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Enhancing productivity, economics and energy efficiency through precision nitrogen and water management in conservation agriculture-based maize (*Zea mays*) in the Indo-Gangetic Plains

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Maize (*Zea mays* L.) cultivation in India is significantly contributing to food security, livestock and poultry feed (Malhotra 2017). Nitrogen (N) is an essential component of amino acids, proteins and chlorophyll, and enhances photosynthesis (Marschner 2011). Optimal crop yields rely on sufficient N availability and imbalanced fertilization leads to environmental risks, elevated cultivation costs, and energy inputs. To address these challenges, real time N management is crucial (Singh 2014, Singh *et al.* 2021). The use of Green Seeker^{TM}, a handheld optical sensor based on the Normalized Difference Vegetation Index, has shown promise in real-time N management (Singh 2014, Singh *et al.* 2016). Precision irrigation emerges as a sustainable solution, offering efficient water and energy use, minimizing wastage, and optimizing crop yield (Humphreys *et al.* 2010, Kumar *et al.* 2023).

Conservation agriculture (CA) use minimal soil disturbance, crop residue retention and legume diversification, enhances biodiversity, sequesters carbon, and promotes sustainable agriculture (Singh *et al.* 2016). While many researchers have found positive impacts of conservation agriculture, precision water and N management in individual studies or with two factors (Singh *et al.* 2016, Jat *et al.* 2020), comprehensive and/or integrated research on all three factors and their combined impact on productivity, economics, and energy efficiency is limited. Hence, present study was carried out during 2019 on enhancing productivity, economics and energy efficiency through integration of precision N and water management in CA based maize. This study aims to bridge this gap by providing a holistic understanding of the synergistic effects.

An experiment was conducted during the rainy (*kharif*) season of 2019 at the research farm of ICAR-Indian Agricultural Research Institute, New Delhi (28° 38' 23"N, 77° 09' 27"E and an elevation of 228.61 meters amsl). The experimental site is situated in the intensively cultivated areas of the western Indo-Gangetic Plains with an average annual rainfall of 714 mm, of which 75% is received during the monsoon season. Delhi's climate is characterized as semi-arid, sub-tropical, with hot dry summers and cold winters, with a mean annual temperature of 25°C. The mean maximum temperature of 45°C occurs in June, and the mean minimum temperature is recorded in January. The soil at the experimental site was sandy loam with a neutral to alkaline reaction. Key soil properties include oxidizable organic carbon at 0.43%, available N at 247 kg/ha, 0.5M $NAHCO_3$ extractable phosphorus at 14 kg/ha, and 1N NH_4 OAC extractable potassium at 253 kg/ha. The experimental design followed a split-split plot, with 2 crop establishment techniques (CET), viz. conservation agriculture (CA); and conventional tillage (CT) in the main plots; 3 irrigation regimes (IR) in subplots, viz. irrigation at critical crop growth stages (W_1); 25% depletion in available soil moisture (DASM) (W_2); and 50% DASM (W_3). In the sub-sub plots, 4 N scheduling options, viz. No-N (Control); conventional N application at 150 kg/ha at basal + 2 splits (N_1); 50% basal N + remaining guided by GreenSeeker™ (N_2); and 75% basal N + remaining guided by GreenSeeker™ (N_3) were taken. N doses were applied according to the treatment specifications. The GreenSeeker^{TM} system, an optical sensor in precision agriculture, assesses crop health and real-time nitrogen status. It measures light reflected by the crop canopy, specifically calculating the Normalized Difference Vegetation Index (NDVI) with the formula:

$$NDVI = (NIR - Red)/(NIR + Red)$$

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The amount of N applied based on GreenSeeker[TM] readings was calculated following the method given by Raun *et al.* (2002). Irrigation was managed based on treatment requirements using evaporation and soil moisture data. Each treatment received a predetermined amount of irrigation water through a water channel, measured using a water meter. Standard methods were employed to measure the cost of cultivation and grain yield. The net energy was calculated by subtracting the energy input from the energy output (MJ/ha). The energy ratio was determined by dividing the output energy by the input energy, while energy productivity was computed as the crop economic yield per hectare divided by the energy input. Energy equivalents and Statistical analysis were done as per Devasenapathy *et al.* (2009) and Gomez and Gomez (1984) respectively.

Grain yield of maize was significantly differed due to different CET, irrigation regimes and N scheduling (Fig. 1). The highest grain yield of maize was recorded under CA, which was 13.3% higher over CT. The increment in yield under CA over CT has been also reported by Jat *et al.* (2013) and Singh *et al.* (2016). This increment in yield was owing to the nutrient release from residue decomposition of previous greengram crop, higher water holding capacity and microbial population, resulted in improved uptake of nutrients (Kumar *et al.* 2022). The application of N in the form of 75% at basal + remaining as per GreenSeeker[TM] (N_3) provided highest grain yield, followed by 50% basal + GS; conventional basal + 2 splits; and control. Optimized nutrient supply as per the crop demand and sufficient moisture availability during crop growth, leads efficient utilization of indigenous nutrient supply. In different irrigation regimes, the highest maize grain yield was recorded under W_2 (Irrigation at 25% DASM). This increment in yield due to adequate amount of water present in rhizosphere throughout the growing period enhanced the nutrient uptake, transpiration, and photosynthesis, which led to the improvement in growth parameters and yield attributes of maize (Kumar *et al.* 2021). The maximum grain yield of maize (6.36 t/ha) was found with irrigation at W_2 under CA. The average grain yield under CA (5.96 t/ha) across the different IR was 13.3% higher over CT (5.26 t/ha). The maximum grain yield of maize (6.36 t/ha) was found with irrigation at W_2 under N_3. The enhancement in the maize grain yield due to site specific nitrogen management (SSNM) and its splits application has also been reported by many workers (Singh *et al.* 2015).

The cost of cultivation incurred under CA was 30,421 ₹/ha, which was 23.7% lesser than CT. The gross returns under CA and CT were ₹1,16,007 and ₹1,01,028/ha with a net benefit ratio of 2.78 and 1.48, respectively. The net returns obtained under CA were ₹85,586/ha which showed an additional income of ₹22,208/ha (Fig. 2). The lower cost and higher return in CA based grown maize over CT were also suggested by Jat *et al.* (2013) and Singh *et al.* (2016). The highest gross and net return under CA was attributed to the higher yield with lesser cost. With different irrigation regimes, the maximum cost, gross return, net return and net benefit cost ratio were observed under W_2, where water was applied most frequently as per treatment (Fig. 2). But, since it enhanced the cost and the yield was higher, therefore, the GR, NR and in N scheduling N_3 gave best result, viz. the highest gross and net returns (₹13,497/ha and ₹97,927/ha) as well as net B:C ratio was registered under N_3 (Fig. 2). In comparison to W_1, an additional cost of ₹1976/ha was incurred under W_2, whereas irrigating field at 50% DASM, (W_3) saves ₹471/ha over W_1. On the other hand, additional monitory gain of ₹15492/ha was recorded with W_2 over W_1, but irrigation as per W_3 regime significantly reduced net income by ~₹4109/ha (Fig. 2). The application of N as per N_2 and N_3 had additional returns of ₹4,330/ha and ₹10,641/ha over conventional 03 splits (N_1). Enhancing crop yield, economics, and resource efficiency have also been reported by Singh *et al.* (2015).

The total energy used under CA was 10,531 MJ/ha. Growing maize under CA saved 33.1% energy as compared to CT (14,022 MJ/ha) (Table 1). The energy output under CA was 2,07,669 MJ/ha and under CT, it was 1,82,546 MJ/ha. In term of energy output, CA had 13.8% higher energy output over CT (1,82,546 MJ/ha). The energy ratio in

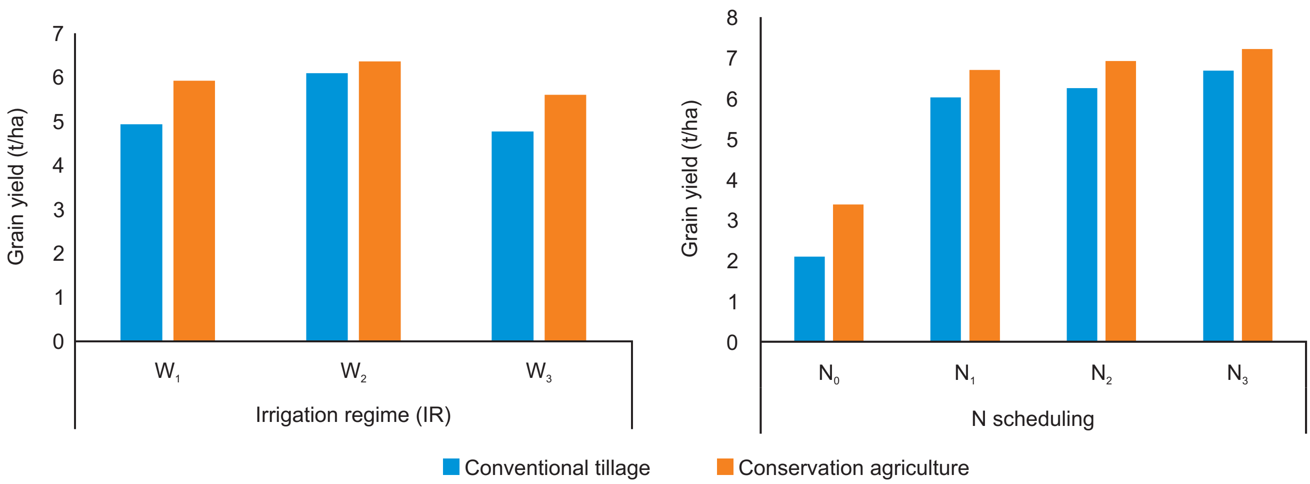

Fig. 1 Interactive effect of precision nitrogen and water management on productivity of maize grown under conservation agriculture. Refer to the methodology for treatment details.

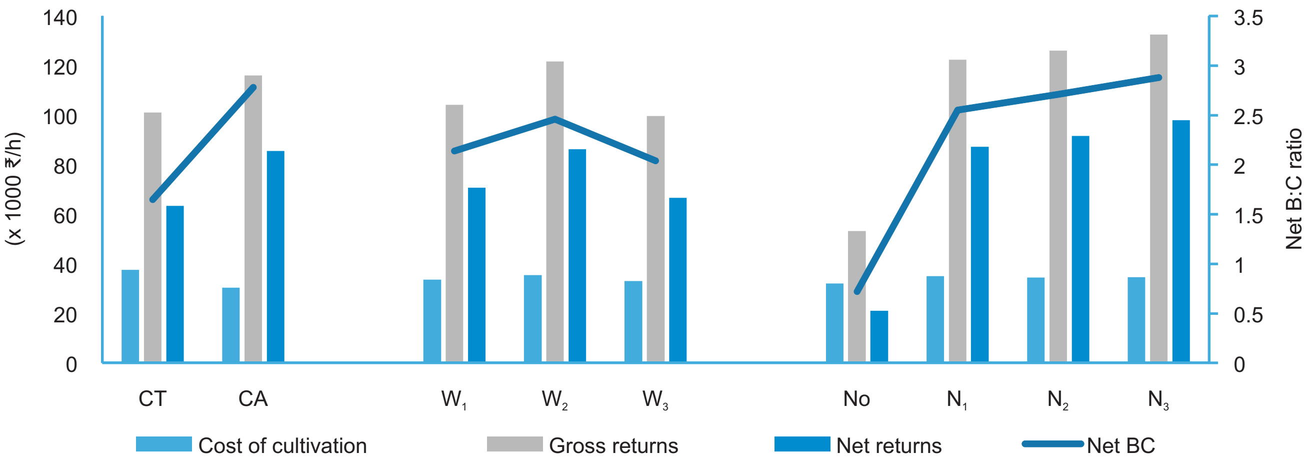

Fig. 2 Interactive effect of precision nitrogen and water management on economics of maize grown under conservation agriculture. Refer to the methodology for treatment details.

CA and CT was 21.4 and 12.7, respectively, and the net energy saving in CA over CT was 16.9%. In different IR, the maximum amount of energy was used in W_2, followed by W_1 and W_3, respectively. The energy requirement under W_2 and in N_3 was significantly higher over other options. The energy input ranged between 11,919 to 12,983 MJ/ha and 5,830 to 14,920 MJ/ha under different irrigation regime and N scheduling options, respectively. Among different CET, irrigation regime and N scheduling combinations, energy parameters, viz. energy output, energy ratio, energy productivity and net energy saving were higher under CA with W_2 and N_3 treatments over other treatment studied. On the other hand, the lowest energy output, energy productivity energy ratio, and net energy saving were recorded with CT with W_1 and no-N treatments. The energy ratio under different IR was lowest with W_3. Lower energy used and higher energy use efficiency under CA over CT has also been reported by Sidhu and Duiker *et al.* (2006).

Table 1 Interactive effect of precision nitrogen and water management on energy equivalents of maize grown under conservation agriculture

Treatment	Energy input (MJ/ha)	Energy output (MJ/ha)	Energy ratio	Net energy saving (MJ/ha)	Energy productivity (kg/MJ)
Crop establishment techniques					
CT	14022	182546	12.71	168524	0.36
CA	10531	207669	21.43	197138	0.61
SEm±	-	609	0.06	609	0.01
LSD (*P*=0.05)	-	3708	0.38	3708	0.03
Irrigation regime					
W_1	11928	188227	17.39	176299	0.49
W_2	12983	215501	17.69	202518	0.52
W_3	11919	181595	16.12	169677	0.45
SEm±	-	1099	0.13	1099	0.004
LSD (*P*=0.05)	-	3584	0.42	3584	0.014
N scheduling					
N_0	5830	102324	20.33	96494	0.55
N_1	14920	223271	15.22	208351	0.43
N_2	14031	224005	16.30	209973	0.48
N_3	14324	230831	16.42	216507	0.49
SEm±	-	2231	0.21	2231	0.01
LSD (*P* =0.05)	-	6399	0.60	6399	0.02

Refer to the methodology for treatment details

SUMMARY

Present study focuses on improving maize productivity, economics, and energy efficiency in the Indo-Gangetic Plains through the integration of CA, precision nitrogen and water management. Maize grain yield significantly differed among treatments, with CA outperforming CT by 13.3%, recording the highest yield with optimal N application (N_3) and irrigation at 25% DASM. The CA incurred 23.7% lower cultivation costs (₹30,421/ha) compared to CT. Gross returns and net returns were higher under CA (₹1,16,007/ha and ₹85,586/ha) with a net benefit ratio of 2.78, showcasing its economic viability. Energy efficiency was a crucial aspect considered, with CA proving to be 33.1% more energy-efficient than CT. In different irrigation regimes, CA with W_2 treatment exhibited superior energy parameters. The study also highlighted the significance of optimal N scheduling (N_3) in achieving higher economic returns (₹97,927/ha) compared to conventional N splits (N_1) and its integration. The most effective integration involved combining CA with precision N management (75% basal, GreenSeekerTM-guided top dressing) and irrigation at 25% DASM, resulting in higher grain yield (7.21 t/ha), gross returns (₹132,497/ha), and impressive energy output (230,831 MJ/ha). In conclusion, CA, especially when combined with optimal irrigation and nitrogen management, not only enhances maize yield and economic returns but also proves to be more energy-efficient, promoting sustainable and resource-efficient agricultural practices. The study recommends this integrated approach for enhancing maize productivity, energy efficiency and economic returns.

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