Maximizing Growth and Yield Components: Comparative Analysis of Surface and Subsurface Drip Irrigation in Intensively Farmed Rice Systems

Abstract

Water scarcity, encompassing issues such as water shortage, water stress, and deficits, is a significant issue in arid and semi-arid areas around the world. To address water scarcity, micro irrigation methods such as surface and subsurface drip systems were often recommended for their excellent uniformity and high efficiency. The study results indicated that direct seeded rice followed by zero-til wheat with subsurface drip irrigation at 60-cm spacing increased grain yield of rice by 6.52% and 18.82%, straw yield by 7.68% and 13.45% and total biomass by 8.30% and 9.73%, respectively during 2020 and 2021 compared to puddled transplanted rice followed by zero-till wheat. The findings indicated that the direct-seeded rice followed by zero-till wheat system emerged as a viable solution for sustainable intensification and efficient use of inputs such as water and energy. This approach has significant potential for widespread adoption across larger regions.

Key words: Direct seeded rice, sub surface drip irrigation, puddled transplanted rice, zero-til wheat

Introduction

Rice is a vital staple crop, underpinning the food security of over half the global population. Fluctuations in rice production can have profound effects on food security and contribute to significant price volatility in the international market. These production variations not only affect local economies and food availability but also influence global economic stability and commodity price inflation. Therefore, enhancing the stability and efficiency of rice production systems is essential for ensuring both food security and market stability worldwide. To address the needs of a growing global population, it is crucial to sustainably increase rice yields and productivity while minimizing the use of inputs and reducing the strain on natural resources. This challenge is significant for rice growing countries around the world.

Comment [sv1]: across the world

The rice-wheat (RW) cropping system relies heavily on traditional practices such as puddling and manual transplanting of rice seedlings. This method involves extensive dry and wet tillage operations and consumes a substantial amount of water. Puddled transplanted rice (PTR) requires between 900 and 2,500 mm of water from land preparation through to harvest (1), which contributes to excessive groundwater extraction and a rapid decline in the water table (2). Furthermore, the intensive tillage associated with this practice leads to significant soil degradation (3 and 4), making the RW cropping system increasingly unsustainable. Traditional irrigation techniques for rice cultivation involve flooding paddy fields with standing water ranging from 2 to 5 cm deep throughout various stages of crop growth (5).

Comment [sv2]: depth

To promote sustainable food security and protect groundwater resources, it is crucial to develop and implement alternative rice production systems that are both high-yielding and resource-efficient (6). Practices such as direct-seeded rice, drip irrigation, and irrigation scheduling based on soil matric potential are identified as sustainable and climate-smart approaches for enhancing agricultural productivity and resource management (7). Drip irrigation, which provides water slowly and frequently to maintain near-optimal soil moisture (8 and 9), has been shown to enhance plant growth and productivity (10). Adopting drip irrigation proved to be an effective solution for addressing water scarcity and enhancing water use efficiency (11). However, surface drip irrigation systems, with their laterals on the soil surface, hindered in-season field operations and constrained their adoption in conventional tillage-based rice production. Subsurface drip irrigation (SSD), in combination with conservation agriculture (CA), offered a promising solution to these issues (12 and 13).

Rice is conventionally grown under flooded conditions, but it can also be cultivated in unsaturated soils to reduce freshwater consumption. Studies have demonstrated that drip irrigation, which utilizes 50% less water, results in a 29% increase in rice yield compared to traditional dryland farming practices (14). Zero-till direct-seeded rice conserves more soil moisture compared to traditional puddled transplanting. This enhanced moisture retention supports better growth for subsequent crops and improves overall productivity (15). Drip irrigation has shown numerous benefits globally, primarily in the cultivation of vegetables, horticultural crops, and single field crops (16 and 17). However, its potential for addressing future water scarcity in rice-based multiple cropping systems has not been fully explored. This study aims to optimize irrigation practices to enhance crop yields, water productivity, and water savings in rice-wheat and rice-maize cropping systems. The research also seeks to compare the performance of drip irrigation with the conventional surface irrigation methods typically employed in these systems.

Materials and methods

This study forms part of an ongoing experiment evaluating the effectiveness of drip irrigation systems on the growth and productivity of direct-seeded rice within various cropping systems. The experiment takes place at the research farm of International Rice Research Institute (IRRI), South Asia Regional Centre, Varanasi during 2020-2021 and 2021-2022. The site, located at 25°18'N and 88°03'E and and its elevation of 128.93 metres meters above sea level and features a sub-humid climate with silty loam soil. In this study, direct-seeded rice was compared with puddled transplanted rice from July to November 2020, followed by wheat and maize were sown directly into the residue of the previous crops using a zero-till method .

Rice seeds were drilled in rows 30 cm apart at a rate of 20 kg/ha. Fertilizers were applied according to the recommended doses of 130 kg/ha of Di-ammonium phosphate, 210 kg/ha of urea, and 67 kg/ha of muriate of potash for rice and wheat while 130 kg/ha of Di-ammonium phosphate, 275 kg/ha of urea, and 67 kg/ha of muriate of potash for maize.

Comment [sv3]: viz.,

Weeds were manually uprooted as they appeared in the experimental field. The crops were harvested from the base of the stems, with the net plot harvest kept separate from the border areas. The harvested material was sun-dried for 4–5 days, then weighed and threshed to estimate the grain and straw yields.

The experiment was laid out in Randomized Complete Block Design with eight distinct treatments. The treatments included: T_1- Rice (Direct Seeded Rice, DSR) followed by Zero-Till (ZT) wheat with surface drip irrigation, with laterals placed 60 cm apart; T_2 - Rice (DSR) followed by ZT wheat with sub-surface drip irrigation, with laterals placed 60 cm apart; T_3 -Rice (DSR) followed by ZT maize with surface drip irrigation, with laterals placed 60 cm apart; T_4 - Rice (DSR) followed by ZT maize with sub-surface drip irrigation, with laterals placed 60 cm apart; T_5 - Rice (DSR) followed by ZT wheat with flood irrigation applied at 10 kPa for rice and at critical growth stages for wheat; T_6 - Rice (DSR) followed by ZT maize with flood irrigation applied at 10 kPa for rice and at 35 kPa for maize; T_7 - Puddled transplanted rice followed by ZT wheat; and T_8 - Puddled transplanted rice followed by ZT maize.

~~At the time of sowing~~, five plants were randomly selected from each plot to record various growth and yield parameters, including plant population, plant height, number of tillers, number of panicles per square meter, panicle length, panicle weight, number of grains per panicle, 1000-grain weight, grain yield, and straw yield. The collected data were analyzed using Fisher’s analysis of variance technique, and differences among treatment means were assessed using a Randomized Block Design (RBD) test with a confidence level of 5%.

Results and discussion

Plant growth parameters

The effects of the various treatments on rice crop population and growth parameters recorded on the 20th and 60th days after sowing (DAS) was illustrated in Table 1. Drip and sub-surface irrigation practices, combined with the corresponding crop management strategies in various rice-based cropping systems, had a significant impact on growth parameters. The treatment T_1, which featured drip emitters, recorded the highest average plant population (37.78/ 1 m length of drip line) during 2020 and T_3 (40.67/1 m length of drip line), probably due to the more uniform water distribution provided to the seeds. The highest average plant height of 78.06 cm and 110.51 cm was recorded with the sub-surface drip irrigation practice as T_2 (Rice as direct seeding followed by zero til Wheat with SSDI at 60-cm spacing, and T_4 which achieved a height of 77.98 cm and 109.96 cm, ~~respectively~~ during 2020 and 2021, respectively. Similarly, the highest number of tillers per square meter was recorded under rice as direct seeding followed by ZT Wheat with SSDI at 60-cm spacing (491.98 and 566.66) and rice (DSR) followed by ZT Maize with SSDI at 60-cm spacing (485.4 and 557). The lowest plant heights and number of tillers m^{-2} were observed in the flooded irrigation methods for the rice-wheat cropping system (T_5 and T_6) and in the puddled transplanted rice treatments (T_7 and T_8) during both the years.

Among various advanced agronomical technologies aimed at conserving water and energy, direct seeding rice (DSR), mechanical transplanters for rice, no-till wheat cultivation, and happy seeder for wheat planting stand out. These innovative techniques are expected to significantly reduce unwanted irrigation water losses, particularly in areas facing water scarcity (18). Drip irrigation technology, by continuously providing soil moisture near the root zone throughout the growing period, promotes favorable crop growth and minimizes stress in the root zone, resulting in reduced irrigation requirements and improved ~~the~~ growth parameters. Subsurface drip irrigation minimized evaporation by keeping the soil surface dry and enhanced water use efficiency by delivering moisture directly to the root zone. This method promoted healthier crop growth, reduced weed growth, and lowered the risk of soil erosion. It also allowed for precise fertilizer application, making it an efficient and environmentally friendly irrigation method.

This finding aligns with (19) who reported that the sub-surface drip fertigation system (SSDF), with laterals spaced at 67.5 cm and installed at a depth of 15 cm, offers significant benefits in terms of water and energy savings. The SSDF system enhances nutrient use efficiency and increases net income within conservation agriculture (CA) based rice-wheat cropping systems in South Asia. Specifically, irrigation water savings ranged from 48-53% for rice and 42 -53% for wheat when using SSDF in combination with CA, compared to traditional flood irrigation. A similar improvement in water productivity was observed for both crops. This was further supported by (20) who recommended conservation agriculture-based sub-surface drip irrigation for its effectiveness in precise water utilization and in reducing unproductive water loss components such as evaporation and deep drainage.

Yield parameters

Table 2 illustrated the significant impact of direct-seeded rice using drip irrigation practices on various yield attributes. The results showed that emitters spaced 60 cm apart resulted in the highest number of panicles at maturity (586.0 and 595 per m²), the greatest number of filled grains per panicle (183.67 and 155.20), unfilled grains per panicle (39.13 and 33.14) and the longest panicle length (28.67 and 28.83 cm). Additionally, this setup recorded the lowest number of unfilled grains per panicle (39.13 and 33.136). These outcomes were observed for direct-seeded rice, followed by zero-till wheat with subsurface drip irrigation at 60-cm spacing (T_2), during both 2020 and 2021. This was followed by direct seeded rice *fb* zero til maize with sub surface drip irrigation at 60-cm spacing (T_4) which was about 579.0, 182.6, 38.96 and 28.60 during 2020 whereas 594.0, 154.93, 31.97 and 28.76 during 2021 in terms of highest number of panicles, greatest number of filled grains per panicle, number of unfilled grains per panicle and panicle length, respectively. As like growth parameters the lowest yield attributes were recorded in conventional flooded irrigation methods for the rice-wheat cropping system (T_5 and T_6) and in the puddled transplanted rice treatments (T_7 and T_8) during both the years.

Subsurface drip irrigation reduced evapotranspiration, enhanced crop water productivity, and improved irrigation water productivity, resulting in significantly higher yield attributes and biomass compared to both surface drip irrigation and flooded irrigation. Literature supported this, showing that under flooded irrigation conditions, direct-seeded rice (DSR) achieved greater production due to higher panicle numbers, increased 1,000-grain eight, and lower sterility percentages (21).

Table 1. Influence of growth parameters by surface and sub surface irrigation

	Treatments	**Initial Plant population (1 m row length)**		**Plant Height (cm)**		**No. of tillers (/m^2)**	
		20 DAS		**60 DAS**		**60 DAS**	
		2020	**2021**	**2020**	**2021**	**2020**	**2021**
T_1	**Rice (DSR) *fb* ZT Wheat with SDI at 60-cm spacing**	37.78	38.67	74.5^{ab}	100.00^{b}	462.45^{b}	489.33^{b}
T_2	**Rice (DSR) *fb* ZT Wheat with SSDI at 60-cm spacing**	34.78	34.67	78.06^{a}	110.51^{a}	491.98^{a}	566.66^{a}
T_3	**Rice (DSR) *fb* ZT Maize with SDI at 60-cm spacing**	35.56	40.67	74.23^{b}	97.78^{b}	460.71^{b}	483^{b}
T_4	**Rice (DSR) *fb* ZT Maize with SSDI at 60-cm spacing**	30.89	32.33	77.98^{a}	109.96^{a}	485.4^{a}	557^{a}
T_5	**Rice (DSR) *fb* ZT Wheat with Flood irrigation at 10 Kpa and critical growth stages for wheat**	36.89	36.33	69.9^{c}	86.94^{c}	434.43^{c}	403.33^{c}
T_6	**Rice (DSR) *fb* ZT Maize with Flood irrigation at 10 Kpa and 35 Kpa for Maize**	30.00	33.33	68.93^{c}	83.8^{c}	427.9^{c}	370^{c}
T_7	**PTR rice *fb* ZT wheat**	0.00	0.00	70.65^{c}	88.71^{c}	437.43^{c}	423^{c}
T_8	**PTR rice *fb* ZT Maize**	0.00	0.00	69.16^{c}	83.92^{c}	429.71^{c}	389^{c}
	SEm±	**-**	**-**	**1.14**	**1.99**	**7.42**	**18.07**
	CD (P = 0.05)	**-**	**-**	**3.46**	**6.04**	**22.52**	**54.81**

Additionally, zero-tillage direct-seeded rice (ZTDSR) provided the benefit of time savings, as it was harvested 7–10 days earlier and benefited the subsequent crop in the cycle (22). According to (19) who reported similar results in comparable ecological conditions with lateral spacings of 45–60 cm. This aligns with the findings of (23) who observed that sub-surface drip irrigation (SSDI) and flooded irrigation (FI) resulted in higher panicle numbers per lysimeter, more filled kernels, and heavier kernel weights, indicating uniform soil moisture availability throughout the growth period. SSDI produced greater aboveground biomass than FI, primarily due to a larger number of panicles and higher straw weight from the consistently wet subsurface soil during the vegetative growth period. Both FI and SSDI achieved high grain yields due to the highest spike weight and number. However, while SSDI had more spikes compared to FI, the spike weight was heavier in FI than in SSDI for wheat.

Grain yield and straw yield

The experimental results revealed that T_2 (Rice as direct seeded followed by zero-till wheat with subsurface drip irrigation at 60-cm spacing) achieved the highest rice grain yields of 6,997.85 kg/ha and 7,592.35 kg/ha, straw yields of 8,193 kg/ha and 9,081.66 kg/ha, 1,000-grain weight of 24.92 g and 26.47 g, and biomass yields of 15,304.24 kg/ha and 16,530.68 kg/ha during 2020 and 2021, respectively. This was followed by T_4 (Rice (DSR) *fb* ZT Maize with SSDI at 60-cm spacing). The lowest value was reported in both conventional rice transplanting cultivation and flooded irrigation method (Table 3). In 2020, Treatment T_2 yielded grain, straw, and total biomass amounts that were 6.52%, 7.68%, and 8.30% higher, respectively, compared to PTR rice followed by zero-till wheat (T_7). In 2021, these figures increased further, with T_2 showing 18.82% higher grain yield, 13.45% higher straw yield, and 9.73% higher total biomass compared to T_7. Similarly, during 2020, Treatment T_2 outperformed PTR rice followed by zero-till maize (T_8), with increases of 6.86% in grain yield, 8.67% in straw yield, and 8.54% in total biomass. By 2021, the differences were even more pronounced, with T_2 achieving 22.26% higher grain yield, 15.23% greater straw yield, and 11.84% more total biomass compared to T_8. In surface drip irrigation (SDI), soil moisture was quickly depleted due to soil evaporation, which restricted water uptake by roots and imposed severe physiological limitations, including damage to the photosynthetic system. This led to a shortened development period, impaired assimilate translocation, reduced carbon fixation, and diminished grain set. Consequently, frequent use of subsurface drip irrigation (SSDI) effectively reduces soil evaporation losses and enhances yield. This was further supported by the literature from (23).

Table 2. Effect of Drip irrigation system on yield attributes of DSR rice during 2020 and 2021

Treatments		Yield attributes							
		No. of panicles/m^{2}		Length of Panicle (cm)		No. of filled grains/Panicle		No. of unfilled grains/Panicle	
		2020	2021	2020	2021	2020	2021	2020	2021
T_1	**Rice (DSR) *fb* ZT Wheat with SDI at 60-cm spacing**	535.33^{b}	550.33^{b}	28.20^{ab}	28.20^{ab}	172.83^{b}	148.06^{b}	35.50^{b}	28.73^{b}
T_2	**Rice (DSR) *fb* ZT Wheat with SSDI at 60-cm spacing**	586.0^{a}	595.0^{a}	28.67^{ab}	28.83^{ab}	183.67^{a}	155.20^{a}	39.13^{a}	33.136^{a}
T_3	**Rice (DSR) *fb* ZT Maize with SDI at 60-cm spacing**	534.63^{b}	545.63^{b}	28.17^{ab}	28.13^{abc}	171.59^{b}	146.4^{b}	34.73^{b}	27.89^{b}
T_4	**Rice (DSR) *fb* ZT Maize with SSDI at 60-cm spacing**	579.0^{a}	594.0^{a}	28.60^{ab}	28.76^{a}	182.6^{a}	154.93^{a}	38.96^{a}	31.97^{a}
T_5	**Rice (DSR) *fb* ZT Wheat with Flood irrigation at 10 Kpa and critical growth stages for wheat**	487.0^{c}	500.0^{c}	27.75^{b}	27.33^{bcd}	160.8^{c}	136.73^{c}	30.50^{c}	24.2^{c}
T_6	**Rice (DSR) *fb* ZT Maize with Flood irrigation at 10 Kpa and 35 Kpa for Maize**	476.0^{c}	489.0^{c}	27.6^{b}	26.86^{d}	154.86^{c}	134.0^{c}	29.36^{c}	23.36^{c}
T_7	**PTR rice *fb* ZT wheat**	491.0^{bc}	502.0^{c}	27.76^{b}	27.63^{bcd}	161.4^{c}	139.33^{c}	31.30^{c}	24.63^{c}
T_8	**PTR rice *fb* ZT Maize**	483.00^{c}	495.0^{c}	27.7333^{b}	27.13^{cd}	159.53^{c}	135.6^{c}	30.19^{c}	23.5^{c}
SEm±		**14.33**	**12.99**	**0.25**	**0.31**	**3.03**	**2.23**	**1.05**	**1.05**
CD (P = 0.05)		**43.47**	**39.41**	**0.76**	**0.94**	**9.21**	**6.78**	**3.19**	**3.19**

Table 3. Effect of Drip irrigation system on yield attributes of DSR rice during 2020 and 2021

Treatments		Yield attributes							
		Grain Yield (kg/ha)		**Straw Yield (kg/ha)**		**Test Weight (g)**		**Total biomass yield (kg/ha)**	
		2020	**2021**	**2020**	**2021**	**2020**	**2021**	**2020**	**2021**
T_1	**Rice (DSR) *fb* ZT Wheat with SDI at 60-cm spacing**	6792.71^{b}	7050.09^{b}	7898.33^{ab}	8566.67^{a}	24.50^{a}	26.22^{a}	14720.87^{b}	15795.54^{b}
T_2	**Rice (DSR) *fb* ZT Wheat with SSDI at 60-cm spacing**	6997.85^{a}	7592.35^{a}	8193^{a}	9081.66^{a}	24.92^{a}	26.47^{a}	15304.24^{a}	16530.68^{a}
T_3	**Rice (DSR) *fb* ZT Maize with SDI at 60-cm spacing**	6766.56^{b}	6892.95^{b}	7898^{ab}	8551.67^{a}	24.40^{a}	25.91^{ab}	14696.19^{b}	15701.9^{b}
T_4	**Rice (DSR) *fb* ZT Maize with SSDI at 60-cm spacing**	6990.71^{a}	7580.20^{a}	8187^{a}	9078.33^{a}	24.83^{a}	26.42^{a}	15281.72^{a}	16441.76^{a}
T_5	**Rice (DSR) *fb* ZT Wheat with Flood irrigation at 10 Kpa and critical growth stages for wheat**	6557.05^{c}	6285.93^{c}	7568.66^{c}	7915.33^{b}	24.02^{a}	25.44^{bc}	14125.23^{c}	14835.54^{c}
T_6	**Rice (DSR) *fb* ZT Maize with Flood irrigation at 10 Kpa and 35 Kpa for Maize**	6534.15^{c}	6178.87^{c}	7525.66^{c}	7716.67^{b}	23.64^{a}	24.26^{d}	14068.38^{c}	14606.72^{c}
T_7	**PTR rice *fb* ZT wheat**	6569.24^{c}	6390.05^{c}	7608.33^{bc}	8005^{b}	24.07^{a}	25.84^{ab}	14131.48^{c}	15064.62^{c}
T_8	**PTR rice *fb* ZT Maize**	6548.53^{c}	6210.23^{c}	7539.66^{c}	7881.67^{b}	24.01^{a}	24.95^{cd}	14100.38^{c}	14780.93^{c}
SEm±		**47.00**	**75.67**	**94.91**	**165.70**	**0.46**	**0.24**	**181.64**	**198.13**
CD (P = 0.05)		**142.58**	**229.52**	**287.88**	**502.62**	**1.40**	**0.72**	**550.96**	**600.91**

Conclusion

The study concluded that using drip irrigation in direct-seeded rice, followed by zero-till practices, provided significant agronomic and economic benefits compared to paddy transplantation. Subsurface drip irrigation, in particular, led to markedly higher plant growth, effective tillers, number of panicles per square meter, and grain yield compared to surface drip irrigation, flooded irrigation, and conventional transplanting methods. The evidence analyzed indicates that using drip irrigation for direct-seeded rice is a promising strategy to reduce the water and energy demands of rice-wheat systems, which are becoming scarcer and more expensive, while also enhancing grain yield. Nevertheless, to establish the precise levels of water and energy savings achievable under various conditions, long-term, multi-location trials will be necessary.

Availability of data and materials:

The authors assure that the data supporting the research findings are available in the publication and its supplementary materials.

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