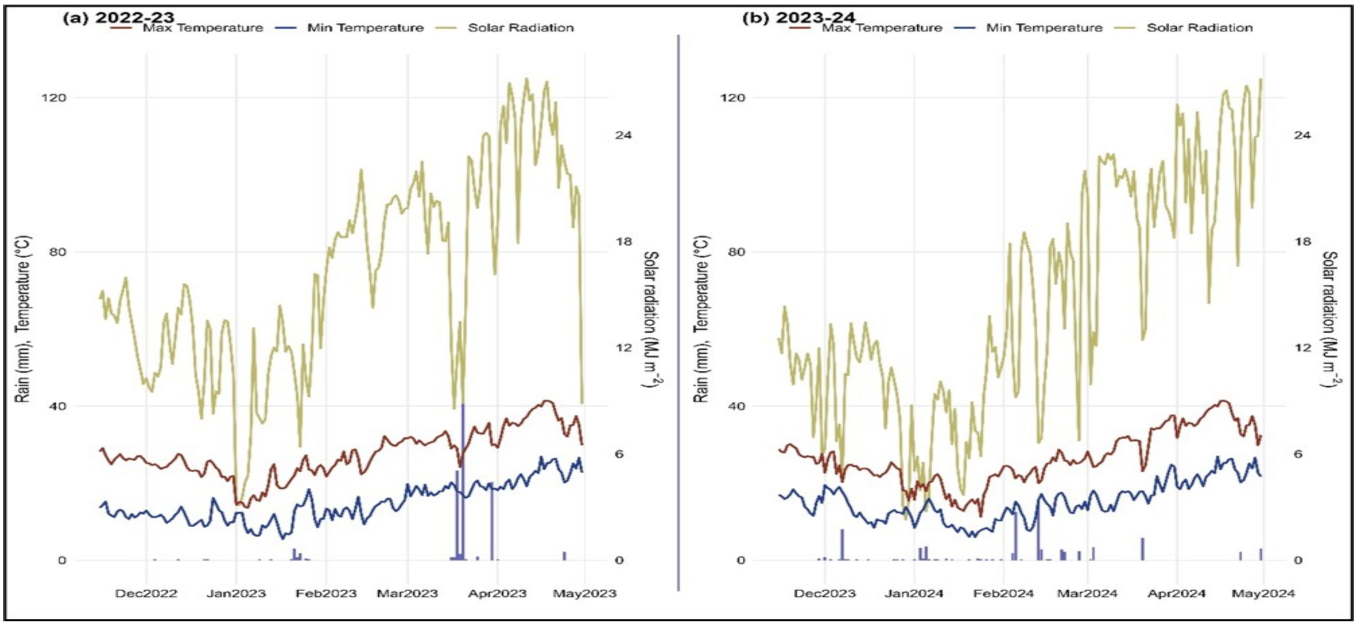

Fig. 1. Weather conditions at the maize growing period during *rabi* seasons of (a) 2022-23 and (b) 2023-24.

Treatments and experimental details

The experiment was conducted during the *rabi* seasons of 2022 -23 and 2023-24 to evaluate the combined effect of CA, drip fertigation and nitrogen levels on succeeding maize crop in the RM system. Maize was sown in the first fortnight of November using a ZT seed drill, with 30 % of rice residues left over in the field, estimated on a dry weight basis. The hybrid maize variety P-3355 (140-150 days maturity period during *rabi* season) was used for the experiment. The seeds were sown at a rate of 20 kg ha^{-1}, with a spacing of 60 cm × 20 cm. The experiment was conducted in a Randomized Complete Block Design (RCBD), comprising 9 treatment combinations with three replications. Each experimental plot measured 35 m^2 (7 m × 5 m) and a 2.5 m wide irrigation channel was provided between them. The detailed description of the treatments is provided in the Table 1. The recommended dose of fertiliser was 120:60:40 N, P_2O_5, K_2O. The full dose of P_2O_5, 50 % of K_2O and 30 % nitrogen was applied as a basal, uniformly across all N management treatments. The remaining nitrogen was supplemented in three and five equal splits at critical stages of maize in flooded and drip fertigated treatments, respectively. Whereas the remaining 50 % K_2O was applied at the grain filling stage in all the treatments. Irrigation was given at 50 % depletion of available water, sensing through a pre-installed PR2 soil moisture profile probe (Delta-T Devices, UK). In the SD and SSD, laterals with an inner diameter of 16 mm were installed at a 60 cm spacing. In the SSD, laterals were buried at a 10 cm depth, parallel to the crop rows. The in-line emitters spaced 30 cm apart, discharge water at a rate of 2.0 litre hr^{-1}. Nitrogen was fertigated using a venturi meter with the desired injection rate.

Measurement of growth and yield attributes of maize

After crop establishment, 1 m row length was marked at the 3rd row on both sides of each plot tangentially for recording biometric observations. Plant height was measured from five plants at the extremes of the marked row at periodic intervals. Similarly, from the 2nd row (both sides of the plot), one plant was selected randomly from either side, was clipped from the ground surface using a sickle for dry matter accumulation. The samples were air dried for 2-3 days and then placed in an oven for complete drying by maintaining a temperature of 65 °C. Once the sample weight became constant it was recorded and expressed in terms of gm p $lant^{-1}$. ACCUPAR LP-80, a hand-held ceptometer was used to measure LAI and fraction of Photosynthetically Active Radiation (PAR), at 30-day intervals. At physiological maturity, cobs in an area of 1.0 m^2 were counted (from three randomly selected spots in each plot), averaged and converted to number of cobs ha^{-1}. Similarly, five cobs were selected randomly from each plot to take the yield attribute readings like cob length, cob girth, number of grains per row and number of grains per cob. After drying and cleaning, a representative grain sample from each plot was used to measure the 100-grain weight. The crop was manually harvested, leaving three border rows on either side and 0.5 meters from both ends unharvested to minimise border effects and ensure accurate yield estimation from central area. This is a standard practice in field experiments to avoid variability, resulting in a net plot size of 10 m^2. The total harvested produce, including grain, stover, husk and stalk, was weighed after sun/air drying and expressed as biological yield in tons per hectare (t ha^{-1}). After manual shelling, maize grains were collected, oven-dried at 65 to 70 °C for 48 hours and then weighed to determine grain yield, adjusted to a moisture content of 14 % and expressed in t ha^{-1}. The harvested stalk was sun-dried, weighed and similarly expressed in t ha^{-1}. The Harvest Index (HI) was calculated by dividing the economic yield (grain yield) by the biological yield (total produce) and expressed as a percentage (Eqn. 1).

$$HI = \frac{\text{Economic yield}}{\text{Biological yield}} \times 100 \quad \text{(Eqn. 1)}$$

Statistical analysis

The Analysis of Variance (ANOVA) was built using the agricolae package in R software. Differences between treatment means were assessed through the least significant difference test at $P<0.05$ significance level (21). Additionally, all visual representations were done using R software (22).

Results

Growth attributes

No significant differences in plant height were observed at 30 DAS among the treatments. However, by 60 DAS, ZTM-DSR-SSD-100N (79.3 cm) showed significantly greater plant height compared to other treatments (Table 2). This advantage was maintained throughout the crop growth, with ZTM-DSR-SSD-100N achieving the maximum plant height of 213.7 cm at harvest, which was approximately 13.9 % taller than the lowest-performing treatment, CTM-PTR-100N (187.6 cm). This was followed closely by ZTM-DSR-SD-100N (213.3 cm) and ZTM-DSR-SSD-75 N (206.2 cm). Similarly, the ZTM-DSR-SD-100 N treatment (213.3 cm) performed comparably, suggesting the role of split nitrogen applications through fertigation in enhancing plant height. Dry matter

Table 1. Treatment details

Treatment	Description	Abbreviation
T1	Zero-Tilled Maize (ZTM) followed by DSR with flood irrigation and 75 % RDN	ZTM-DSR-F-75N
T2	ZTM followed by DSR with flood irrigation and 100 % RDN	ZTM-DSR-F-100N
T3	ZTM followed by DSR with surface drip fertigation (SD) and 75 % RDN	ZTM-DSR-SD-75N
T4	ZTM followed by DSR with SD and 100 % RDN	ZTM-DSR-SD-100N
T5	ZTM followed by DSR with subsurface drip fertigation (SSD) and 75 % RDN	ZTM-DSR-SSD-75N
T6	ZTM followed by DSR with SSD and 100 % RDN	ZTM-DSR-SSD-100N
T7	ZTM followed by puddled transplanted rice (PTR) with flood irrigation and 75 % RDN	ZTM-PTR-75N
T8	ZTM followed by PTR with flood irrigation and 100 % RDN	ZTM-PTR-100N
T9	Conventional Tilled Maize (CTM) followed by PTR with 100 % RDN (farmer's practice)	CTM-PTR-100N

Table 2. Effect of different crop establishment techniques, irrigation methods and nitrogen levels on growth attributes of maize (2-year mean basis)

Treatments	Plant height (cm)				Dry matter accumulation (g plant^{-1})				LAI			
	30 DAS	60 DAS	90 DAS	At harvest	30 DAS	60 DAS	90 DAS	120 DAS	30 DAS	60 DAS	90 DAS	At harvest
ZTM-DSR-F-75N	35.7 ± 0.85	72.8 ± 0.64	138.2 ± 1.89	199.7 ± 4.25	19.7 ± 0.24	63.9 ± 0.46	173.7 ± 2.16	268.3 ± 2.93	1.22 ± 0.02	2.45 ± 0.02	5.64 ± 0.12	4.92 ± 0.01
ZTM-DSR-F-100N	36.4 ± 0.89	77 ± 1.36	140.7 ± 1.1	202.2 ± 2.74	19.3 ± 0.21	68.9 ± 0.82	191.6 ± 3.89	281.7 ± 6.45	1.15 ± 0.01	2.76 ± 0.04	6.62 ± 0.08	5.25 ± 0.07
ZTM-DSR-SD-75N	35.5 ± 0.11	76.1 ± 0.24	147.5 ± 0.08	205.4 ± 4.7	16.9 ± 0.38	66 ± 0.93	165.3 ± 3.27	276.5 ± 1.73	1.19 ± 0.02	2.59 ± 0.02	6.11 ± 0.1	5.19 ± 0.01
ZTM-DSR-SD-100N	39.5 ± 0.72	78.9 ± 1.19	145.2 ± 1.21	213.3 ± 2.89	18.9 ± 0.17	64.7 ± 1.18	196.8 ± 1.95	310.3 ± 2.75	1.25 ± 0.01	2.9 ± 0.05	6.4 ± 0.06	5.17 ± 0.03
ZTM-DSR-SSD-75N	39.1 ± 0.71	80 ± 0.96	149.9 ± 3.43	206.2 ± 2.15	20.3 ± 0.3	73.8 ± 0.19	192.5 ± 2.2	298.5 ± 0.93	1.12 ± 0.02	2.78 ± 0.01	6.25 ± 0.01	5.2 ± 0.01
ZTM-DSR-SSD-100N	43.8 ± 0.91	79.3 ± 2.02	154.7 ± 0.32	213.7 ± 1	22.9 ± 0.05	71 ± 0.78	223.3 ± 1.16	316 ± 3.29	1.15 ± 0.02	2.97 ± 0.02	6.74 ± 0.04	5.36 ± 0.11
ZTM-PTR-75N	32.2 ± 0.22	70.4 ± 0.44	136.4 ± 1.85	195.9 ± 2.55	17.5 ± 0.25	53.8 ± 1.2	162.2 ± 1.52	249.4 ± 1.95	1.03 ± 0.02	2.46 ± 0.06	5.58 ± 0.06	4.66 ± 0.1
ZTM-PTR-100N	38.3 ± 0.4	72 ± 0.75	139.6 ± 3.12	197.7 ± 0.51	16.7 ± 0.09	63.9 ± 0.4	186.1 ± 2.81	251.3 ± 4.71	1.1 ± 0.01	2.62 ± 0.03	6.43 ± 0.1	5.04 ± 0.06
CTM-PTR-100N	25.2 ± 0.1	64.8 ± 1.45	128.8 ± 2.28	187.6 ± 3.91	18.4 ± 0.42	56.9 ± 0.8	175.2 ± 3.1	234.2 ± 5	0.95 ± 0.01	2.5 ± 0.06	5.56 ± 0.1	4.8 ± 0.03

Values represent mean ± Standard Error (SE) based on three replications

accumulation increased consistently with higher nitrogen input and improved irrigation practices. At harvest, ZTM-DSR-SSD-100N achieved the highest dry matter accumulation (316 g plant^{-1}), representing a 35 % increase compared to CTM-PTR -100 N (234.2 g plant^{-1}), (Table 2). Similarly, the ZTM-DSR-F-100 N treatment (281.7 g plant^{-1}) outperformed its lower-nitrogen counterpart, ZTM-DSR-F-75 N (268.3 g m^{-2}), by approximately 5 %. The LAI trends mirrored those of dry matter accumulation, with ZTM-DSR-SSD-100 N recording the highest LAI of 6.74 at 90 DAS, approximately 21 % greater than the lowest-performing treatment, CTM-PTR-100 N (5.56). At harvest, the superior canopy growth of ZTM-DSR-SSD-100 N (LAI = 5.36) was evident, while CTM-PTR-100 N and ZTM-PTR-75 N recorded lower LAI values (4.80 and 4.66, respectively).

Yield attributes

The number of cobs per hectare varied significantly, with ZTM -DSR-SSD-100 N recording the highest value (72.18 cobs ha^{-1}), a 10.1 % increase compared to CTM-PTR-100 N (65.56 cobs ha^{-1}). Cob length and girth were significantly higher under ZTM-DSR-SSD-100 N (19.77 cm and 18.01 cm) compared to ZTM-PTR-75 N (17.86 cm and 15.18 cm), representing 11.6 % and 18.7 % increases, respectively (Table 3). The highest grains per cob (559.94 grains) and test weight (24.37 g) were recorded in ZTM-DSR-SSD-100 N, which outperformed ZTM-PTR-75N by 15 % and 10.4 %, respectively.

Grain, straw and biological yield

The grain, straw and biological yields of maize were significantly influenced by different crop establishment techniques, irrigation methods and nitrogen doses (Fig. 2). The highest yields were recorded under the ZTM-DSR-SSD-100 N treatment, with a grain yield of 7.43 t ha^{-1}, straw yield of 10.16 t ha^{-1} and biological yield of 19.43 t ha^{-1}, outperforming all other treatments (Fig. 2). The ZTM-DSR-SD-100 N treatment also performed well, achieving a comparable grain yield of 7.32 t ha^{-1} and biological yield of 19.14 t ha^{-1}. In contrast, the lowest yields were observed in the ZTM-PTR-75 N treatment, with grain, straw and biological yields of 5.82 t ha^{-1}, 8.45 t ha^{-1} and 15.47 t ha^{-1}, respectively. The grain and straw yields of ZTM-DSR-SSD-100 N were 27.6 % and 20.2 % higher, respectively, compared to the puddled system under ZTM-PTR-75 N. The harvest index, ranging from 36.91 % to 38.21 %, showed no significant differences across treatments, indicating consistent biomass partitioning efficiency (Table 3).

Correlation analysis

The correlation analysis presented in the correlation matrix (Fig. 3) provides valuable insights into the relationships among key growth, yield and yield attribute variables in maize. Significant positive correlations were observed between plant height at 90 DAS (PH-90), LAI at 90 DAS (LAI-90) and dry matter accumulation at 90 DAS (DM-90) with grain yield. Yield attributes such as the cob length (r^2 = 0.959***), grains per cob (r^2 = 0.924***) and test weight (r^2 = 0.908***) were also strongly correlated with grain yield. These strong correlations emphasize the contribution of specific yield components to overall productivity (Fig. 3).

Table 3. Effect of different crop establishment techniques, irrigation methods and nitrogen levels on yield attributes of maize (2-year mean basis)

Treatments	Cobs ha^{-1}	Cob length	Cob girth	Grains cob^{-1}	Test weight	Harvest index
ZTM-DSR-F-75N	69.34^{abc}	17.73^{b}	16.07^{ab}	498.30^{b}	22.87^{bcd}	37.11^{a}
ZTM-DSR-F-100N	70.85^{abc}	18.63^{ab}	16.19^{ab}	525.51^{ab}	23.02^{bc}	36.91^{a}
ZTM-DSR-SD-75N	68.57^{bcd}	18.61^{ab}	15.98^{ab}	517.88^{ab}	22.57^{cd}	37.31^{a}
ZTM-DSR-SD-100N	71.02^{ab}	19.27^{ab}	16.41^{ab}	528.30^{ab}	23.89^{a}	38.15^{a}
ZTM-DSR-SSD-75N	70.54^{abc}	19.17^{ab}	17.50^{ab}	534.89^{ab}	23.58^{ab}	37.57^{a}
ZTM-DSR-SSD-100N	72.18^{a}	19.77^{a}	18.01^{a}	559.94^{a}	24.37^{a}	38.21^{a}
ZTM-PTR-75N	67.89^{cd}	17.86^{ab}	15.18^{b}	487.02^{b}	22.08^{d}	37.56^{a}
ZTM-PTR-100N	68.75^{bc}	18.27^{ab}	15.87^{ab}	506.85^{ab}	23.02^{bc}	38.02^{a}
CTM-PTR-100N	65.56^{d}	17.72^{b}	17.45^{ab}	500.95^{b}	22.19^{cd}	37.81^{a}

Means with different letters are significantly different at the 5 % level (LSD, p ≤ 0.05)

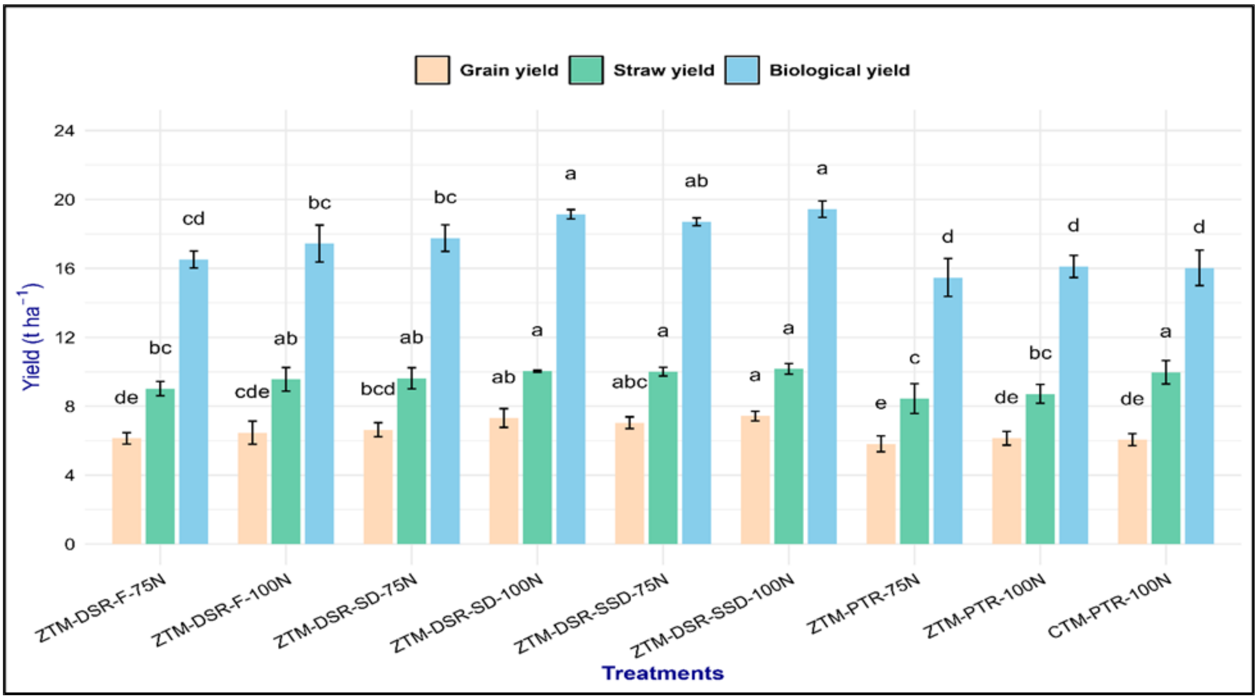

Fig. 2. Effect of different crop establishment techniques, irrigation methods and nitrogen levels on grain, straw and biological yield of maize (2-year mean basis). Means with different letters are significantly different at the 5 % level (LSD, p ≤ 0.05) and vertical bars indicate the Standard Deviation (SD) within each treatment.

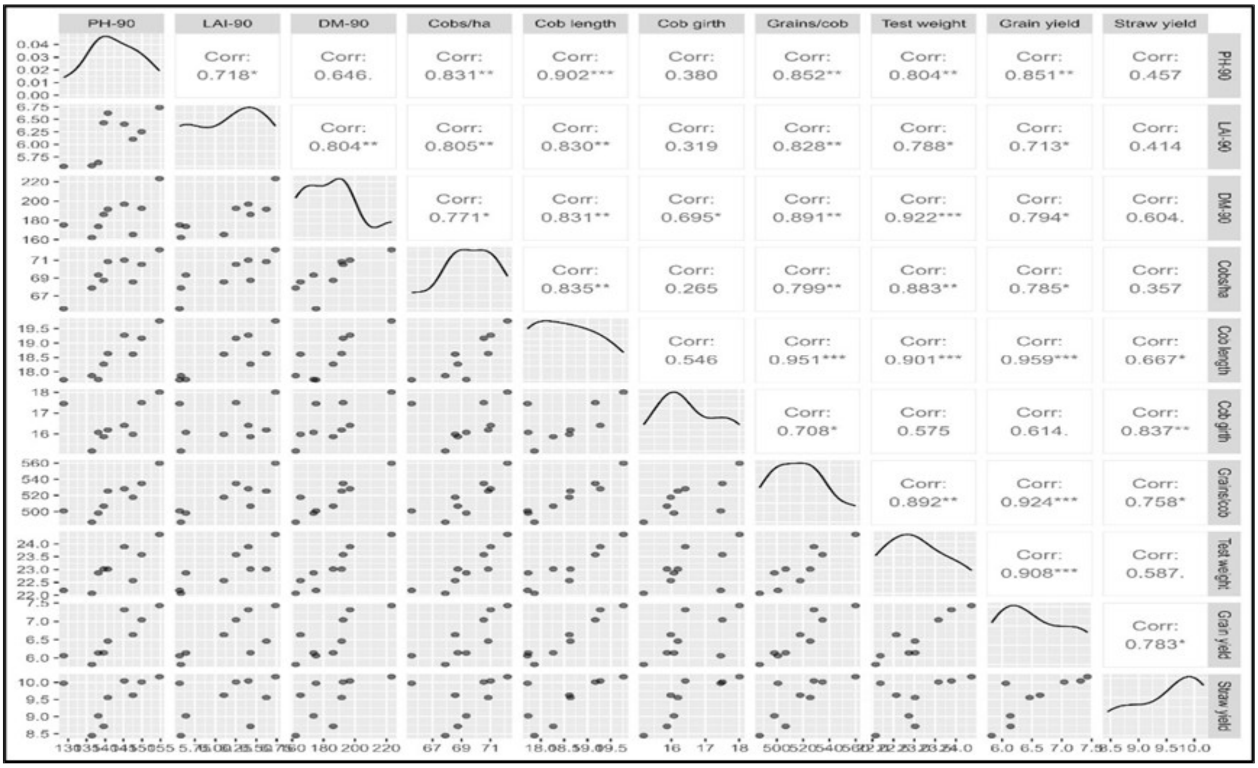

Fig. 3. Correlation between the growth attributes (plant height, LAI and dry matter accumulation at 90 DAS), yield attributes (cobs ha^{-1}, cob length, cob girth, grains cob^{-1}, test weight), grain yield and straw yield of maize.

Discussion

The growth and yield responses observed in this study highlight the importance of improved crop establishment techniques, water management practices and optimal nitrogen application in maximizing maize productivity under conservation agriculture systems (23). The significantly higher plant height and dry matter accumulation observed under ZTM -DSR-SSD-100 N compared to other treatments underscore the benefits of adopting zero tillage and sub-surface drip fertigation, leading to improved soil moisture management and better porosity (23, 24). The maximum plant height achieved under ZTM-DSR-SSD-100 N at harvest indicates that these practices foster superior vegetative growth, likely due to improved nutrient availability and soil moisture regime (25). Similarly, better root aeration and nutrient availability under ZTM-DSR-SSD-100 N, also foster greater photosynthate production and better growth attributes, because the improved root conditions enhance water and nutrient uptake, which supports greater chlorophyll synthesis and stomatal conductance (26). On the contrary, maize in conventional PTR systems showed a significant reduction in plant height, primarily due to puddling-induced root stress and reduced oxygen availability (8, 25) Further, the trends in LAI at 90 DAS and at harvest reflect enhanced canopy structure and photosynthetic potential under ZTM-DSR-SSD-100 N, supporting previous findings that link higher LAI with better radiation interception and assimilation efficiency (26). Fig. 4 highlights a positive linear relationship between dry matter accumulation and LAI and explains the crucial interplay between biomass production and canopy growth.

The significantly higher number of cobs per hectare, cob length, girth, grains per cob and test weight under ZTM-DSR-SSD-100 N demonstrate the efficient water-nutrient synergy, improving yield components (12, 27). The substantial increases in cob length (11.6 %) and girth (18.7 %) under ZTM-DSR-SSD-100 N compared to the conventional puddled transplanted system (CTM-PTR-100N) highlight the positive influence of conservation tillage on reproductive growth. Furthermore, the significantly higher grains per cob and test weight suggest that the integration of these practices enhances grain-filling processes, resulting in improved sink capacity and grain quality (14, 28). In contrast the CTM-PTR-100 N system suffered from waterlogging stress due to the previous puddling effect, which resulted in poor soil aeration, affecting the crop performance (29).

The significantly higher grain, straw and biological yields recorded under ZTM-DSR-SSD-100 N, followed closely by ZTM-DSR-SD-100 N, reinforce the synergistic benefits of zero tillage and optimal nitrogen management in achieving sustainable maize productivity (30, 31). The yield advantages observed in these treatments align with the hypothesis that zero tillage, coupled with split nitrogen application through fertigation and improved soil moisture regimes, optimizes resource use efficiency, rhizosphere environment and minimizes nutrient losses (32). The 27.6 % and 20.2 % increases in grain and straw yields, respectively, compared to the lowest-performing treatment (ZTM-PTR-75 N), indicate the limitations of conventional puddled systems in harnessing maize's yield potential (12). Additionally, the consistent harvest index across treatments suggests that while biomass partitioning was unaffected, the significant differences in total biomass production highlight the superior resource capture and utilization under conservation practices.

The correlation analysis reinforces these findings, indicating that growth attributes such as plant height, LAI and dry matter at 90 DAS, along with yield attributes like cobs per hectare, cob size, grains per cob and test weight, are strongly associated with grain yield (9) (Fig. 4). Notably, cob length (~0.90), grains per cob (~0.92) and test weight (~0.91) showed the highest influence, underscoring their critical role in enhancing resource use efficiency and yield formation in maize. The results provide strong evidence for adopting ZTM-DSR-SSD-100 N as a viable conservation agriculture practice to enhance maize productivity. Similarly, many studies highlighted the importance of advanced irrigation and nutrient management techniques in achieving sustainable yield improvements (9, 13, 14, 16, 32).

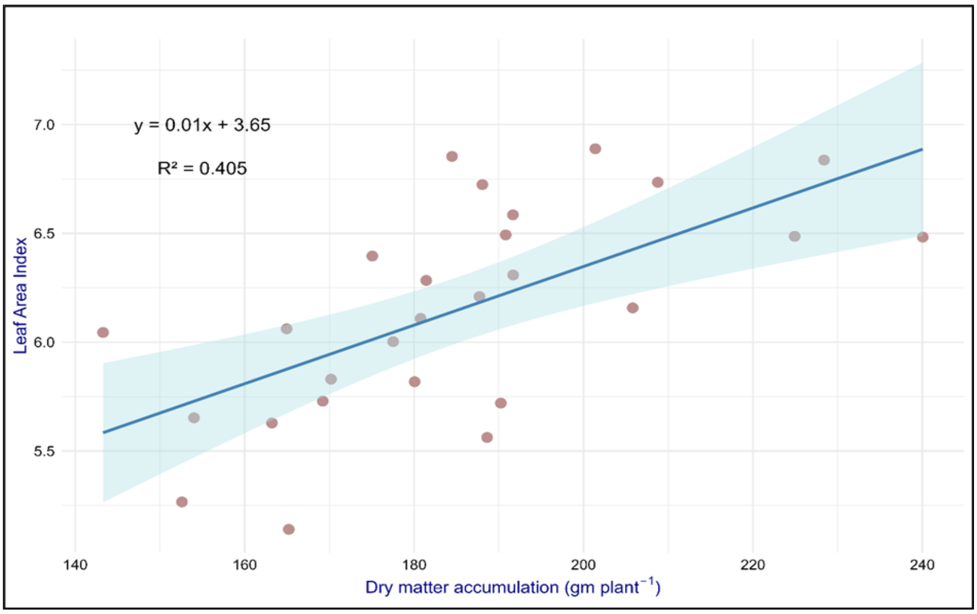

Fig. 4. The relationship between the LAI and dry matter accumulation of maize crop at 90 days after sowing. The shaded band in the graph represents the confidence interval at 95 % significance.

Conclusion

The study concludes that CA practices, DSR and drip fertigation combined with optimum resource management, offer significant advantages in enhancing maize productivity in RM system. These practices improve water and nitrogen use efficiency, reduce nutrient losses and foster better root growth and nutrient uptake, as reflected in higher yields and superior yield attributes such as cob length, grains per cob and test weight. The Correlation analysis further emphasizes the strong relationship between growth and yield attributes and grain yield, underscoring the importance of efficient resource optimization. In contrast maize grown under conventional puddled systems underperform due to waterlogging stress and reduced resource efficiency. SSD and SD emerge as sustainable alternatives, supporting efficient resource utilization and ensuring stable yields. These findings advocate for scaling up the adoption of CA practices, including DSR and SSD to achieve sustainable intensification of maize under RM cropping system, particularly in the eastern IGPs of India.

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Authors' contributions

KSR, CMP and PP did conceptualization. KSR, CMP, PP, KP, SK designed the experiments. KSR, executed the field/lab based work and collected the data. KSR, SLJ, DKS, DRS, RP performed data analysis. KSR, RD, GSR, VK interpretation. KP, AS, AS, SB prepared the manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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