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Research Article

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Rooting characteristics, nutrient dynamics and mobilization of nitrogen in drip irrigated aerobic rice

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Key words: Aerobic rice, fertigation, nutrient uptake, nutrient availability, root characters, nitrogen mobilization

Abstract

Background and aims: Dry-direct seeded rice cultivation saves hefty amount of irrigation water; however, contributes to loss of applied nitrogenous fertilizers through higher run-off volumes. This can be checked by drip irrigation and fertigation in dry-direct seeded rice.
Methods: Field experiment was conducted at College of Agriculture, Rajendranangar, Hyderabad, India during *Kharif* of 2022 & 2023 to study the effect of different rice varieties and irrigation levels combined with 2 different doses of nitrogen (N) on the root characters, nutrient mobilization and spread of N in the soil. The experiment was laid out in split-plot design with 3 rice varieties (M_1: KNM-1638, M_2: JGL-24423 & M_3: DRR Dhan-42) in the main plot and 2 irrigation levels (1.0 Epan & 1.5 Epan) along with 2 nitrogen levels (100% N & 125% N) in the sub-plot.
Results: M_3 registered significantly higher root parameters, dry matter production and uptake of nutrients. Root parameters, dry matter production and nutrient uptake were recorded to be significantly higher when irrigation was scheduled at 1.5 Epan. Lower values for soil available nutrients in post-harvest soil was observed in M_3 and among sub plots; 1.5 Epan with 100% N. Irrigation scheduled at 1.0 Epan registered lower soil available N status both at 15 & 30 cm away from the lateral compared to irrigation scheduled at 1.5 Epan.
Conclusions: Variety, DRR Dhan-42 in combination with 1.5 Epan irrigation with 100% N could be adjudged as the best treatment for obtaining higher grain yield.

Abbreviations

N- Nitrogen, P- Phosphorus, K-Potassium, Epan- Pan evaporation, DAS- Days after sowing, S.Em- Standard error of mean, CD- Critical difference at 5% level of significance, NS- Non significant

Introduction

Rice is a way of life as well as the source of livelihood as manifested in the slogan "Rice is life" put forth by the international year of rice, 2004. Rice cultivation is spread globally to an extent of one fifth of the total cereals cultivated in terms of area (Dey *et al*., 2018) and is consumed by two third of the world's population (Kahani and Hittalmani, 2015). The global area under rice in 2020 is 163 million hectares with a production of 769 million tonnes & productivity of 4717 kg ha^{-1} (GOI, 2023). Among the rice growing countries of the world, India has the largest rice acreage and ranks second in production. In India, it is grown in about 45.77 M ha area with a production of 124.37 Mt and productivity of 2717 kg ha^{-1} during 2020-21 (GOI, 2023).

Rice is one among the most input intensive crops of the world with fertilizers alone contributing 20-25% of the total production cost (Jayanthi *et al.*, 2023). For vigorous growth of rice plants, N fertilizers are essential and are widely used for increasing rice production (Cui *et al*., 2020). Rice cultivation alone consumes 24.7 Mt of fertilizers and accounts for 14% of total annual fertilizer use in the world (Jayanthi *et al.*, 2023). Cereal nitrogen use efficiency was 35% worldwide, 41% in the US, 30% in China, and 21% in India (Omara *et al.*, 2019). Zhang *et al.* (2018) showed that dry direct seeded rice reported 26-30% higher runoff volumes over conventional transplanted rice. There was 48 to 58% loss from applied N depending on the dose in aerobic rice (Kadiyala *et al.*, 2012). Runoff loss of N from paddy fields is significant and has led to eutrophication in the surrounding water bodies (Le *et al*., 2010). Total N runoff loss from paddy fields ranges from 0.12- 65 kg ha^{-1} with an average loss of 12.7 kg N ha^{-1} (Chen *et al*., 2015; Zhao *et al*., 2015; Xue *et al*., 2014; Liang *et al*., 2013). In order to reduce N runoff losses, practices aimed at reducing runoff volumes could be adopted. Water saving irrigation practices can reduce N losses by reducing runoff volumes (Gao *et al*., 2002).

Fertilizer industry is one among the high energy intensive industries and non-judicious application of fertilizers poses threat to environment and questions sustainable development. So an ideal nutrient management strategy needs to be introduced in rice culture, that would not only enhance productivity, profitability and nutrient use efficiency but should also be eco-friendly and environmentally sustainable. One of the precise ways for supplying nutrients to the growing crop is fertigation which is the scientific usage of micro-irrigation for controlled nutrient release using water-soluble fertilizers. It is an efficient strategy to reduce leaching losses of nutrients. Combining irrigation and fertilizer application via fertigation reduces the cost associated with both the operations. Incorporating water saving drip irrigation method with efficient fertilizer management via fertigation could potentially reduce runoff volumes as well as total N losses in dry direct seeded rice. Fertigation can spoon feed nutrients to a crop with minimum wastages and enhance crop yields besides reducing groundwater pollution from nitrates (Lamm *et al*., 2001). Mobilization of N in soil is of keen importance with respect to the availability and uptake of N by the crop in drip irrigation. Studies conducted so far, limit themselves to growth and yield potential in drip irrigated dry-direct seeded rice. The present study unravels the nutrient dynamics in drip irrigated aerobic rice along with mobility of N in soil as influenced by irrigation levels.

Materials and methods

Experimental site

Field experiment was conducted at College Farm, College of Agriculture, Rajendranangar, Hyderabad, Telangana, India (17° 19' 24.7" N; 78° 24' 34.0" E; 542.6 m above mean sea level) during *kharif* seasons of 2022-23 and 2023-24. The soil was sandy clay loam in texture. The physico-chemical characters of the experimental soil are furnished in Table 1.

Weather parameters

Meteorological parameters recorded from meteorological observatory situated at Agro Climate Research Centre, ARI, PJTSAU, Rajendranagar were used to characterize the weather conditions prevailed during the crop growing seasons.

Table 1. Physical, physico-chemical and chemical properties of soil in the experimental field

Sl No.	Particulars	Value	Method of analysis
A	**Mechanical analysis**		
1.	Sand (%) Silt (%) Clay (%)	72 20 22	Bouyoucos hydrometer method (Piper, 1966)
	Textural class	Sandy clay loam	
2.	Hydraulic conductivity (cm h^{-1})	5.78 (Moderate)	Constant pressure head method (Singarao *et al*., 2005)
3.	Soil bulk density (g cc^{-1})	1.44	Core sampler method (Dastane, 1967)
B	**Chemical analysis**		
1.	pH (1:2.5 soil water suspension)	7.6 (Mildly alkaline)	Blackman's glass electrode pH meter (Jackson, 1973)
2.	Electrical conductivity (dS m^{-1} at 25ºC)	1.03 (Normal)	Conductometric method (Jackson, 1967)
3.	Organic carbon (%)	0.53 (Low)	Wet digestion method (Walkley and Black, 1934)
4.	Available nitrogen (kg ha^{-1})	245.4 (Low)	Alkaline potassium permanganate method (Subbaiah and Asija, 1956)
5.	Available phosphorus (kg ha^{-1})	48.2 (High)	Olsen's extractant method (Olsen *et al*., 1954)
6.	Available potassium (kg ha^{-1})	528 (High)	Neutral normal ammonium acetate method (Jackson, 1967)

Weekly mean maximum temperature during crop growing season of *kharif*, 2022 ranged from 27.40 – 31.40^{0}C with a mean value of 29.62^{0}C. Range of weekly mean minimum temperature happened to be between 13.80 – 23.40^{0}C with a mean value of 18.66^{0}C. During *kharif*, 2023, weekly mean maximum temperature ranged between 27.70 – 33.10^{0}C with a mean value of 30.64^{0}C; whereas, weekly mean minimum temperature ranged between 13.90 – 24.00^{0}C with a mean value of 20.67^{0}C.

The weekly mean morning relative humidity (RH I) ranged between 77.90 - 97.10% with a mean value of 88.24% during *kharif,* 2022; whereas, weekly mean afternoon relative humidity (RH II) fluctuated between 36.00 - 77.00% with a mean value of 54.34%. In *kharif*, 2023, mean weekly RH I varied between 79.70 - 93.40% with a mean value of 86.07%; whereas, mean weekly RH II ranged between 29.60 - 79.70% with a mean value of 55.07%.

During crop growing period of *kharif,* 2022, weekly mean bright sunshine hours day^{-1} ranged between 2.20 - 9.10 with a mean value of 6.27; while in *kharif*, 2023, it ranged between 1.00 - 10.20 with a mean value of 6.02. The weekly mean wind speed ranged between 2.00 - 8.60 km h^{-1} & 2.50 - 7.70 km h^{-1} with mean value of 3.49 & 4.40 km h^{-1} during *kharif*, 2022 & 2024 respectively.

In *kharif* of 2022, a total of 409.40 mm of rainfall was received in 23 rainy days. Total rainfall received during *kharif*, 2023 was 329.50 mm in 18 rainy days. Mean weekly evaporation during *kharif*, 2022 ranged between 2.70 - 4.80 mm with a mean value of 3.44 mm; whereas in *kharif*, 2023 it ranged between 2.80 - 5.40 mm with a mean value of 3.94 mm.

Experimental design

The experiment was laid out in split-plot design with 3 rice varieties in the main plot and 2 levels of irrigation with 2 levels of N through surface drip in the sub-plot which were replicated thrice.

Main plots: 3 (Varieties)

- M_1 : KNM-1638
- M_2 : JGL-24423
- M_3 : DRR Dhan-42

Sub plots: 4 [Irrigation levels (2) vs Nitrogen levels (2)]

1. S_1 :Irrigation scheduled at 1.0 Epan with 100% N (150 kg N ha^{-1})
2. S_2 :Irrigation scheduled at 1.0 Epan with 125% N (187.5 kg N ha^{-1})
3. S_3 :Irrigation scheduled at 1.5 Epan with 100% N (150 kg N ha^{-1})
4. S_4 :Irrigation scheduled at 1.5 Epan with 125% N (187.5 kg N ha^{-1})

Crop management

Dry seed treatment was done using carbendazim 50% WP at a dosage of 2 g kg^{-1}. Line sowing of seeds was done. Seed rate was 30 kg ha^{-1}. Solid row seeding was done at 20 cm spacing between rows. Thinning was done at 12 DAS, to maintain 10 cm distance between plants. Two germination irrigations were given on 1st and 5th day after sowing with 30 mm water regardless of treatment. Irrigation on treatment basis was commenced on 8th day after sowing. Irrigation was scheduled on alternate days based on pan evaporation (USWB class 'A' open pan evaporimeter) obtained from Agro Climate Research Centre, Agricultural Research Institute, PJTSAU, Rajendranagar.

The recommended dose of fertilizer was 150:60:40 kg NPK ha^{-1}. Urea (46% N), single super phosphate (16% P_2O_5) and potassium sulphate (50% K_2O) were used to supply N, P and K respectively. Entire dose of P was supplied as basal. Entire dose of N and K were supplied through fertigation. The dose of N was adjusted as per treatment (100% N; 150 kg N ha^{-1} & 125% N; 187.5 kg N ha^{-1}). Fertigation was commenced on 10th day after sowing and continued up to panicle initiation stage at 10 days interval. Total 10 fertigations were given during the crop growth period. Required quantity of fertilizer was dissolved in water. Fertilizer solution thus prepared was filled in a basin and connected to the suction device of ventury. To combat iron chlorosis, 2% $FeSO_4$ spray was given twice (at 20 & 40 DAS). Foliar spray of 0.5% zinc EDTA was done once at 30 DAS.

Pre-emergence application of pendimethalin was done on 2nd day after sowing @ 5ml L^{-1}. Post emergence spray of triafamone 20% + ethoxysulfuron 10% (Council Active) was done on 15 DAS (2-3 leaf stage of weeds) at a rate of 90 g $acre^{-1}$ (0.45 g L^{-1}). One hand weeding was performed at 35 DAS. Harvesting was done when 80% of the panicles turned straw yellow in colour.

Recording of biometric observations

Root parameters at periodical intervals of crop growth were recorded from the 5 hills pulled out of the gross plot area. Root length was recorded from such plants using a meter scale and expressed in cm. Roots were shade dried followed by oven drying at 65^{0}C till a constant weight was obtained. From such roots dry weight was recorded and expressed in g $hill^{-1}$. Root volume was measured by employing the displacement technique proposed by Mishra and Ahmad (1987). Roots after thorough cleaning were immersed in a measuring cylinder containing known volume of water. According to Archimedes principle the volume of water displaced will be equal to the volume of root immersed.

Five plants from the sampling row were uprooted randomly at 60 DAS, 90 DAS & harvest. Roots were removed and the plants were shade dried for 24 h followed by oven drying at 65^{0}C till a constant weight was attained. The mean dry weight of plants was expressed as kg ha^{-1}. For recording grain yield, plants from the net plot area was harvested, sun dried for 3 days, threshed and winnowed. It was weighed at 14% moisture level and expressed as kg ha^{-1}.

Soil analysis

Soil samples were drawn from 0-15 cm depth at 5 random points within the net plot area. A composite sample was made out of the collected samples by quartering method. The samples were air-dried, powdered using wooden pestle and mortar followed by sieving. Samples were sieved through 2 mm sieve for NPK analysis. Available N in soil was estimated by alkaline potassium permanganate method put forth by Subbaih

and Asija (1956) using Kjeldal distillation unit and expressed in kg ha^{-1}. Extraction of available phosphorus was done in Olsen's reagent (0.5 N $NaHCO_3$, pH; 8.5) as described by Olsen *et al.* (1954). For colour development, ascorbic acid method was made use of; and the intensity of the blue colour was measured at 660 nm wavelength by using Spectrophotometer (Shimadeu UV-1800 double beam spectrophotometer) and expressed in kg ha^{-1}. Extraction of available potassium was done using neutral normal ammonium acetate at pH 7.0 (Muhr *et al.*, 1965) and was determined using flame photometer (Elico CL 378) as described by Jackson (1967) and expressed in kg ha^{-1}.

Plant analysis

The tagged plants from the net plot area were uprooted at harvest stage. They were shade dried for 24 h followed by oven drying at 65^0C till constant weight was achieved. Grains and straw were powdered separately and stored in polyethylene zip covers for further analysis. By adopting the standard procedures (Piper, 1966), samples were analysed for N, P and K contents. Nitrogen, phosphorus and potassium contents in grain & straw samples were analysed treatment wise separately. From the NPK contents of grain & straw samples the total uptake of the specific nutrient was determined.

Nitrogen content in plant sample can be analysed by modified Kjeldhal's method (Jackson, 1967) using Kelplus N analyser after digesting the plant sample in conc. H_2SO_4 and H_2O_2 (Piper, 1966) and the nitrogen content was expressed in %. For the estimation of phosphorus content, the plant sample was digested using di-acid mixture (HNO_3 and $HClO_4$ in 9:4 ratio). The extract was subjected to Vanadomolybdo phosphoric yellow colour method as described by Jackson (1967). The intensity of yellow colour developed was measured using spectrophotometer (Shimadeu UV-1800 double beam spectrophotometer) at 420 nm and the P content was expressed in %. For the estimation of potassium content, the plant sample was digested using di-acid mixture (HNO_3 and $HClO_4$ in 9:4 ratio). Flame photometer (Elico CL 378) readings of di-acid digested samples give the potassium content of the given sample in % (Piper, 1966).

Uptake of the specific nutrient can be arrived at from the content of the particular nutrient by following the given formula.

$$Nutrient\ uptake\ (kg\ ha^{-1}) = \frac{Nutrient\ content\ (\%) \times Dry\ matter\ (kg\ ha^{-1})}{100}$$

Sum of nutrient uptake by grain and straw gives the total nutrient uptake by plant.

Results

Root length

Root length was significantly influenced by varieties as well as levels of irrigation and nitrogen. Root length of rice as influenced by varieties and levels of irrigation and nitrogen during both the years of study was analysed statistically and presented in Table 2. The highest root length was registered by DRR Dhan-42 at 60 & 90 DAS. Irrigation scheduled at 1.5 Epan with either 100% (S_3) or 125% N (S_4) did not differ significantly for root length during both the years of experimentation. However, it was significantly higher than irrigation scheduled at 1.0 Epan.

Root dry weight

Varieties and levels of irrigation and nitrogen had a significant effect on root dry weight (Table 2). Highest root dry weight was observed in DRR Dhan-42 during all the stages of growth during both the years; whereas, KNM-1638 had the lowest root dry weight. Irrigation scheduled at higher moisture regime had a positive effect on root dry weight. Significantly higher root weight at all growth stages was recorded when irrigation was scheduled at 1.5 Epan over 1.0 Epan. Within the same level of irrigation, doses of N did not produce any significant effect.

Root volume

Root volume of rice in response to varietal differences and levels of irrigation and nitrogen during both the years of study was analysed statistically and presented in Table 2. During 60 DAS & 90 DAS, DRR Dhan-42 registered significantly higher root volume over JGL-24423 & KNM-1638. In the first year of study, irrigation scheduled at 1.5 Epan with 100% N recorded significantly higher root volume which was on par to irrigation at 1.5 Epan with 125% N. Root volume registered at 1.0 Epan was significantly lower to that

registered at 1.5 Epan. This was true for the second year of experimentation as well. The highest root volume was recorded in S_3 (irrigation at 1.5 Epan with 100% N), which was on par to S_4 (irrigation at 1.5 Epan with 125% N). There was no significant difference between 100 & 125% N at 1.0 Epan, but it was statistically inferior to irrigation scheduled at 1.5 Epan.

Dry matter production

Dry matter production as influenced by varietal difference as well as irrigation and N levels at 60 & 90 DAS is depicted in Table 3. The highest dry matter production at all the growth stages was reported in M_3 (DRR Dhan-42) during both the years. The lowest dry matter production at all the growth stages was registered by KNM-1638. JGL -24423 remained mid-way between DRR Dhan-42 & KNM-1638. Levels of irrigation and nitrogen had significant effect on dry matter production at 60 & 90 DAS during both the years of study. It was noted that higher levels of irrigation secured higher dry matter production. Irrigation at 1.5 Epan with 125% N (S_4) recorded the highest dry matter production which was on par to S_3 (1.5 Epan with 100% N) during all the stages of growth. Lowest dry matter production was registered in S_2 (1.0 Epan with 125% N) and was statistically comparable to S_1 (irrigation scheduled at 1.0 Epan with 100% N). Similar findings of reduced dry matter production under lower levels of irrigation compared to 1.5 Epan were reported by Colak (2021) in dry seeded rice.

Varieties & levels of irrigation along with N interacted for dry matter production at harvest (Fig. 1). The highest mean dry matter production was registered by DRR Dhan-42 when irrigated at 1.5 Epan with 125% N (M_3S_4) (12965 kg ha^{-1}). It was on par to DRR Dhan-42 irrigated at 1.5 Epan with 100% N (12901 kg ha^{-1}). M_2S_3, M_2S_4, M_3S_1 & M_3S_2 were found to be statistically comparable to each other i.e., irrigation scheduled at 1.0 Epan with either 100 or 125% N in DRR Dhan-42 is equally promising to irrigation scheduled at 1.5 Epan with either 100 or 125% N in JGL-24423. The lowest dry matter production among all the varieties was reported in KNM-1638 (9301 kg ha^{-1}). It did not differ significantly across irrigation and nitrogen levels. Dry matter accumulation recorded in M_1S_1, M_1S_2, M_1S_3 & M_1S_4 was at par. There observed significant difference between neither irrigation regimes nor doses of N. Mean dry matter production recorded in M_1S_1, M_1S_2, M_1S_3 & M_1S_4 were 9259, 9270, 9317 & 9359 kg ha^{-1} respectively.

Grain yield

Grain yield as influenced by varieties as well as levels of irrigation and nitrogen is presented in Table 4. The highest grain yield was recorded in M_3S_3 (DRR Dhan-42 under 1.5 Epan irrigation regime + 100% N) (5937 kg ha^{-1}). It was at par with M_3S_4 (DRR Dhan-42 under 1.5 Epan irrigation regime + 125% N) (5727 kg ha^{-1}). In DRR Dhan-42, irrigation scheduled @ 1.0 Epan along with either 100 (5082 kg ha^{-1}) or 125% N (4782 kg ha^{-1}) was comparable to grain yield in JGL-24423 with 1.5 Epan irrigation along with 100 (4978 kg ha^{-1}) or 125% N (4893 kg ha^{-1}). It implies that the lower levels of irrigation in DRR Dhan-42 performed equally to higher levels of irrigation in JGL-24423. Variety, KNM-1638 was found to have registered the lowest grain yield; however, all the treatments were at par with each other. This implies that irrigation scheduled at 1.0 Epan was equally effective to irrigation scheduled at 1.5 Epan in KNM-1638.

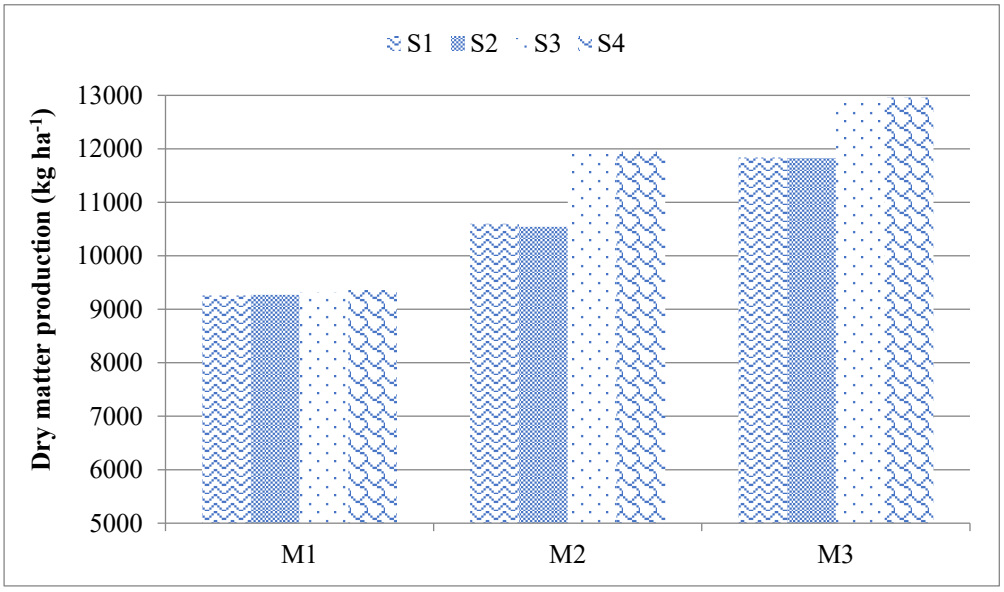
252 **Table 2. Root length (cm hill^{-1}), root dry weight (g hill^{-1}) & root volume (cc hill^{-1}) of rice varieties as influenced by levels of nitrogen and irrigation through**
253 **surface drip**

Treatments	Root length (cm hill^{-1})				Root dry weight (g hill^{-1})				Root volume (cc hill$^{-1)}$			
	60 DAS		90 DAS		60 DAS		90 DAS		60 DAS		90 DAS	
	2022	2023	2022	2023	2022	2023	2022	2023	2022	2023	2022	2023
Main plots: Varieties												
M_1 : KNM-1638	6.9	7.1	10.1	10.1	2.82	2.88	4.60	4.81	8.46	8.63	12.68	12.87
M_2 : JGL-24423	8.1	8.3	11.7	11.6	3.58	3.67	5.67	5.77	9.60	9.88	14.85	14.90
M_3 : DRR Dhan-42	11.7	11.7	14.3	14.5	4.60	4.68	6.56	6.66	10.19	10.59	19.96	20.23
S. Em±	0.1	0.2	0.2	0.2	0.07	0.05	0.07	0.10	0.14	0.09	0.14	0.28
CD (P=0.05)	0.5	0.6	0.8	0.8	0.26	0.21	0.29	0.40	0.54	0.36	0.54	1.09
Sub plots: Irrigation levels vs Nitrogen levels												
S_1 : 1.0 Epan + 100% N	8.5	8.7	11.8	11.7	3.40	3.50	5.28	5.48	9.07	9.46	14.90	14.90
S_2 : 1.0 Epan + 125% N	8.4	8.4	11.6	11.8	3.48	3.59	5.41	5.52	9.23	9.50	15.07	15.36
S_3 : 1.5 Epan + 100% N	9.4	9.5	12.4	12.4	3.97	4.03	5.92	6.01	9.77	9.97	16.93	17.22
S_4 : 1.5 Epan + 125% N	9.3	9.5	12.2	12.3	3.83	3.85	5.83	5.98	9.60	9.88	16.42	16.52
S. Em±	0.1	0.2	0.2	0.2	0.05	0.12	0.06	0.11	0.11	0.11	0.22	0.32
CD (P=0.05)	0.4	0.5	0.4	0.6	0.16	0.35	0.18	0.31	0.33	0.34	0.64	0.95
Interaction												
Sub plot at same main plot												
S. Em±	0.3	0.3	0.3	0.3	0.09	0.20	0.10	0.18	0.19	0.20	0.38	0.55
CD (P=0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Main plot at same or different level of sub plot												
S. Em±	0.3	0.3	0.3	0.4	0.10	0.18	0.12	0.19	0.22	0.19	0.35	0.55
CD (P=0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

254

Table 3. Dry matter production (kg ha^{-1}) of rice varieties as influenced by levels of nitrogen and irrigation through surface drip

Treatments	Dry matter production (kg ha^{-1})					
	60 DAS		90 DAS		Harvest	
	2022	2023	2022	2023	2022	2023
Main plots: Varieties						
M_1 : KNM-1638	3490	3758	6609	6894	9197	9406
M_2 : JGL-24423	3968	4200	7669	7932	11080	11422
M_3 : DRR Dhan-42	4721	4965	8406	8859	12136	12631
S. Em±	43	51	103	117	137	210
CD (P=0.05)	168	199	403	459	536	824
Sub plots: Irrigation levels vs Nitrogen levels						
S_1 : 1.0 Epan + 100% N	3661	3931	6992	7317	10441	10689
S_2 : 1.0 Epan + 125% N	3826	4074	7137	7508	10448	10646
S_3 : 1.5 Epan + 100% N	4278	4533	7964	8304	11142	11611
S_4 : 1.5 Epan + 125% N	4473	4693	8152	8450	11184	11665
S. Em±	104	102	82	83	117	139
CD (P=0.05)	310	303	243	245	349	412
Interaction						
Sub plot at same main plot						
S. Em±	181	177	142	143	203	240
CD (P=0.05)	NS	NS	NS	NS	604	713
Main plot at same or different level of sub plot						
S. Em±	162	161	160	170	223	295
CD (P=0.05)	NS	NS	NS	NS	742	1020



M1- KNM-1638, M2- JGL-24423, M3- DRR Dhan-42; S1- 1.0 Epan +100% N, S2- 1.0 Epan + 125% N, S3- 1.5 Epan +100% N, S4- 1.5 Epan + 125% N

Fig 1 Mean dry matter production (kg ha^{-1}) at harvest as influenced by rice varieties and levels of irrigation and nitrogen

Table 4 Interaction effect of varieties and levels of nitrogen and irrigation through surface drip on mean grain yield (kg ha^{-1})

Main plot / Sub plot	Varieties			Mean
Irrigation levels vs Nitrogen levels	**M_1 : KNM-1638**	**M_2 : JGL-24423**	**M_3 : DRR Dhan-42**	
S_1 : 1.0 Epan with 100% N	3334	3988	5082	4135
S_2 : 1.0 Epan with 125% N	3305	4101	4782	4063
S_3 : 1.5 Epan with 100% N	3258	4978	5937	4724
S_4 : 1.5 Epan with 125% N	3356	4893	5727	4659
Mean	3313	4490	5382	
	Varieties	**Irrigation vs nitrogen levels**	**Interactions**	
			Sub plot at same main plot	Main plot at same or different level of sub plot
S.Em±	105	94	163	176
CD (P=0.05)	412	279	483	581

Soil available nitrogen

Rice being an exhaustive crop, there could have been no appreciable increase in soil N status after harvest of crop besides having an initial low N status (245.4 kg ha^{-1}). The soil N data after harvest of crop was statistically analysed and presented in Table 5. Varieties significantly influenced soil available nitrogen during both the years of study. In 2022, significantly higher soil available N was observed in KNM-1638 (M_1) (225.92 kg ha^{-1}) followed by JGL-24423 (M_2) (191.30 kg ha^{-1}) and DRR Dhan-42 (M_3) (177.19 kg ha^{-1}). A similar trend was observed during 2023 as well and from the highest to lowest varieties followed the order M_1 (217.77 kg ha^{-1}), M_2 (181.60 kg ha^{-1}) & M_3 (166.24 kg ha^{-1}).

Irrigation & nitrogen levels had significantly influenced soil available N status during both the years of study. Significantly higher N status was observed in irrigation scheduled at 1.0 Epan with 125% N (221.17 & 211.15 kg ha^{-1} in 2022 & 2023 respectively). It was followed by irrigation scheduled at 1.0 Epan with 100% N (206.14 & 195.19 kg ha^{-1} during 2022 & 2023 respectively). The lowest N status was observed with irrigation scheduled at 1.5 Epan with 100% N (175.46 & 166.70 kg ha^{-1} during 2022 & 2023 respectively). It was followed by irrigation scheduled at 1.5 Epan with 125% N (189.77 & 181.11 kg ha^{-1} during 2022 & 2023 respectively).

Soil available phosphorus

Varieties as well as levels of irrigation & nitrogen did not influence soil available phosphorus (P) status either in the first or in the second years of study. Statistically analysed data is presented in Table 5.

Soil available potassium

Varieties as well as levels of irrigation & nitrogen did not influence soil available potassium (K) status in either years of experimentation. Statistically analysed data is presented in Table 5.

Table 5. Available N (kg ha^{-1}), available P (kg ha^{-1}) & available K (kg ha^{-1}) in the post-harvest soil as influenced by rice varieties & levels of nitrogen and irrigation through surface drip

Treatments	Available N (kg ha^{-1})		Available P (kg ha^{-1})		Available K (kg ha^{-1})	
	2022	2023	2022	2023	2022	2023
Main plots: Varieties						
M_1 : KNM-1638	225.92	217.77	51.51	51.93	407.65	412.71
M_2 : JGL-24423	191.30	181.60	50.34	51.39	415.53	422.81
M_3 : DRR Dhan-42	177.19	166.24	49.87	51.25	404.71	407.64
S. Em±	3.23	3.02	0.84	0.69	7.40	4.08
CD (P=0.05)	12.66	11.87	NS	NS	NS	NS
Sub plots: Irrigation levels vs Nitrogen levels						
S_1 : 1.0 Epan + 100% N	206.14	195.19	50.34	51.41	416.45	423.04
S_2 : 1.0 Epan + 125% N	221.17	211.15	51.68	52.47	400.25	412.18
S_3 : 1.5 Epan + 100% N	175.46	166.70	50.37	51.93	408.96	410.80
S_4 : 1.5 Epan + 125% N	189.77	181.11	49.90	50.28	411.51	411.52
S. Em±	4.56	4.54	0.86	0.79	4.90	4.34
CD (P=0.05)	13.56	13.48	NS	NS	NS	NS
Interaction						
Sub plot at same main plot						
S. Em±	7.90	7.86	1.49	1.36	8.49	7.52
CD (P=0.05)	NS	NS	NS	NS	NS	NS
Main plot at same or different level of sub plot						
S. Em±	7.57	7.45	1.54	1.37	10.43	7.68
CD (P=0.05)	NS	NS	NS	NS	NS	NS

Soil N status at periodical intervals

Soil N status was determined from sowing to 95 DAS at 15 days interval from 0-15 cm depth of soil, at a distance of 15 cm & 30 cm away from the lateral. Only 1 fertigation event had happened at the first stage of observation (15 DAS). From 31 DAS – 79 DAS, 2 new fertigation events had happened between 2 consecutive observations. Between 79 & 95 DAS, one fertigation was scheduled. After 95th day there were no fertigation events.

Variation in soil N status among varieties during 2022 & 2023 at 15 cm away from the lateral is presented in Fig. 2a & Fig. 2b respectively. Variation in soil N status among varieties during 2022 & 2023 at 30 cm away from the lateral is presented in Fig. 2c & Fig. 2d respectively. The varietal difference for soil N status at periodical intervals of crop growth was hardly traceable as observed in the figures (2a - 2d). Pattern of Soil N status was similar in both the years of experimentation. Soil N status was found to increase from 15 DAS to 95 DAS. After 95th day, soil N status steeply goes down. Between 31 – 63 DAS, soil N status slightly decelerates as observed from Fig. 2c. However, it was not clearly visible at 15 cm distance from the lateral. The increase in N status from 63 - 95 DAS was also obtuse both at 15 cm away from lateral & 30 cm away from the lateral. At 111 DAS, both at 15 cm away from the lateral as well as 30 cm away from the lateral, soil N status was more for M_1 (KNM-1638), followed by M_2 (JGL-24423). The lowest N availability was observed in M_3 (DRR Dhan-42).

Variation in soil N status among irrigation and nitrogen levels during 2022 & 2023 at 15 cm away from the lateral is presented in Fig. 3a & Fig. 3b respectively & at 30 cm away from the lateral is presented in Fig. 3c & Fig. 3d respectively. Soil N status is found to be more uniform at 15 cm distance from the lateral. Soil N status at 15 cm away from the lateral from 15 to 95 DAS kept on increasing with higher N status being observed in S_4. It was closely followed by S_3. A slight reduction in Soil N status was observable in S_1 & S_2, where S_2 superseded S_1. At 111 DAS, higher available N was found in S_4 compared to S_3 and in S_2 compared to S_1. There observed clear-cut difference in soil N status between 1.0 Epan & 1.5 Epan at 30 cm away from the lateral than 15 cm. Soil N status at 30 cm away from the lateral in S_3 & S_4 (which received 1.5 Epan irrigation) was more or less similar to soil N status at 15 cm away from the lateral. However, in S_1 & S_2 (which received 1.0 Epan irrigation) there was remarkable reduction in soil N status at 30 cm distance from the lateral compared to 15 cm.

Nitrogen uptake

Nitrogen (N) uptake was significantly influenced by varieties as well as levels of irrigation and nitrogen during both the years of study as well as in mean. Data was analysed statistically and the results are presented in Table 6. During both the years of experimentation, significantly higher grain & straw N uptake was recorded by DRR Dhan-42 (M_3). It was followed by JGL-24423 (M_2) & KNM-1638 (M_1). Significantly higher total N uptake was observed in DRR Dhan-42 followed by JGL-24423 during both the years of study. Significantly lower total N uptake was observed in KNM-1638.

Levels of irrigation and nitrogen significantly influenced N uptake by grain, straw as well as total N uptake. Significantly higher N uptake by grain and straw was registered by irrigation scheduled at 1.5 Epan with 100% N (S_3) and was at par with irrigation scheduled at 1.5 Epan with 125% N (S_4). Irrigation scheduled at 1.0 Epan secured significantly lower N uptake during both the years of experimentation. Grain, straw & total N uptake registered by S_3 (1.5 Epan irrigation + 100% N) was 10.84, 17.14 & 13.03% higher than that registered by S_1 (1.0 Epan + 100% N) respectively.

Phosphorus uptake

Uptake of phosphorus (P) by crop as influenced by varieties as well as irrigation and N was analysed statistically and depicted in Table 7. Varieties significantly influenced P uptake by grain & straw as well as total P uptake. Significantly higher grain P uptake was registered by DRR Dhan-42 (M_3) during both the years of experimentation. Straw & total P uptake also followed the same trend. It was followed by JGL-24423. Significantly lower grain, straw & total P uptake was registered by KNM-1638. Levels of irrigation and nitrogen significantly influenced grain, straw & total P uptake by crop. Significantly higher grain, straw & total P uptake was registered by irrigation scheduled at 1.5 Epan + 100% N (S_3) during both the years of study. It was on par to irrigation scheduled at 1.5 Epan + 125% N (S_4).

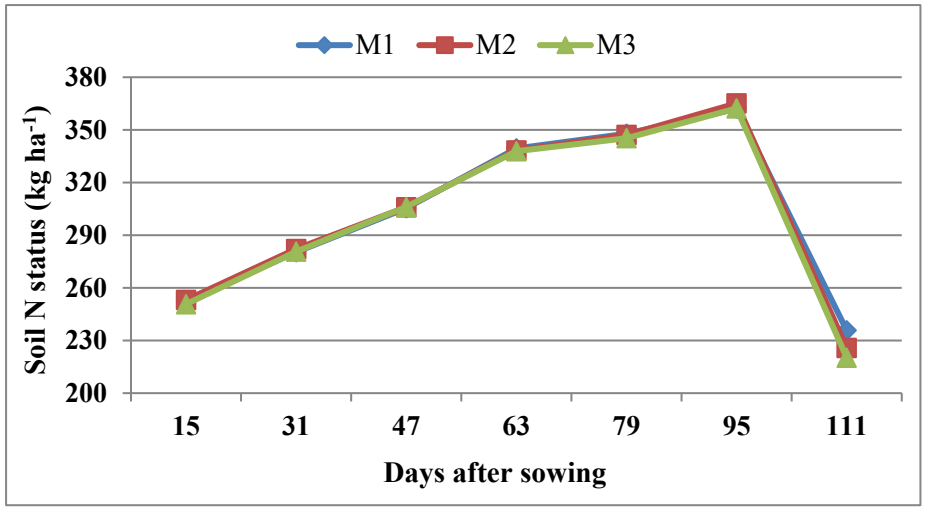


Fig 2a Soil N status at periodical intervals as influenced by varieties at 15 cm away from the lateral during *kharif,* 2022

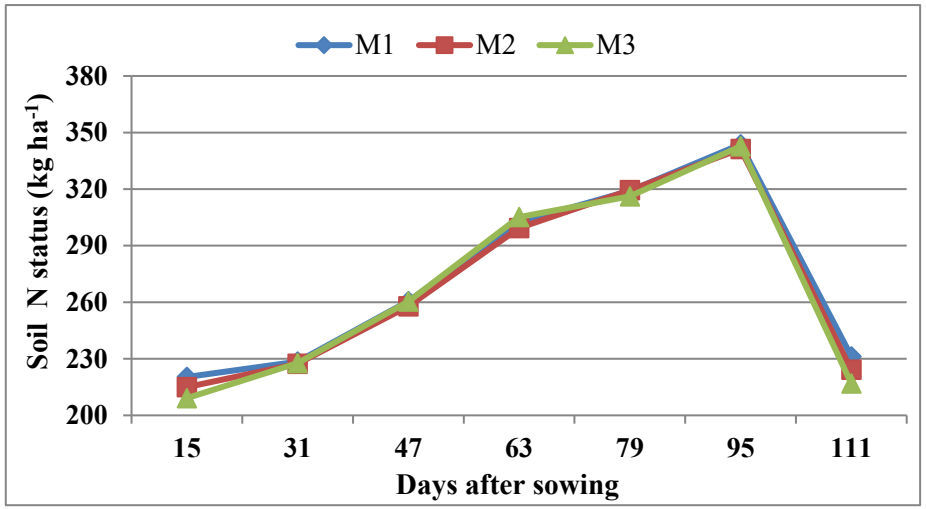


Fig 2b Soil N status at periodical intervals as influenced by varieties at 15 cm away from the lateral during *kharif,* 2023

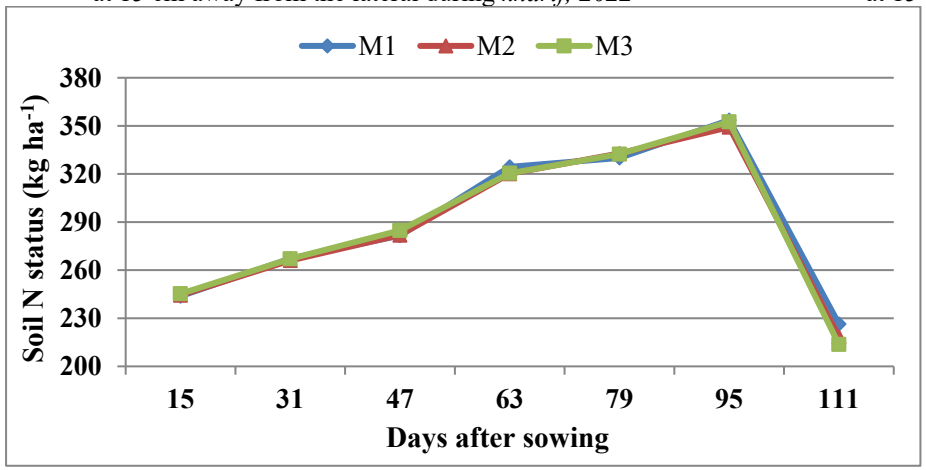


Fig 2c Soil N status at periodical intervals as influenced by varieties at 30 cm away from the lateral during *kharif,* 2022

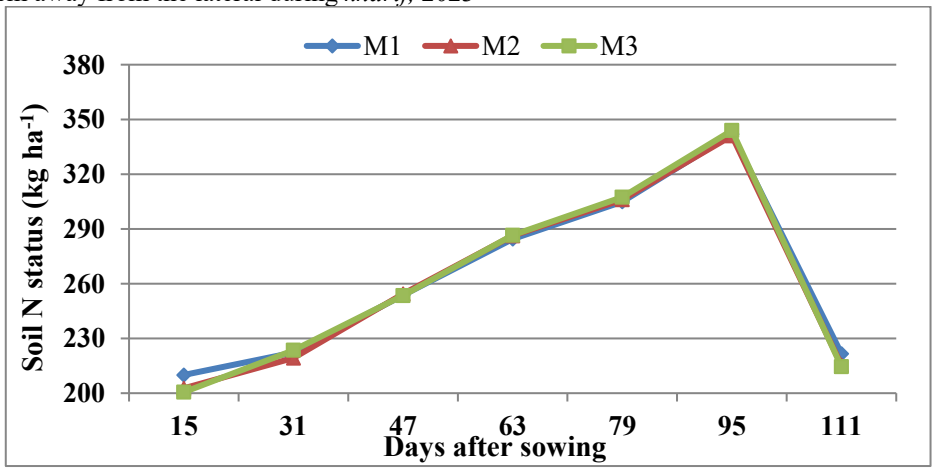


Fig 2d Soil N status at periodical intervals as influenced by varieties at 30 cm away from the lateral during *kharif,* 2023

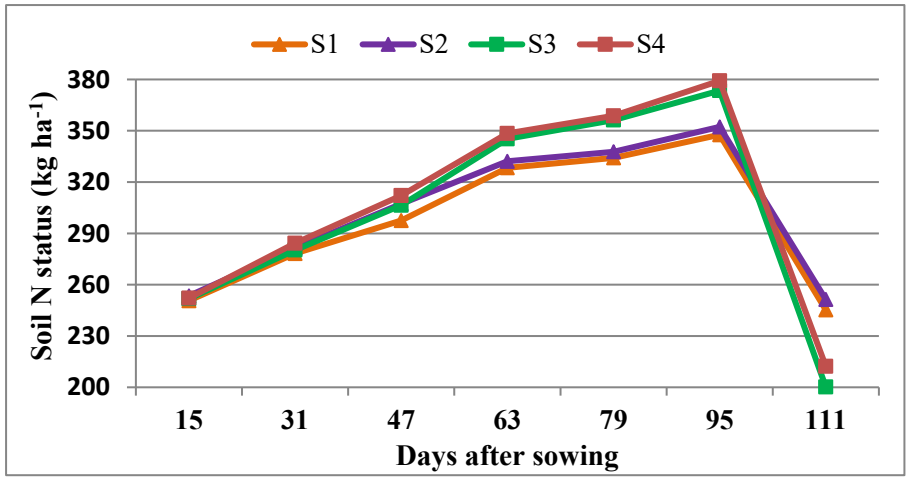


Fig 3a Soil N status at periodical intervals as influenced by irrigation & N levels at 15 cm away from the lateral during *kharif,*2022

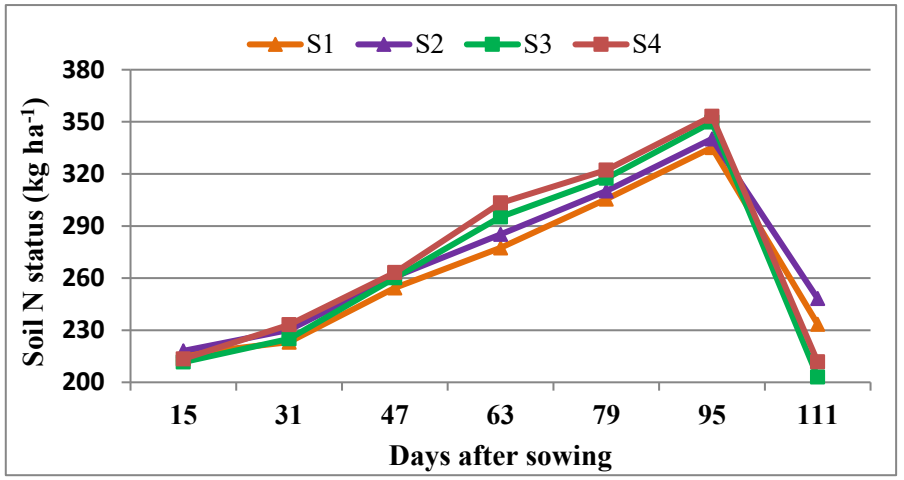


Fig 3b Soil N status at periodical intervals as influenced by irrigation & N levels at 15 cm away from the lateral during *kharif,*2023

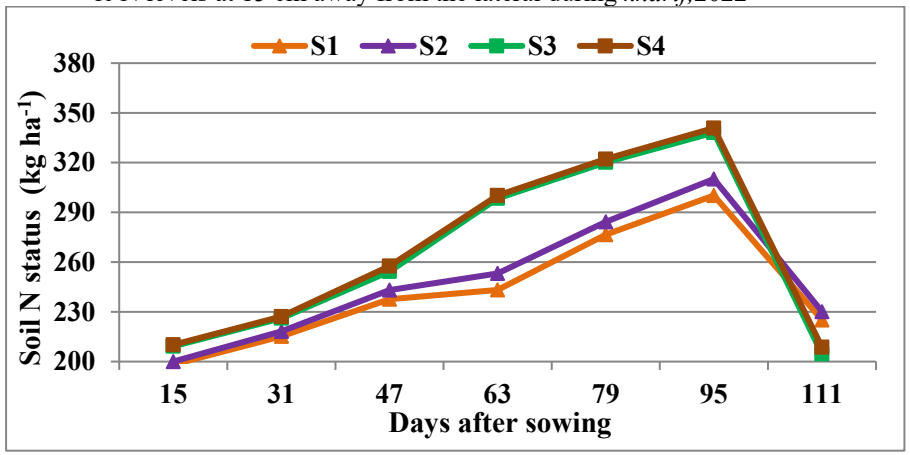


Fig 3c Soil N status at periodical intervals as influenced by irrigation & N levels at 30 cm away from the lateral during *kharif,*2022

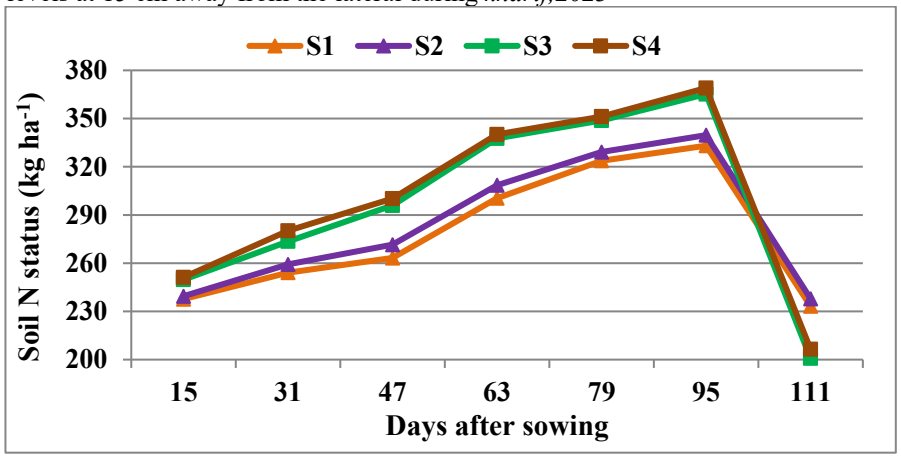


Fig 3d Soil N status at periodical intervals as influenced by irrigation & N levels at 30 cm away from the lateral during *kharif,*2023

Table 6. Nitrogen uptake (kg ha^{-1}) as influenced by rice varieties & levels of nitrogen and irrigation through surface drip

Treatments	N uptake (kg ha^{-1})					
	2022			2023		
	Grain	Straw	Total	Grain	Straw	Total
Main plots: Varieties						
M_1 : KNM-1638	37.02	17.75	54.77	41.55	20.77	62.32
M_2 : JGL-24423	44.30	24.52	68.82	56.68	29.51	86.19
M_3 : DRR Dhan-42	49.57	33.59	83.16	71.51	40.34	111.85
S. Em±	0.65	0.66	1.29	1.32	0.98	2.29
CD (P=0.05)	2.57	2.58	5.04	5.18	3.86	8.99
Sub plots: Irrigation levels vs Nitrogen levels						
S_1 : 1.0 Epan + 100% N	42.30	23.31	65.62	53.08	27.57	80.65
S_2 : 1.0 Epan + 125% N	41.76	24.08	65.84	52.59	28.62	81.21
S_3 : 1.5 Epan + 100% N	45.20	27.04	72.24	60.52	32.57	93.09
S_4 : 1.5 Epan + 125% N	45.24	26.73	71.96	60.13	32.07	92.21
S. Em±	0.87	0.55	1.15	1.13	0.63	1.58
CD (P=0.05)	2.57	1.64	3.43	3.35	1.87	4.68
Interaction						
Sub plot at same main plot						
S. Em±	1.50	0.96	2.00	1.95	1.09	2.73
CD (P=0.05)	NS	NS	NS	5.79	NS	8.11
Main plot at same or different level of sub plot						
S. Em±	1.45	1.06	2.15	2.14	1.36	3.29
CD (P=0.05)	NS	NS	NS	7.14	NS	11.30

Table 7. Phosphorus uptake (kg ha^{-1}) as influenced by rice varieties & levels of nitrogen and irrigation through surface drip

Treatments	P uptake (kg ha^{-1})					
	2022			2023		
	Grain	Straw	Total	Grain	Straw	Total
Main plots: Varieties						
M_1 : KNM-1638	9.88	7.52	17.40	10.89	4.50	15.39
M_2 : JGL-24423	12.48	9.87	22.35	15.52	7.00	22.53
M_3 : DRR Dhan-42	14.40	12.05	26.45	19.65	9.39	29.05
S. Em±	0.37	0.32	0.69	0.55	0.16	0.68
CD (P=0.05)	1.45	1.26	2.69	2.18	0.62	2.68
Sub plots: Irrigation levels vs Nitrogen levels						
S_1 : 1.0 Epan + 100% N	11.43	9.13	20.57	14.33	6.26	20.59
S_2 : 1.0 Epan + 125% N	11.54	9.40	20.94	13.93	6.69	20.62
S_3 : 1.5 Epan + 100% N	13.25	10.52	23.78	16.52	7.70	24.22
S_4 : 1.5 Epan + 125% N	12.79	10.19	22.99	16.64	7.21	23.85
S. Em±	0.40	0.28	0.65	0.47	0.22	0.61
CD (P=0.05)	1.18	0.84	1.94	1.38	0.64	1.81
Interaction						
Sub plot at same main plot						
S. Em±	0.69	0.49	1.13	0.81	0.37	1.06
CD (P=0.05)	NS	NS	NS	NS	NS	NS
Main plot at same or different level of sub plot						
S. Em±	0.70	0.53	1.20	0.89	0.36	1.14
CD (P=0.05)	NS	NS	NS	NS	NS	NS

Potassium uptake

Uptake of potassium (K) by crop as influenced by varieties as well as irrigation and N was analysed statistically and depicted in Table 8. Varieties significantly influenced K uptake by crop during both the years of study. In the first & second years of experimentation significantly higher grain & straw K uptake was registered by variety DRR Dhan-42 (M_3). Irrigation & nitrogen levels significantly influenced K uptake by crop. Irrigation scheduled at 1.5 Epan with 100% N (S_3) recorded significantly higher grain (9.71 kg ha^{-1}), straw (39.24 kg ha^{-1}) and total K (49.95 kgha^{-1}) uptake. It was on par to irrigation scheduled at 1.5 Epan with 125% N. Significantly lower K uptake by crop was registered in irrigation scheduled at 1.0 Epan with 100% N (S_1) and was on par to 1.0 Epan with 125% N (S_2).

Table 8. Potassium uptake (kg ha^{-1}) as influenced by rice varieties & levels of nitrogen and irrigation through surface drip

Treatments	K uptake (kg ha^{-1})					
	2022			2023		
	Grain	Straw	Total	Grain	Straw	Total
Main plots: Varieties						
M_1 : KNM-1638	6.24	20.94	27.18	6.71	22.66	29.37
M_2 : JGL-24423	7.82	31.29	39.11	9.44	34.00	43.44
M_3 : DRR Dhan-42	10.17	52.44	62.61	13.59	55.90	69.49
S. Em±	0.09	0.64	0.65	0.27	0.44	0.61
CD (P=0.05)	0.37	2.53	2.53	1.04	1.73	2.39
Sub plots: Irrigation levels vs Nitrogen levels						
S_1 : 1.0 Epan + 100% N	7.64	31.65	39.29	8.93	34.36	43.28
S_2 : 1.0 Epan + 125% N	7.81	31.94	39.74	9.43	34.44	43.87
S_3 : 1.5 Epan + 100% N	8.53	38.03	46.56	10.89	40.46	51.35
S_4 : 1.5 Epan + 125% N	8.33	37.95	46.27	10.41	40.83	51.24
S. Em±	0.22	1.68	1.77	0.31	1.70	1.93
CD (P=0.05)	0.65	4.98	5.27	0.92	5.06	5.73
Interaction						
Sub plot at same main plot						
S. Em±	0.38	2.90	3.07	0.54	2.95	3.34
CD (P=0.05)	NS	NS	NS	NS	NS	NS
Main plot at same or different level of sub plot						
S. Em±	0.34	2.59	2.74	0.53	2.59	2.95
CD (P=0.05)	NS	NS	NS	NS	NS	NS

Discussion

Root system plays a pivotal role in acquisition of water & nutrients, anchorage, synthesis of plant hormones and also acts as the point of interaction with soil micro flora. Frequent aeration of soil in drip irrigation favours the fibrous root system of rice paving its way for longer roots (Parthasarathy *et al*., 2018). In the present study, it was observed that irrigation scheduled at 1.5 Epan increased root length over irrigation scheduled at 1.0 Epan. Well watered crop of rice produced longer roots than those grown in dry conditions (Gu *et al*., 2017). Higher irrigation schedules could promote congenial soil-moisture conditions leading to better root growth (Ghosh *et al*., 2012). On account of the deeper root system, plants are better able to search deeper soil layers and a larger area of soil for water and nutrients. Larger root system is associated with better resilience to moisture stress in rice (Thakur *et al.*, 2018). Parthasarathy *et al.* (2018) suggested that the optimal water supply in drip irrigation is highly advantageous for good root function. Uncoupling effect of leaf carbon production and its use in root during moisture stress might have resulted in reduced root length in water-limited situations (Muller *et al*., 2011).Vigorous root growth encourages deeper root penetration for larger extraction of sub-surface moisture (Kato *et al*., 2007; Bouman and Tuong, 2001), increased nutrient uptake and N use efficiency (Richards, 2008; Peng and Bouman, 2007). Higher root length recorded in DRR Dhan-42 might have led to higher root dry weight and the reverse is true for KNM-1638. Increased root length favours lateral root branching (Kato and Okami, 2011) which in turn promotes root dry weight. Larger root volume enables better exploration of soil with respect to water & nutrients. Significantly higher dry matter accumulation recorded in DRR Dhan-42 could be attributed to its higher root volume. Higher irrigation schedules could promote congenial soil-moisture conditions leading to better root growth (Ghosh *et al*., 2012). Vigorous root growth encourages deeper root penetration for larger extraction of sub-surface moisture (Kato *et al*., 2007; Bouman and Tuong, 2001) increased nutrient uptake and N use efficiency (Richards, 2008; Peng and Bouman, 2007). Rajesh

and Thanunathan (2003) observed that higher root length and volume favoured increased uptake of nutrients and dry matter accumulation. The higher dry matter accumulation observed at higher irrigation regime (Table 3) could have been resulted from the higher root volume it registered.

Compared to other methods of irrigation in aerobic rice, drip irrigation ensures better wetting pattern, distribution of water in soil and water use by plants (Sharma *et al*., 2013a) which in turn encourages early vigorous vegetative growth (Gurusamy *et al*., 2013). Lower levels of irrigation reduce tiller production and encourage leaf senescence leading to lower assimilatory surface area. This would in turn reduce photosynthesis leading to reduced dry matter production (Sathisha *et al.*, 2022). Reduced dry matter production in moisture stress could be linked to lowered photosynthetic activity coupled with oxidative tissue damage. Under increased irrigation levels, growth attributes of plant increases leading to more dry matter production. Sinaki *et al*. (2007) and Zubaer *et al*. (2007) noted that reduced shoot growth and dry matter production under lower levels of irrigation could be seen as a consequence of reduction in leaf area and the resulting impairment in photosynthesis. Results clearly show that along the same level of irrigation, dose of N did not produce any remarkable difference. Split application of N mediated through fertigation ensured optimum availability of the nutrient that has direct effect on chlorophyll production indirectly affecting the rate of photosynthesis (Subedi *et al*., 2019). The data on N uptake indicates that DRR Dhan-42 recorded a significantly higher N uptake (Table 6). Higher N uptake promotes rate of photosynthesis (Subedi *et al*., 2019) leading to higher dry matter production.

Higher dry matter production registered M_3S_3 & M_3S_4 (Fig. 1) might have been the reason for the higher harvest, as there exists a strong positive correlation between dry matter accumulation and grain yield (Fig. 4). Nitrogen uptake by grain shows a positive correlation with grain yield (Fig. 5). Treatments, M_3S_3 & M_3S_4 reported to have significantly higher grain N uptake (65.02 & 64.21 kg ha^{-1} respectively) paving its way for higher grain yield. M_2S_3, M_2S_4, M_3S_1 & M_3S_2 were found to be statistically comparable to each other. Nitrogen uptake by grain also followed similar trend (Table 6). Nitrogen uptake by grain contributes to 99.47% of explained variation in grain yield (Fig. 5). As a result, grain yield was in line with N uptake. This implies that irrigation scheduled at 1.0 Epan was equally effective to irrigation scheduled at 1.5 Epan in KNM-1638. Dry matter production at harvest also shows similar trend. There was no significant difference between irrigation scheduled at 1.0 Epan & 1.5 Epan in KNM-1638 for dry matter production (Table 3). Dry matter production at harvest contributes to 98.33% of total explained variation in grain yield (Fig. 4). As a result grain yield was in line with dry matter production at harvest.

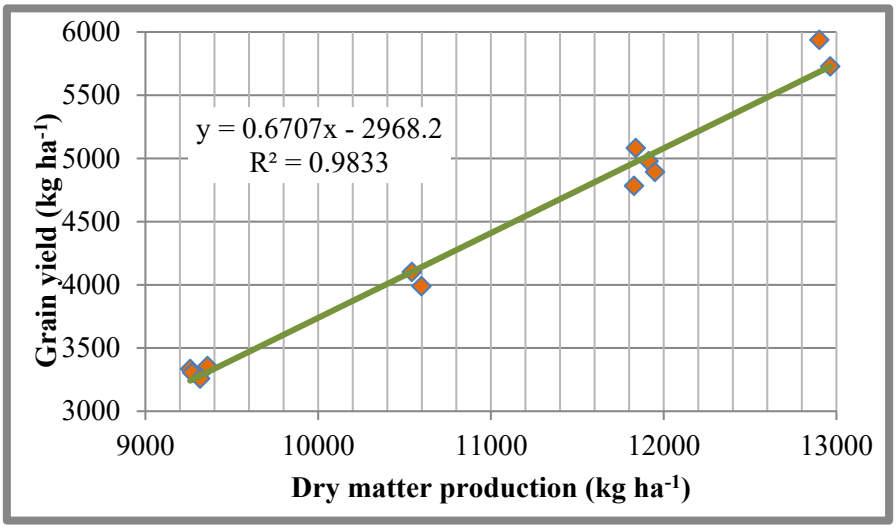


Fig 4 Regression of mean grain yield of dry direct seeded rice on mean dry matter production at harvest

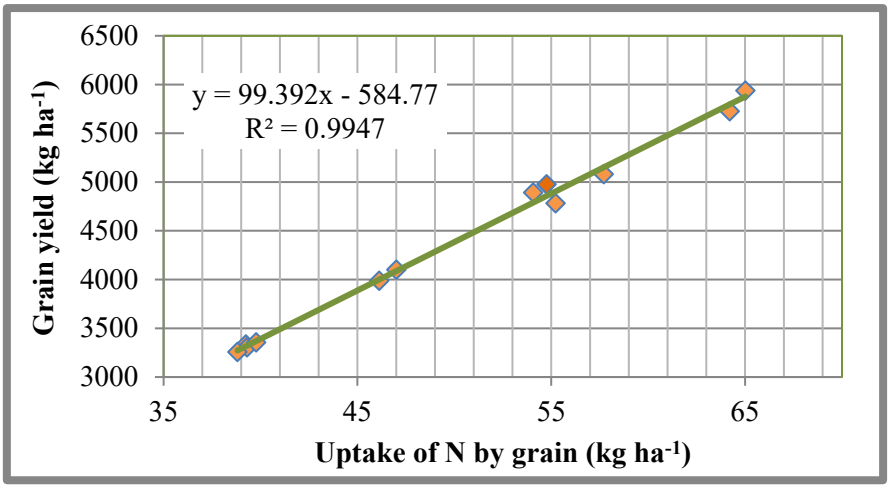


Fig 5 Regression of mean grain yield of dry direct seeded rice on mean N uptake by grain at harvest

Alternate wet dry irrigation favours soil physical, chemical and biological properties. It promotes deep root system, better micro-climate and enables soil micro-organisms to enhance the availability of various nutrients (Stoop *et al*., 2002). Variety DRR Dhan-42 showed significantly higher vegetative growth in terms of dry matter production (Table 3). This signifies the higher N requirement of the crop. Further, DRR Dhan-42 registered higher values for root parameters in terms of root length (Table 2), root volume (Table 2) & root dry weight (Table 2). Significantly higher root parameters combined with higher N demand of the crop might have led its way to significantly higher N uptake finally producing a lower N availability after harvest of the crop. Compared to M_3, M_2 & M_1 produced lower growth which was evident from their dry matter production. As reduced crop growth and development of a variety restricts uptake and utilization of nutrients from soil and increases its availability in soil (Sathisha *et al.,* 2022), M_1 & M_2 registered significantly higher available N than M_3. KNM-1638 (M_1) with lower N uptake (Table 6) was found to have registered significantly higher N availability in the soil. This was in line with the findings of Fageria *et al*. (2010) and Kumar *et al.* (2017) who revealed that rice variety with the lowest nutrient uptake potential was reported to register higher soil available nutrient status. The significantly lower N availability when irrigation was scheduled at 1.5 Epan could be attributed to its higher N uptake. There observed a strong negative correlation between uptake & availability of N in paddy (Fig. 6). The correlation co-efficient was -0.83 with a differential co-efficient of 0.69. The significantly higher values of available N found in 125% N over 100% N within the same irrigation regime could be attributed to the higher dose in the former. It implies that the higher N dose applied rather benefited the soil N status than the crop.

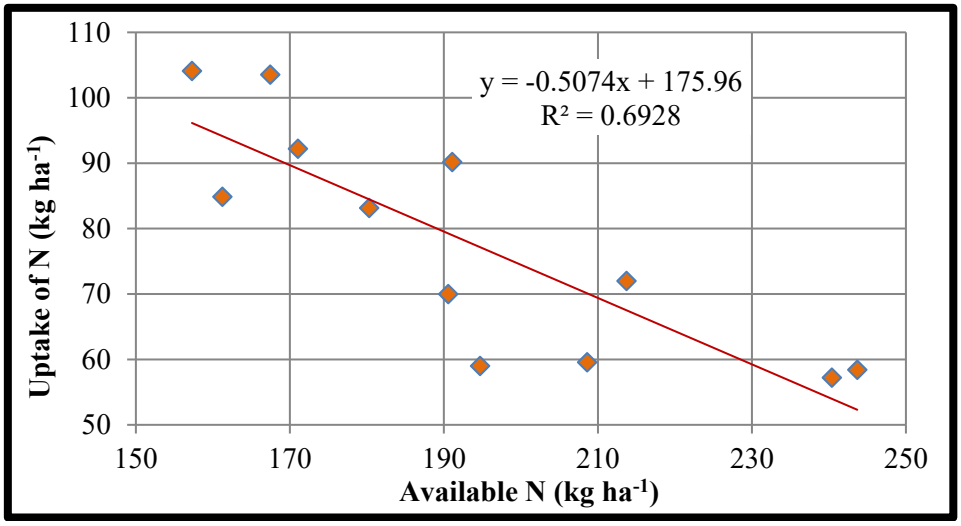


Fig 6 Regression of mean total N uptake by dry direct seeded rice at harvest on mean available N in soil after harvest of crop

The initial available P status of the experiment soil itself was high (48.2 kg ha^{-1}). It was again supplemented by basal application of 60 kg ha^{-1} P as per recommended dose of fertilizers. As a result, there was no traceable difference in available P status, in spite of the difference in P uptake of rice varieties. Phosphorus is highly immobile in soil. Therefore there could have been a difference in P uptake by crop ascribed to the variation in root growth of rice varieties and thereby a variation in available P status. However, it was non-traceable due to the higher initial available P status. Due to the initial high available P status of soil and fertilizer addition of P, there was no traceable difference in mobilization of P by different irrigation regimes. Further, application of urea caused a slight reduction in soil pH bringing it to the neutral range making more soil P available to crop. Fageria *et al.* (2010) observed that application of N by means of urea decreased soil pH and it increased crop yield in paddy.

Varieties did not produce any statistical difference in soil available K status in either years of study. Results are in conformity with the findings of Choudhary and Suri (2014) and He *et al*. (2007). This could be credited to the high initial K status of the soil (528 kg ha^{-1}) which was again supplemented by 40 kg ha^{-1} K via fertigation. Application of fertilizers might have left some residual nutrients in the soil in addition to the nutrients that crops absorb. Devi *et al*. (2012) opined that with the addition of fertilizers root growth of rice substantially increased which on break down add nutrients to soil. The combined effect of all these factors led to non-significant effect on available K after harvest of the crop. There observed no significant difference in available K status of soil owing to irrigation & N levels. Potassium in soil is a less mobile cation. It is soluble in soil water and ensuring optimum soil moisture could have increased the uptake of soil K leading to reduced available K status. However, it was not accountable due to the initial higher available K status of the soil.

The varietal difference for soil N status at periodical intervals of crop growth was hardly traceable as observed in the figures (2a - 2d). During 2022, soil N status was found to increase from 15 DAS to 95 DAS as there were incremental additions of nitrogen mediated through fertigation. After 95^{th} day there was no fertigation event. However, crop uptake would be prominent as this period coincides with flowering. As a result, soil N status steeply goes down past 95 DAS. Between 31 – 63 DAS, soil N status slightly decelerates as observed from Fig. 2c. This could be the consequence of increased crop uptake arising out of the active tillering stage. However, it was not clearly visible at 15 cm distance from the lateral. The increase in N status from 63 - 95 DAS was also obtuse both at 15 cm away from lateral & 30 cm away from the lateral. This could be ascribed to the fact that the given stage is the physiologically active stage of the crop which involves panicle initiation & booting that considerably increases the nutrient demand of the crop resulting in a rather slow increase in nutrient status. At 111 DAS, both at 15 cm away from the lateral as well as 30 cm away from the lateral, soil N status was more for M_1 (KNM-1638), followed by M_2 (JGL-24423). The lowest N availability was observed in M_3 (DRR Dhan-42). This is in line with the soil available N status of post-harvest soil as observed earlier (Table 5). Most of the crop's active nutrient uptake ceases between 95-111 DAS, as grain setting starts in. Since the available N status was less for DRR Dhan-42, it could be concluded that more nutrient uptake might have happened in the given variety than the other 2 varieties which is true as observed in the N uptake studies (Table 6).

The range of available N did not differ prominently between the 2 given distances from the lateral (15 & 30 cm). Each lateral serves 4 rows of crop, 2 each located on either sides of the lateral. Out of which one crop row is located at 10 cm away from the lateral and the other is at 30 cm away from the lateral on either sides of the lateral (Fig. 7). Since there observed no much variation between N status at 15 cm & 30 cm away from the lateral, both the rows of crop will be nourished adequately. Hence one lateral can ideally serve crop rows spread up to 30 cm away from it on both sides. This is the clear indication that the chosen lateral distance is ideal for aerobic rice.

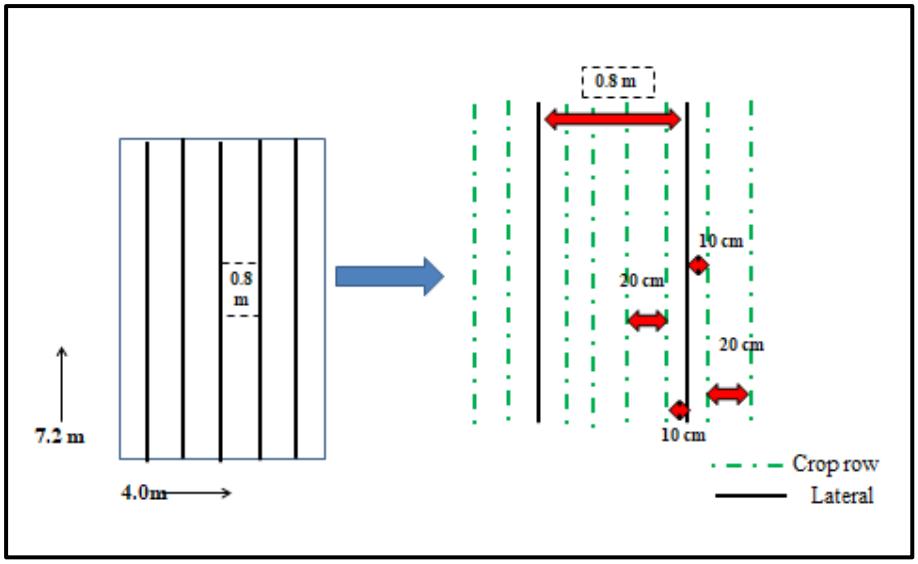


Fig 7 Distribution of drip laterals in the experimental field

During 2023, the initial N status was found to be lesser than that it in 2022. It might be due to the exhaustive N uptake by the previous crop of rice. The initial N status was higher in M_1 during 2023 which was in line with the available N status of the soil after harvest of the crop in 2022. From 15 DAS – 95 DAS, there was increase in N status of the soil similar to 2022 as a consequence of incremental additions of N via fertigation. Similar to 2022, a slight deceleration in N status was observable between 63 & 95 DAS at both 15 cm & 30 cm away from the lateral. At 111 DAS, the lowest N status was observed in M_3 which can be attributed the higher N uptake encountered. There observed not much difference in N status between 15 cm & 30 cm distance away from the lateral.

The variation in soil N status at periodical intervals of crop growth in response to irrigation and nitrogen levels is depicted in Fig 3a to 3d. Maintenance of optimum soil moisture was instrumental in mobilization and uniform spread of N. Although higher dose of N applied was applied in S_2, N status was found to be lower compared to S_3 & S_4. This could have been resulted from the lower volume of applied water in S_2 compared to S_4. Benjamin *et al.* (1997) pointed out that limited moisture condition in the soil limits movement of nitrogen reducing its uptake and use efficiency. The variable distribution of N observed between 2022 & 2023 could be attributed to 31% more rainfall received during 2022. Higher amount of rainfall induces leaching losses of N reducing its availability for crop uptake. At 111 DAS, higher available N was found in S_4 compared to S_3 and in S_2 compared to S_1. Most of the crop's active nutrient uptake ceases between 95-111 DAS, as grain setting starts in. Hence the higher availability of soil N at 111 DAS in S_2 & S_4 indicate that that the higher dose of applied N only improved the soil N status rather than being amenable to crop absorption for more yield and productivity.

There observed clear-cut difference in soil N status between 1.0 Epan & 1.5 Epan at 30 cm away from the lateral than 15 cm. Soil N status at 30 cm away from the lateral in S_3 & S_4 (which received 1.5 Epan irrigation) was more or less similar to soil N status at 15 cm away from the lateral. Adequate soil moisture levels promoted movement and uniform spread N in these treatments. However, in S_1 & S_2 (which received 1.0 Epan irrigation) there was remarkable reduction in soil N status at 30 cm distance from the lateral compared to 15 cm. As a result, 50% of the crop rows might have been nourished inadequately. Significantly lower growth and yield parameters observed in S_1 & S_2 could be attributed to this non-uniform spread of N in response to lower levels of irrigation. Although S_2 received more N, it was incapable of producing higher yields and dry matter owing to the non-uniform distribution of N.

Uptake of N registered strong positive correlation with root dry weight (correlation co-efficient = 0.98, R^2= 0.96) as seen in Fig 8. Significantly higher root dry weight registered by DRR Dhan-42 during all the stages of growth (Table 2) might have led to higher N uptake. Better root system helps in uptake of applied nutrients without leaving them for leaching losses (Stoop *et al*., 2002). However, leaching losses are considerably reduced in drip irrigation wherein water is applied directly to the ball of root (Nagaraju *et al.*, 2017) which enhances nutrient uptake (Jayanthi *et al.*, 2023). In fertigation, frequent application of urea results in the formation of NH_4^+ that gets adsorbed to clay complex and its availability is prolonged. Gradually it gets oxidized to nitrate nitrogen (Rao *et al*., 2003) and become available to crop. Better root capacity ultimately results in high

productivity by way of supplying sufficient nutrients to the shoots leading to high photosynthetic rate (Osaki *et al*., 1997). Nutrient uptake is a function of total dry matter production and nutrient content in the biomass. Increased dry matter production in DRR Dhan-42 (Table 3) might also have led to higher nutrient uptake. The sparse root growth in KNM-1638 as evident from the lower root dry weight (Table 2) & lower dry matter production (Table 2) resulted in poorer nutrient uptake.

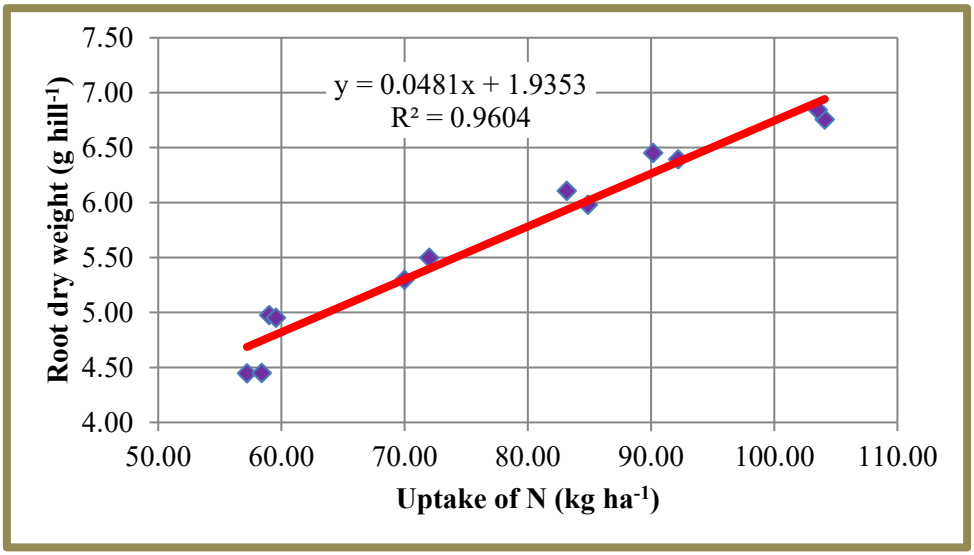


Fig 8 Regression of mean root dry weight at 90 DAS on mean total N uptake by dry direct seeded rice at harvest

Maintenance of optimum soil moisture in the root zone of crop has far reaching benefits stretching out from improvement in root growth & solubilisation of nutrients to favourable effects on soil biological activity. Irrigation through drip maintains soil moisture at or near field capacity level unlike flooded soil, which is ideal for the activity of soil micro flora that makes nutrients available to the crop. Bacterial, fungal and actinomycete population in soil was higher when irrigation was scheduled at 1.5 Epan compared to 1.0 Epan (Sathisha *et al.*, 2023). Beneficial microbes in soil increases uptake of nutrients by way of enhancing N fixation. They act as key regulators of long term soil fertility. The increased nutrient availability at optimum soil moisture regime facilitated higher uptake by the crop. Benjamin *et al.* (1997) pointed out that limited moisture condition in the soil limits movement of nitrogen reducing its uptake and use efficiency. Lower soil moisture limits nitrate reductase activity & nitrification leading to reduced uptake of these nutrients (Jagadish *et al.*, 2019). Maintenance of optimum soil moisture in the root zone of crop helps in mineralization and solubilisation of nutrients favouring its availability and uptake (Venkateswarlu *et al*., 1997). Under higher level of irrigation, growth and vigour of plant was promoted leading to increased photosynthetic rate and higher dry matter accumulation. Higher dry matter accumulation registered in 1.5 Epan irrigation regime might have led to higher nutrient uptake. Along the same level of irrigation, 125% N has lower magnitude for uptake compared to 100% N. This could be ascribed to the fact that higher dose of N promotes shoot growth rather than root growth leading to lower uptake. Reduced N uptake observed at lower irrigation regime might be due to osmotic stress arising at limited moisture condition (Goud *et al.*, 2022b). The non-uniform availability of N at 1.0 Epan compared to 1.5 Epan (Fig. 3c & Fig. 3d) also reduced crop uptake at lower soil moisture regime. Higher N application at reduced moisture condition may adversely affect plant growth and development rather than benefiting it (Halvorson *et al*., 2005).

There observed a strong positive correlation between root volume and P uptake by crop (Fig. 9) with a correlation co-efficient of 0.95 & R^2 = 0.9. Phosphorus being an immobile nutrient in soil, higher root volume enhances the foraging area and aids in greater uptake. As a result, M_3 with significantly higher root volume (Table 2) recorded higher P uptake. The variation in varieties with respect to nutrient uptake can also be seen as the difference in dry matter production and nutrient content in plant tissue (Sathisha *et al.*, 2022). Higher soil moisture regimes maintained by higher irrigation regimes facilitate higher nutrient uptake (Jagadish *et al.*, 2019; Anusha, 2015). Lower soil moisture limits diffusion of P through soil to root surface leading to reduced uptake (Jagadish *et al.*, 2019). Root volume observed in S_3 & S_4 was significantly higher (Table 2) which could be the possible reason for higher uptake as root volume accounts for 90% of the total explained variation in P uptake (Fig. 9). Aerobic soil environment favours growth and proliferation of soil inhabiting microbes (Anita *et al*., 2017). Beneficial microbes in soil increases uptake of nutrients by way of enhancing solubilisation of P.

Significantly lower root volume recorded under irrigation regime of 1.0 Epan resulted in lower P uptake by crop. Sandhu and Mahal (2014) observed that adequate soil moisture increased solubilisation of nutrients particularly phosphorus and thereby its uptake by paddy. Adequate availability of moisture increases solubility of nutrients hence renders it more available for crop uptake which in turn increases the nutrient use efficiency (Prasad *et al*., 2016).

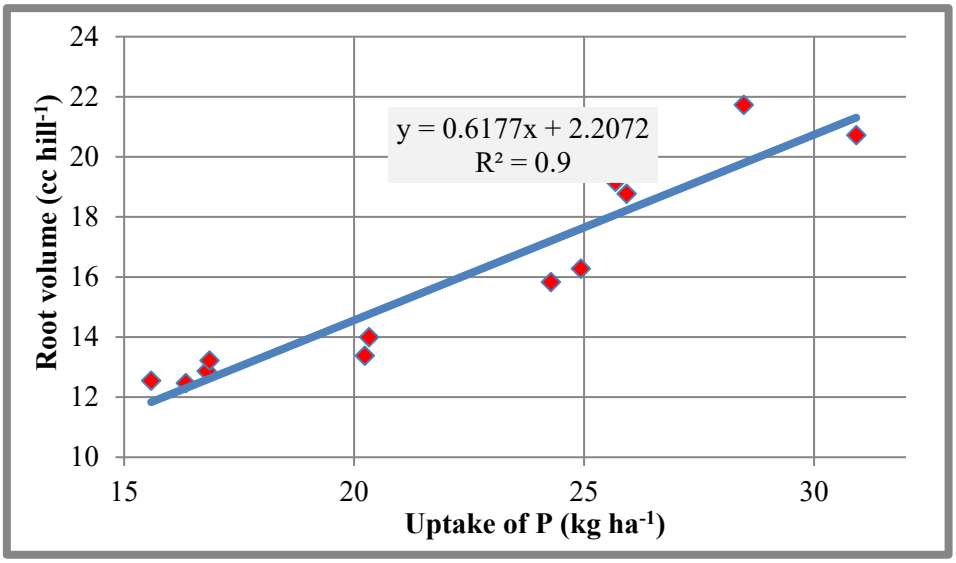


Fig. 9. Regression of mean root volume at 90 DAS on mean total P uptake by dry direct seeded rice at harvest

Increased growth & development of roots might have favoured the uptake of potassium in DRR Dhan-42. Parthasarathy *et al.* (2018) revealed that the primary factor that determines how much water and nutrients are absorbed by crop is its total root length. There observed a strong positive correlation between K uptake & root length (Fig. 10) with correlation co-efficient of 0.99 & $R^2 = 0.99$. Higher soil moisture brings nutrients to soil solution easily and thus makes it more available for plant uptake. Higher levels of irrigation promoted root growth & development that has favourably influenced uptake of K. Making nutrients available at the critical growth stages as well as maintaining adequate moisture in soil increases nutrient uptake by crop (Meisner *et al*., 2002). When nutrients were applied in more splits at lower doses as it is done through fertigation, fixation and leaching losses are reduced making nutrients available for plant uptake (Jayanthi *et al.*, 2023). The ease of nutrient capture was further enhanced due to use of water soluble fertilizers (Jayanthi *et al.*, 2023). Veeranna (2000) has reported the increased uptake of nutrients by crop due to complete solubility, availability and efficiency of water soluble fertilizers compared to conventional fertilizers.

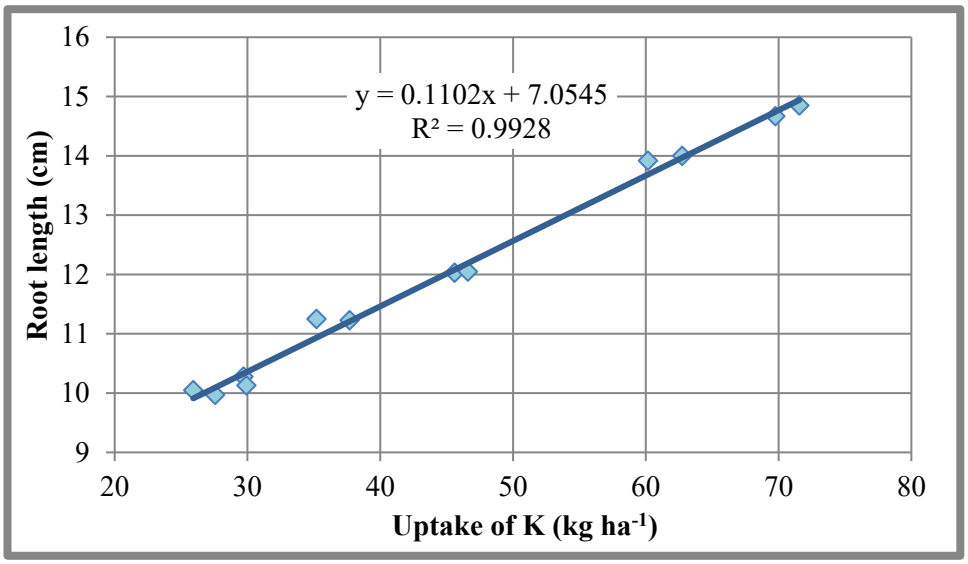


Fig. 10. Regression of mean root length at 90 DAS on mean total K uptake by dry direct seeded rice at harvest

Conclusions

Root growth is a function of varietal characters and irrigation regime. Variety, DRR Dhan-42 recorded higher values for all the root characters and among irrigation regimes, irrigation scheduled at 1.5 Epan registered significantly higher values for root parameters compared to 1.0 Epan. Increased root growth in these treatments in turn resulted in higher dry matter production, nutrient uptake and lower soil available N. DRR Dhan-42 @ 1.5 Epan recorded significantly higher grain yield where there was no significant difference between 100 (5937 kg ha^{-1}) & 125% N (5727 kg ha^{-1}). Available P & K were not significantly influenced by varieties & levels of irrigation & N. Significantly higher available N (221.84 kg ha^{-1}) was registered by KNM-1638. Among sub-plots, significantly higher available N (216.16 kg ha^{-1}) was recorded at 1.0 Epan with 125% N. Soil N status at 15 days interval kept on increasing up to 95 DAS followed by a decline both at 15 & 30 cm away from the lateral. Irrigation scheduled at 1.0 Epan registered lower soil available N status both at 15 & 30 cm away from the lateral compared to irrigation scheduled at 1.5 Epan. Mobilization & spread of N was limited by limited soil moisture availability in 1.0 Epan. The range of available N did not differ prominently between the 2 given distances from the lateral (15 & 30 cm). As a result, the 4 rows of crops 2 each located on either sides of the lateral are nourished adequately. This is the clear indication that the chosen lateral distance is ideal for aerobic rice. Soil N status at 30 cm away from the lateral in S_3 & S_4 (which received 1.5 Epan irrigation) was more or less similar to soil N status at 15 cm away from the lateral. Adequate soil moisture levels promoted movement and uniform spread N in these treatments. However, in S_1 & S_2 (which received 1.0 Epan irrigation) there was remarkable reduction in soil N status at 30 cm distance from the lateral compared to 15 cm. As a result, 50% of the crop rows might have been nourished inadequately. Significantly lower growth and yield parameters observed in S_1 & S_2 could be attributed to this non-uniform spread of N in response to lower levels of irrigation. Although S_2 received more N, it was incapable of producing higher yields and dry matter owing to the non-uniform distribution of N. Significantly higher grain, straw & total uptakes of N, P & K were observed in DRR Dhan-42. Among sub-plots, significantly higher uptake was registered by irrigation scheduled at 1.5 Epan with 100% N which was on par to irrigation scheduled at 1.5 Epan with 125% N. So from the present study, it was concluded that drip irrigation scheduled at 1.5 Epan with 100% N through fertigation was found to be ideal for securing higher yields in dry direct seeded rice and among varieties, DRR Dhan-42 performed ideally under the given sub-plot treatment.

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Competing Interests

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Author Contributions

Conceptualization: K. Suresh; Methodology: K. Suresh, Krishnasree R K; Formal analysis and investigation: Krishnasree R K; Writing - original draft preparation: Krishnasree R K; Writing - review and editing: K. Suresh, Latheef Pasha, Ch Aruna Kumari K Pavan Chandra Reddy; Funding acquisition: K. Suresh; Resources: Md. Latheef Pasha, Ch Aruna Kumari; Supervision: K Pavan Chandra Reddy

Data Availability

The datasets analysed during the current study are available from the corresponding author on reasonable request.