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Research paper

Improving the growth, yield, and quality of ginger (*Zingiber officinale* Rosc.) through irrigation and nutrient management: a study from an Inceptisol of India

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A proper protocol of efficient irrigation and nutrient management for ginger is a necessity for boosting the productivity and quality of the crop in high-intensity cultivated lands. For this, a field experiment for 3 consecutive years was conducted in an Inceptisol of India to optimize irrigation schedule and nutrient management for augmenting rhizome yield and crop water productivity (CWP) of ginger. The trial was laid out in a split plot design with 12 treatment combinations consisting of 4 levels of irrigation schedules viz., rainfed (I_1) and a ratio of 0.6 (I_2), 0.9 (I_3) and 1.2 (I_4) of irrigation water to cumulative pan evaporation (IW/CPE) and 3 levels of nutrient management: 100% recommended dose of fertilizer (RDF) through inorganic (N_1), 75% RDF (inorganic) + 25% RDF through vermicompost (VC) (N_2) and 50% RDF (inorganic) + 50% RDF through VC (N_3). Mean maximum growth and yield components, quality parameters, green rhizome yield (12.63 $Mg{\cdot}ha^{-1}$) and highest nutrient uptake were obtained with I_4N_2, which was statistically on par with I_3N_2. The treatment combination I_1N_2 exhibited maximum CWP. Well-managed irrigation and nutrient scheduling is key to improving ginger production and its marketability for better financial returns.

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INTRODUCTION

Ginger (*Zingiber officinale* Rosc.), belonging to the Zingiberaceae family, is a commercially important herbaceous perennial, usually grown as an annual spice. It is extensively cultivated in the tropical to temperate climates of the world for its flavour, and pungency, and aromatic and healing characteristics associated with its essential oil and oleoresin contents (Srinivasan et al., 2018). India has the largest share in total area under ginger cultivation (34.6%) and annual production (29%) in the world and exports 10–15% of its produce. However, average ginger productivity in India is only 3.6 $Mg{\cdot}ha^{-1}$, far below the global average (Kallappa et al., 2015).

The availability of water is a significant constraint which determines the growth, yield and quality of produce. Excessive or deficit irrigation during critical growth stages negatively affects yield and quality (Pereira et al., 2009). Ginger can be grown under both rainfed and irrigated conditions depending on the frequency and distribution of rainfall (Sharma and Sharma, 2012). The flood method of irrigation is widely practiced, resulting in losses of water to deep percolation, seepage, runoff and evaporation (Arjun, 2009). With a limited water supply, optimum irrigation scheduling is vital to providing a congenial soil water regime in the root zone at the appropriate time (Himanshu et al., 2013). Deficit irrigation is a modern irrigation management strategy in water-scarce areas, maintaining soil moisture below field capacity during some non-critical periods or across the total growing season, and can prevent soil water stress, improve water use efficiency and achieve substantial water-saving with minimum yield decline (Pereira da Silva et al., 2013; Pawar et al., 2020; Tolossa, 2021). The climatological approach of irrigation scheduling based on the ratio of depth of irrigation water to cumulative pan evaporation (IW/CPE) has been widely used as it is simple, easily operative, interpretable and adaptable at the farmer's level (Bandyopadhyay et al., 2005; Lordwin et al., 2007).

Ginger is a shallow-rooted plant and a gross feeder of nutrients and hence requires a plentiful supply of nutrients at critical growth stages. Imbalance, low or no fertilizer application is a constraint which adversely affects growth and yield of rhizomes (Dinesh et al., 2012; Bekeko, 2014). However, the injudicious and indiscriminate use of chemical fertilizers deteriorate the soil's physical, chemical and biological environment, and reduce yield considerably (Patra and Sengupta, 2022). Vermicompost is the bio-degradable product of organic matter by mutual interactions of earthworms and microorganisms. It is an excellent nutrient-rich natural biofertilizer, plant growth promoter, and soil conditioner that supplies primary, secondary, and micronutrients to plants and improves soil properties and yield (Singh and Singh, 2007; Singh et al., 2008). Providing adequate and balanced nutrients by combining organic manures and inorganic chemical fertilizers in suitable proportions remains a viable choice for sustainable crop production, maintaining soil health and safeguarding the environment (Shaikh et al., 2010; Yanthan et al., 2010; Taheri et al., 2011; Ayalew and Dejene, 2012; Singh et al., 2015).

In the Gangetic plains of India, ginger is a promising high-value crop and is growing in popularity due to fetching high prices on the market. The resource-poor small and marginal farmers traditionally grow the crop under rainfed conditions. But due to uncertain or uneven rainfall distribution, the crop experiences water-stressed conditions at different physiological stages, resulting in lower marketable yield and rhizome quality. Many studies have addressed the individual response to integrated nutrient management or irrigation scheduling in improving growth and yield of ginger. But there is little information on the coupling effects of variable water-stressed conditions and integrated nutrient management. The present study was, therefore, conducted to explore the combined effects of irrigation scheduling and nutrient management on growth, yield attribute, fresh rhizome yield and quality, and water productivity of ginger in an Inceptisol of the lower Gangetic plains region of India.

MATERIALS AND METHODS

Experimental site and soil characteristics

The field experiment was conducted on sandy loam soil (69.8% sand, 15.5% silt and 14.7% clay; Typic Fluvaquept) for 3 successive years, 2016-17, 2017-18 and 2018-19, at the Central Research Farm, Regional Research Station, Bidhan Chandra Krishi Viswavidyalaya, Gayeshpur, Nadia, West Bengal, India (22°58’31” N, 88°26’20” E and altitude of 9.75 m amsl). The site has a sub-tropical humid climate with an average annual rainfall of 1 450 mm. The mean monthly meteorological parameters for the crop growth period across the three experimental years are given in Table A1 (Appendix). The groundwater table depth fluctuates from 6.2 to 7.6 m below ground level. The experimental soil (0–20 cm) has a bulk density of 1.49 $Mg \cdot m^{-3}$, hydraulic conductivity of 22.8 $mm \cdot h^{-1}$, field capacity of 52.37% (w/w), permanent wilting point of 15.64% (w/w), pH 6.7, EC 0.37 $dS \cdot m^{-1}$, organic carbon of 5.6 $g \cdot kg^{-1}$, CEC 15.6 $cmol(+) \cdot kg^{-1}$ and is low in available nitrogen (153.7 $kg \cdot ha^{-1}$), medium in available phosphorus (27.8 $kg \cdot ha^{-1}$) and available potassium (145.5 $kg \cdot ha^{-1}$).

Experimental design and treatments

The experiment, comprising 12 treatment combinations, was laid down in a split-plot design with 3 replicates. Four irrigation schedules, viz., I_1 = rainfed, I_2 = 0.6 IW/CPE, I_3 = 0.9 IW/CPE, and I_4 = 1.2 IW/CPE, were assigned in main plots, and 3 nutrient management treatments, viz., N_1 = 100% recommended dose of inorganic fertilizer (RDF), N_2 = 75% RDF + 25% RDF as organic vermicompost (VC), and N_3 = 50% RDF + 50% RDF as VC was allotted in sub-plots.

Agronomic manipulations and data recording

The land was brought to a fine tilth by 3 cross ploughings with a rotary power tiller followed by harrowing and levelling. The experimental field was partitioned into 3 equal blocks and each block divided into 12 sub-plots of 3.5 m × 2.5 m and raised to 0.15 m in height, keeping 0.60 m between beds and a 1.0 m wide irrigation channel between blocks. Disease- and pest-free healthy medium-sized (25–30 cm) rhizomes (cv. Gorubathan) were planted in the raised beds with crop geometry of 0.25 m row to row and 0.25 m plant to plant distance, accommodating a plant population of 140 per plot (160 000 ha^{-1}). The seed rhizomes were planted on 19 April 2016, 12 April 2017 and 15 April 2018 and harvesting was completed on 23 February 2017, 18 February 2018 and 20 February 2019, respectively. The growing period of the crop was 310–312 days. The RDF was $N:P_2O_5:K_2O$::75:50:50 $kg \cdot ha^{-1}$ applied in the form of urea, single superphosphate and muriate of potash. A full dose of P and K and half dose of N, as per adopted treatment schedules, were applied as basal at the time of planting, and the remaining half dose of N was top-dressed in two equal splits at 45 and 90 days. The vermicompost containing 2.5% N, 1.48% P, and 1.2% K was incorporated into the soil as a single basal dose and mixed with the soil during the final land preparation. The routine intercultural and standard plant protection measures were followed uniformly.

Measurements of plant parameters, yield and quality

Five plants from the centre of each treatment and replicate were randomly selected and tagged at the time of harvest, and used to record the growth parameters: plant height; number of leaves per plant; yield attributes like finger length; green (fresh) rhizome yield. The plant height and finger length were determined using a measuring tape, while the number of leaves per plant was counted manually. The quality attributes of fresh rhizome, i.e., essential oil and oleoresin contents, were determined by laboratory analysis.

Irrigation scheduling

Irrigation scheduling was imposed based on irrigation water to cumulative pan evaporation (IW/CPE) ratios of 0.6, 0.9 and 1.2. The depth of irrigation water for each irrigation treatment was 0.05 m. The quantity of water applied was measured with the help of a Parshall flume installed at the head of the experimental plot. The CPE data was monitored from a standard USWB Class A Pan evaporimeter located inside the experimental site. Irrigations were given when IW/CPE ratio reached the target level. The farmers’ practice of non-irrigated (rainfed) treatment was taken as control. The number of irrigations, depending on the rainfall condition, were 1, 1 and 2 for 2016-17; 4, 6 and 7 for 2017-18 and 3, 4 and 5 for 2018-19 at IW/CPE ratio of 0.6, 0.9 and 1.2, respectively. The amount of irrigation water applied under different irrigation schedules is given in Table A2 (Appendix), based upon the crop growth stages of germination (0–30), vegetative (31–90), rhizome initiation (91–135), rhizome development (136–225) and maturity (226–270 days after planting).

Seasonal crop water use

Seasonal crop water use (CWU) or actual crop evapotranspiration (ETa) during the entire growing period (planting to harvest) of ginger was computed by the one-dimensional field water balance equation (Simsek et al., 2005) as follows:

$$\mathrm{ETa} = I + P \pm \Delta\mathrm{SW} - \mathrm{Dp} + \mathrm{Cp} - \mathrm{Rf}$$

where I = irrigation water applied (mm), P = precipitation (mm), ΔSW = change in soil water storage between planting and harvest (mm), Dp = deep percolation (mm), Cp = water use by crop through capillary rise from groundwater table (mm) and Rf = runoff (mm). The effective rooting depth of ginger plants was estimated to be 0.45 m, although periodic soil moisture contents to a depth of 0.60 m were recorded. Cp is assumed to be negligible as the depth of groundwater was 5–6 m below the ground surface. Both Rf and Dp were eliminated, as irrigation water application was carefully managed to prevent bund-overflow or runoff. The portion of rainwater retained in the root zone and extracted by the plant is considered effective rainfall (Patra et al., 2022). Effective rainfall (Re) was calculated by deducting Dp from P. Thus, ETa = I + Re ± ΔSW.

Crop water productivity

The crop water productivity (CWP) is computed as the ratio of rhizome yield to the amount of water depleted by crop evapotranspiration, as proposed by Kang et al. (2009) as CWP = Y/ETa ($kg \cdot m^{-3}$), where Y is fresh rhizome yield ($kg \cdot ha^{-1}$), and ETa is actual seasonal crop evapotranspiration ($m^3 \cdot ha^{-1}$).

Crop yield response factor

Crop yield response factor (Ky) is the response of yield to water use during the crop growing season and was quantified using Stewart’s model (Bhowmik et al., 2020; Saha et al., 2021) as, $\mathrm{Ky} = \frac{1-\mathrm{Ya/Ym}}{1-\mathrm{ETa/ETm}}$ where Ya and Ym are the actual and maximum rhizome yield ($kg \cdot ha^{-1}$), ETa and ETm are the actual and maximum evapotranspiration (mm), and Ky is the yield response factor of ginger to deficit irrigation, i.e., the slope of the linear relationship between the reduction in relative yield and evapotranspiration.

Soil water determination

Profile soil water contents were computed by thermo-gravimetric method at planting, before, and 24 h after, irrigation and rainfall, every fortnight, and at harvest. Treatment-wise, soil samples were collected from the plot centre at 0.15 m depth intervals to a depth of 0.6 m by a soil auger.

Soil and plant analysis

The basic physicochemical and chemical properties of the representative soil samples were analysed for pH and electrical conductivity (EC) using a 1:2 soil to water suspension (Panda and Patra, 2018), organic carbon by wet digestion method (Panda and Patra, 2018), cation exchange capacity (CEC) by NH_4OAc extraction method (Momin et al., 2018), available N (Patra and Sengupta, 2022), available P (Sengupta et al., 2021) and available K (Dasgupta et al., 2021). The soil mechanical composition was determined by the hydrometer method (Saha et al., 2021), while the bulk density, saturated hydraulic conductivity (HC), field capacity (FC) and permanent wilting point (PWP) were estimated using the standard methods (Momin et al., 2018). Whole plant samples (both below- and above-ground parts) were collected at maturity, dried, ground to fine powder, digested in the triacid mixture (HNO_3:$HClO_4$:H_2SO_4 : 10:4:1, v/v) and N, P and K concentrations in the extract were determined (Saha et al., 2021). The nutrient uptake by the plant was calculated as the product of the concentration of the respective element and dry matter yield. The quality parameters assessed through the essential oil (% v/w) and the oleoresin contents of fresh ginger were determined by petroleum ether and by hexane solvent, respectively, following the methods of Sadasivam and Manickam (1996).

Statistical analysis

The data obtained for plant and soil variables were subjected to one-way analysis of variance techniques using Microsoft Excel 2016 and R-studio. Statistical significance between means of individual treatments and their interactions were assessed using the Fisher's least significant difference (LSD) test at $p \le 0.05$ (Gomez and Gomez, 1984). Analysis of one-way ANOVA revealed that the variations in data across the cropping seasons and the interaction effects between year × irrigation and year × nutrient management were not significantly different. Further, since the variation in data across the experimental years was estimated to be homogeneous by performing Bartlett's chi-square test, and interactions between irrigation and nutrient management were almost similar, the year variance was pooled with the experimental error variance to draw the inferences.

RESULTS AND DISCUSSION

Effect of irrigation and nutrition on fresh rhizome yield, growth and yield attributes

Irrigation and nutrient management had significant influences on fresh rhizome yield in each experimental year and for the pooled values (Table 1) and growth and yield attributes (Table 2) of ginger.

Table 1. Effect of different irrigation schedules and nutrient management on green rhizome yield of ginger during the three growing seasons

Treatment	Green rhizome yield ($Mg \cdot ha^{-1}$)			
	2016-17*	2017-18*	2018-19*	Pooled
Irrigation (I)				
I_1	6.87	7.23	7.20	7.10
I_2	8.62	8.90	8.76	8.76
I_3	10.83	11.06	10.66	10.85
I_4	10.88	11.14	10.73	10.92
LSD (p = 0.05)	1.53	1.47	1.51	1.48
Nutrient management (N)				
N_1	9.48	9.73	9.46	9.56
N_2	10.57	10.92	10.38	10.62
N_3	7.86	8.10	8.17	8.05
LSD (p = 0.05)	0.83	0.87	0.75	0.84
Interaction (I × N)				
I_1N_1	6.75	7.22	7.17	7.05
I_1N_2	7.36	7.65	7.52	7.51
I_1N_3	6.51	6.81	6.91	6.74
I_2N_1	8.41	8.61	8.53	8.52
I_2N_2	9.52	9.85	9.59	9.65
I_2N_3	7.93	8.23	8.16	8.11
I_3N_1	11.35	11.52	11.05	11.31
I_3N_2	12.67	13.02	12.19	12.63
I_3N_3	8.48	8.63	8.74	8.62
I_4N_1	11.39	11.57	11.07	11.34
I_4N_2	12.71	13.15	12.23	12.70
I_4N_3	8.53	8.71	8.88	8.71
LSD (P = 0.05)	1.65	1.72	1.29	1.53

I_1: rainfed, I_2: irrigation at 0.6 IW/CPE, I_3: irrigation at 0.9 IW/CPE, I_4: irrigation at 1.2 IW/CPE; N_1: 100% RDF as fertilizers, N_2: 75% RDF as fertilizers + 25% RDF as vermicompost, N_3: 50% RDF as fertilizers + 50% RDF as vermicompost; RDF (recommended dose of fertilizer): 75:50:50 kg N, P_2O_5, K_2O ha^{-1}; IW: irrigation water at 50 mm depth, CPE: cumulative pan evaporation.

**The seed rhizomes were planted on 19 April 2016, 12 April 2017 and 15 April 2018 and harvesting was completed on 23 February 2017, 18 February 2018 and 20 February 2019, respectively.*

Table 2. Effect of different irrigation scheduling and nutrient management on growth attributes and quality parameters of ginger plants (pooled data of 3 years)

Treatment	Plant height (cm)	Leaves · plant^{-1}	Finger length (cm)	Essential oil (%)	Oleoresin (%)
		Irrigation (I)			
I_1	60.84	18.39	3.38	0.38	3.42
I_2	65.44	19.66	3.46	0.39	3.51
I_3	70.22	21.85	3.65	0.42	3.72
I_4	70.70	21.98	3.72	0.43	3.75
LSD (p = 0.05)	1.47	0.65	0.07	0.02	0.06
		Nutrient management (N)			
N_1	65.92	20.02	3.54	0.40	3.61
N_2	70.78	22.15	3.70	0.45	3.74
N_3	63.70	19.25	3.42	0.37	3.46
LSD (p = 0.05)	1.85	0.59	0.08	0.02	0.09
		Interaction (I × N)			
I_1N_1	60.92	18.31	3.36	0.37	3.41
I_1N_2	64.31	19.23	3.47	0.41	3.49
I_1N_3	57.28	17.63	3.31	0.35	3.35
I_2N_1	63.58	19.12	3.41	0.39	3.53
I_2N_2	70.82	21.50	3.58	0.44	3.62
I_2N_3	61.93	18.37	3.38	0.36	3.38
I_3N_1	69.32	21.24	3.67	0.42	3.72
I_3N_2	73.84	23.89	3.83	0.46	3.91
I_3N_3	67.51	20.42	3.45	0.38	3.54
I_4N_1	69.86	21.39	3.73	0.42	3.77
I_4N_2	74.15	23.97	3.91	0.47	3.93
I_4N_3	68.08	20.58	3.52	0.39	3.56
LSD (p = 0.05)	4.97	2.85	0.29	0.06	0.24

I_1: rainfed, I_2: irrigation at 0.6 IW/CPE, I_3: irrigation at 0.9 IW/CPE, I_4: irrigation at 1.2 IW/CPE; N_1: 100% RDF as fertilizers, N_2: 75% RDF as fertilizers + 25% RDF as vermicompost, N_3: 50% RDF as fertilizers + 50% RDF as vermicompost; RDF (recommended dose of fertilizer): 75:50:50 kg N, P_2O_5, K_2O ha^{-1}; IW: irrigation water at 50 mm depth, CPE: cumulative pan evaporation

The comparatively higher yield was noticed during the 2017-18 experimental season, mainly due to prevailing well-distributed low-intensity rainfall, high evaporation and climatic temperature, and better management of different irrigation interventions all along the plant growth stages (Table A1, Appendix). In 2016-17 and 2018-19 growing seasons, uneven distribution of very high intensity rainfall followed by high levels of deep percolation loss of water (1 598 mm and 3 698 mm) at rhizome initiation (90–135 DAP) and vegetative period (20–90 DAP), respectively, and less evaporation and lower temperature resulted in relatively lower rhizome yield. The pooled data over 3 years showed that the highest average rhizome yield of 10.92 Mg·ha^{-1} was obtained with I_4, which was on par with marginal water stress regime I_3 (10.85 Mg·ha^{-1}). However, both irrigation treatments were statistically superior to the high water stress regime I_2 (8.76 Mg·ha^{-1}). The yield improvement in I_4 and I_3 was mainly due to increased growth and yield constituents in respect of tallest plants, increased number of leaves per plant and longest finger length due to higher irrigation regimes (Table 2). The lowest average rhizome yield (7.10 Mg·ha^{-1}) was found in I_1, with stunted plant height, decreased number of leaves per plant, and smallest finger length. The overall decrease in yield in the varying deficit irrigation regime of I_1, I_2 and I_3 compared to I_4 was 35.0, 19.8 and 0.6%, respectively. It is evident from the computed periodic soil moisture data (Figs 1 and 2) that during the first, second and third years of the experiment the magnitude of soil water storage under 4 irrigation schedules were in the order of $I_4 > I_3 > I_2 > I_1$. In contrast, the magnitude of soil water depletion follows $I_1 > I_2 > I_3 > I_4$. This amply indicates that high soil water stress in rainfed conditions (I_1), as well as in the higher level of deficit irrigation scheduling (I_2), proved to be detrimental to ginger plants, leading to the drastic reduction of rhizome yield, especially during rhizome initiation and rhizome bulking stage in the rainfed situation (Singh et al., 2015).

Water-stressed treatments, due to nil or low amount of irrigation water supply, as compared with well-watered treatments, might have caused more negative effects on plant height, yield attributes and finally rhizome yield by way of depressed crop canopy, greater stomatal closing and lower photosynthetic area, which eventually decreased photosynthesis and translocation to lower storage organs (Gatabazi et al., 2019). These findings agree with those of Islam et al. (2015) that irrigation treatment in a dry period produced enhanced vegetative growth and more leaves per plant, which likely contributed to higher photosynthesis and accumulation of more food material in the underground rhizome. A contrasting result was obtained by Arjun (2009) in the semi-arid tropics of India, where the application of irrigation through a floppy sprinkler system followed by overhead sprinkler and drip irrigation recorded higher growth, yield attributes and fresh rhizome yield of ginger than surface irrigation. Maintaining a marginal deficit irrigation regime (I_3) across the growth stages was the best irrigation treatment, due to better distribution of water around the root zone and concomitant utilization by plants.

The treatment N_2 recorded the highest fresh rhizome yield in each growing season and for the pooled data over 3 years, and was significantly superior to N_1 and N_3. Mean maximum yield was obtained with treatment N_2 (10.62 Mg·ha^{-1}) followed by treatment N_1 (9.56 Mg·ha^{-1}) and the lowest yield with treatment N_3 (8.05 Mg·ha^{-1}). Increased rhizome yield in N_2 could be attributed to the balanced and continuous supply of macro-and micronutrients to ginger plants, where inorganic fertilizers provide readily available nutrients during early growth stages and vermicompost slowly releases nutrients throughout the growth period, which resulted in better growth, yield raising components and higher green rhizome production (Das et al., 2020). It is notable that when more than 25% of expensive chemical fertilizers in RDF

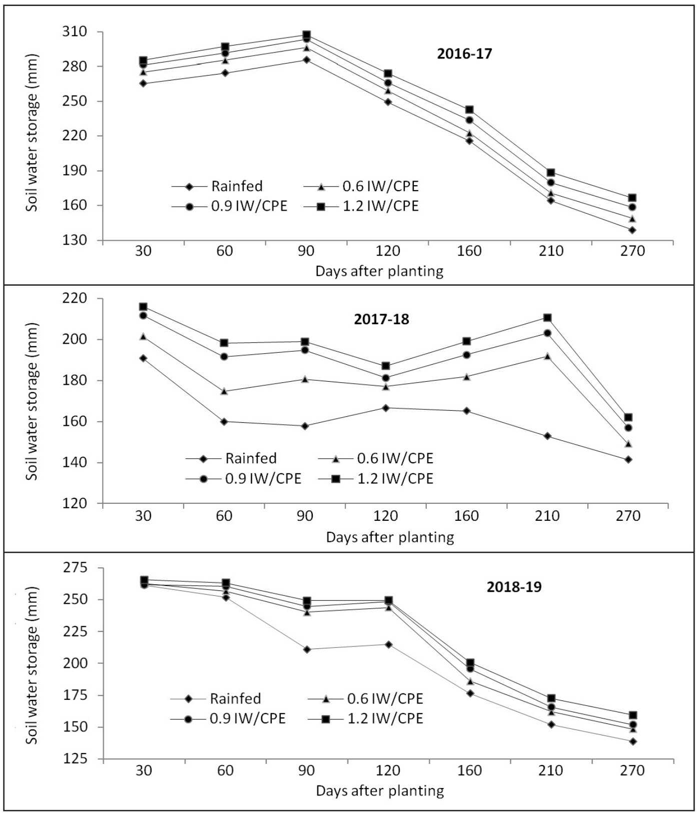

Figure 1. Soil water storage under different irrigation scheduling at different growth stages of ginger plants during the three cropping seasons. Seed rhizomes were planted on 19 April 2016, 12 April 2017 and 15 April 2018 and harvesting was completed on 23 February 2017, 18 February 2018 and 20 February 2019, respectively.

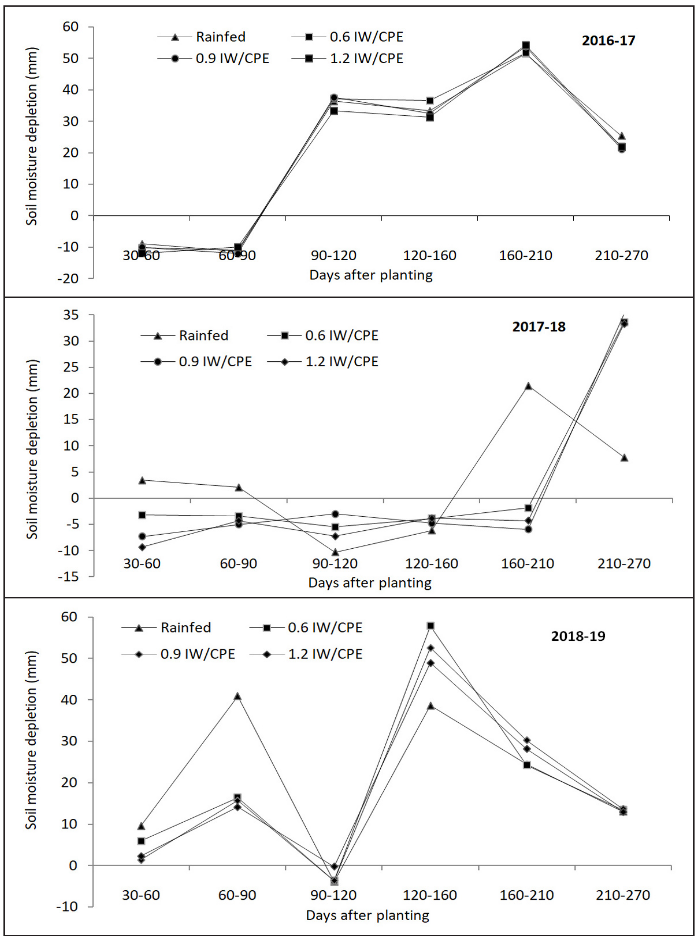

Figure 2. Soil water depletion under different irrigation scheduling at different growth stages of ginger plants during the three cropping seasons. Seed rhizomes were planted on 19 April 2016, 12 April 2017 and 15 April 2018 and harvesting was completed on 23 February 2017, 18 February 2018 and 20 February 2019, respectively.

are substituted by applying organic VC, there is a direct positive influence on growth and yield components. Similar findings were noted by Arjun (2009) and Shaikh et al. (2010) that RDF as mineral fertilizer supplemented with farmyard manure at 25 Mg·ha^{-1} gave maximum green rhizome yield of ginger. In our study, the application of 100% RDF as soluble fertilizers in split doses recorded moderate yield, presumably due to higher losses of nutrients in deep percolation, due to high intensity of rainfall, thereby causing lower plant nutrient uptake. On the other hand, the dual application of 50% RDF as inorganic fertilizers and 50% RDF as organic VC recorded the lowest rhizome yield in all seasons and pooled value (7.86 Mg·ha^{-1} for 2016-17, 8.10 Mg·ha^{-1} for 2017-18, 8.17 Mg·ha^{-1} for 2018-19 and 8.05 Mg·ha^{-1} for pooled data). This could be attributed to slow mineralization and low release of nutrients from organic vermicompost, which did not match plant nutrient requirements at all growth stages.

The interaction effects between irrigation scheduling and nutrient management on growth attributes, yield enhancing component, and fresh rhizome yield were significant in all three seasons and for pooled data (Tables 1 and 2). The highest yield of 12.71, 13.15, 12.23 and 12.70 Mg·ha^{-1} during the growing seasons and in the pooled analysis (described earlier), respectively, was obtained with I_4N_2 and was statistically on par with I_4N_1, I_3N_2 and I_3N_1. This indicated that higher or marginal deficit level of irrigation (I_4 and I_3), coupled with adequate nutrient supply, either through inorganic fertilizers alone (N_1) or integration of inorganic fertilizers and organic vermicompost at a 3:1 ratio in the recommended nutrient schedule (N_2), registered higher growth, yield components and rhizome yields of ginger as a result of higher water and nutrient uptake under favourable soil water–nutrient regimes across the growth stages. Conversely, the significantly lowest green rhizome yield was observed under I_1N_3. This was mainly due to high water stress experienced under rainfed conditions (I_1), coupled with low nutrient supply through the conjoint application of readily available inorganic fertilizers and slowly available organic vermicompost at 1:1 proportion (N_3), resulting in low availability and utilization of water and nutrients by plants. The results support the findings of Arjun (2009) that significant interactions effects exist between irrigation and integrated nutrient management on the fresh rhizome yield of ginger.

Effect of irrigation and nutrition on quality parameters

The pooled data over the three years (Table 2) showed significant differences in the effects of irrigation and nutrition on ginger quality, evaluated through essential oil and oleoresin components. Irrigation I_4 produced mean maximum essential oil (0.43%) and oleoresin (3.75%) contents statistically on par with irrigation I_3. Mean minimum essential oil and oleoresin contents were obtained in irrigation I_1. This revealed that increased water application greatly influenced ginger's essential oil and oleoresin contents.

Likewise, the highest average essential oil and oleoresin contents (0.45 and 3.74%, respectively) were accomplished with treatment N_2 which was significantly superior to other nutrient treatments. By contrast, the lowest average contents of essential oil and oleoresin were found with treatment N_3. Treatment N_1 demonstrated intermediate essential oil and oleoresin contents. Yanthan et al. (2010) recorded the maximum oil yield and oleoresin content with 50% NPK + 50% pig manure application. However, based on 2-year pooled data, Arjun (2009) found maximum oleoresin content with 100% RDN (recommended dose of nitrogen) through organic sources and 75% RDN through organic sources plus 25% RDN through inorganic fertilizer.

The interaction results showed that I_4N_2 yielded the highest essential oil (0.47%) and oleoresin (3.93%) contents, which were statistically similar with I_4N_1, I_3N_2 and I_3N_1. On the other hand, I_1N_3 produced the lowest essential oil and oleoresin contents. The results indicated that higher or marginal deficit irrigation scheduling, accompanied with full RDF or 75% RDF + 25% RDF as VC, resulted in maximum quality attributes of ginger, which is in line with the observations of Seyie et al. (2013).

Seasonal crop water use

The soil water balance components, including ETa and CWP, during the three crop growing periods and for their pooled values are shown in Table 3. The amount of irrigation water applied varied between years based on rainfall and soil water storage distribution. The profile water contribution (PWC) in each experimental year did not vary much; however, the contribution was less during the season of 2017-18, presumably due to the greater depth of the groundwater table due to the relatively lower amount of rainfall received. The amount of effective rainfall during 2017-18 (141 mm) was much less than in 2016-17 (280 mm) and 2018-19 (180 mm). This was due to well-distributed low rainfall intensity all along the growing stages. About 992 mm water out of 1 133 mm of rainfall received was lost to deep percolation, particularly in the rhizome initiation stage. During the growing season of 2016-17, deep percolation loss was about 1 598 mm out of 1 878 mm rainfall received in the cropping period; the maximum loss occurred in vegetative and rhizome initiation stages. In the third growing season, deep percolation loss was about 3 698 mm, especially in the vegetative growth stage (404 mm at 33 days after planting and 1 402 mm at 59 days) out of the maximum 3 878 mm rainfall received, resulting in moderate Re. Irrigation water applied in I_2, I_3 and I_4 was 133.3, 183.3 and 233.3 mm, respectively. The average Re during the experimental years was 200.5 mm each for I_2, I_3 and I_4, while under the rainfed condition it was slightly higher at 228.8 mm. Average PWC, irrespective of adopted irrigation regimes, varied from 19.8 to 22.1 mm. The drier irrigation regime was found to contribute relatively higher soil profile water than wetter irrigation regimes. Thus, the average ETa was 355.0, 404.1 and 454.4 mm for I_2, I_3 and I_4, respectively, and 250.0 mm for I_1.

Crop water productivity

The mean maximum CWP (3.00 kg m^{-3}) was found in I_1, which indicates that whatever water was received from Re and PWC was effectively used for promoting rhizome yield (Table 3). The next higher mean CWP was achieved with I_3 (2.72 kg m^{-3}) which was ascribed to the proportional increase in rhizome yield with a marginal deficit irrigation schedule (Gatabazi et al., 2019). Higher levels of deficit (I_2) and surplus (I_4) irrigation scheduling recorded lower CWP, ranging from 2.43 to 2.47 kg·m^{-3}, indicating that low and excess amounts of irrigation water are harmful for rhizome production. Regarding nutrient management, treatment N_2 accomplished the highest CWP (2.97 kg·m^{-3}) in comparison with N_1 and N_3. This was ascribed to the better supply of more and slow-releasing nutrients through the combined application of inorganic fertilizers and organic VC (Roy and Hore, 2007; Nair, 2019). The interaction effects reveal maximum CWP (3.17 kg·m^{-3}) in I_1N_2, immediately followed by I_3N_2 (3.16 kg·m^{-3}) and minimum (1.94 kg·m^{-3}) in I_4N_3. The remaining irrigation–nutrient treatment combinations showed intermediate CWP. The results also revealed that a marginal deficit irrigation schedule (I_3) coupled with nutrients through inorganic fertilizers and organic vermicompost at a 3:1 ratio in the prescribed RDF (N_2) was suitable for attaining a favourable soil water–nutrient environment around the crop root zone. This might have stimulated better plant growth and development (Dinesh et al., 2012) due to greater absorption of available water and nutrients that resulted in higher green rhizome yield.

Table 3. Components of soil water balance, seasonal water use (ETa) and crop water productivity (CWP) of ginger under different irrigations and nutrient management

Treatment	2016-17*					2017-18*					2018-19*					Pooled				
	PWC (mm)	I (mm)	ER (mm)	ETa (mm)	CWP ($kg \cdot m^{-3}$)	PWC (mm)	I (mm)	ER (mm)	ETa (mm)	CWP ($kg \cdot m^{-3}$)	PWC (mm)	I (mm)	ER (mm)	ETa (mm)	CWP ($kg \cdot m^{-3}$)	PWC (mm)	I (mm)	ER (mm)	ETa (mm)	CWP ($kg \cdot m^{-3}$)
Irrigation (I)																				
I_1	22.8	0	311.3	334.2	2.06	19.8	0	169.7	189.5	3.81	23.7	0	205.4	229.0	3.14	22.1	0	228.8	250.9	3.00
I_2	22.0	50	280.0	352.0	2.45	18.6	200	141.4	360.0	2.47	23.2	150	180.0	353.2	2.48	21.2	133.3	200.5	355.0	2.47
I_3	20.9	50	280.0	350.9	3.09	18.1	300	141.4	459.5	2.41	21.8	200	180.0	401.8	2.65	20.3	183.3	200.5	404.1	2.72
I_4	20.4	100	280.0	400.4	2.72	17.8	350	141.4	509.2	2.19	21.1	250	180.0	451.1	2.38	19.8	233.3	200.5	453.6	2.43
LSD ($p = 0.05$)					0.22					0.24					0.18					0.21
Nutrient management (N)																				
N_1	21.2	50	287.8	359.1	2.62	18.3	213	148.5	379.2	2.75	22.1	150	186.3	358.4	2.69	20.5	137.5	207.5	365.6	2.69
N_2	21.5	50	287.8	359.4	2.92	18.6	213	148.5	379.6	3.05	22.5	150	186.3	358.8	2.94	20.9	137.5	207.5	365.9	2.97
N_3	21.8	50	287.8	359.7	2.19	18.9	213	148.5	379.8	2.36	22.8	150	186.3	359.1	2.37	21.2	137.5	207.5	366.2	2.31
LSD ($p = 0.05$)					0.26					0.27					0.22					0.24
Interaction (I × N)																				
I_1N_1	22.3	0	311.3	333.7	2.02	19.4	0	169.7	189.1	3.82	23.2	0	205.4	228.6	3.14	21.7	0	228.8	250.5	2.99
I_1N_2	22.9	0	311.3	334.2	2.20	19.9	0	169.7	189.5	4.04	23.8	0	205.4	229.1	3.28	22.2	0	228.8	251.0	3.17
I_1N_3	23.3	0	311.3	334.6	1.95	20.2	0	169.7	189.8	3.59	24.0	0	205.4	229.4	3.01	22.5	0	228.8	251.3	2.85
I_2N_1	21.7	50	280.0	351.7	2.39	18.1	200	141.4	359.5	2.39	22.9	150	180.0	352.9	2.42	20.9	133.3	200.5	354.7	2.40
I_2N_2	22.0	50	280.0	352.0	2.70	18.7	200	141.4	360.1	2.74	23.2	150	180.0	353.2	2.72	21.3	133.3	200.5	355.1	2.72
I_2N_3	22.3	50	280.0	352.3	2.25	18.9	200	141.4	360.3	2.28	23.5	150	180.0	353.5	2.31	21.6	133.3	200.5	355.4	2.28
I_3N_1	20.7	50	280.0	350.8	3.24	17.9	300	141.4	459.3	2.51	21.3	200	180.0	401.3	2.75	20.0	183.3	200.5	403.8	2.83
I_3N_2	20.9	50	280.0	350.9	3.61	18.0	300	141.4	459.4	2.83	21.9	200	180.0	401.9	3.03	20.3	183.3	200.5	404.1	3.16
I_3N_3	21.1	50	280.0	351.1	2.42	18.3	300	141.4	459.7	1.88	22.2	200	180.0	402.2	2.17	20.5	183.3	200.5	404.3	2.16
I_4N_1	20.1	100	280.0	400.2	2.85	17.6	350	141.4	509.0	2.27	20.8	250	180.0	450.8	2.46	19.5	233.3	200.5	453.3	2.53
I_4N_2	20.4	100	280.0	400.4	3.17	17.8	350	141.4	509.2	2.58	21.1	250	180.0	451.1	2.71	19.8	233.3	200.5	453.6	2.82
I_4N_3	20.7	100	280.0	400.7	2.13	18.1	350	141.4	509.5	1.71	21.4	250	180.0	451.4	1.97	20.0	233.3	200.5	453.8	1.94
LSD ($p = 0.05$)					0.41					0.37					0.31					0.34

I_1: rainfed, I_2: irrigation at 0.6 IW/CPE, I_3: irrigation at 0.9 IW/CPE, I_4: irrigation at 1.2 IW/CPE; N_1: 100% RDF as fertilizers, N_2: 75% RDF as fertilizers + 25% RDF as vermicompost, N_3: 50% RDF as fertilizers + 50% RDF as vermicompost; RDF (recommended dose of fertilizer): 75:50:50 kg N, P_2O_5, K_2O ha^{-1}, IW: irrigation water at 50 mm depth, CPE: cumulative pan evaporation, PWC: profile water contribution, I: Irrigation applied, ER: effective rainfall, CWP: crop water productivity.

**The seed rhizomes were planted on 19 April 2016, 12 April 2017 and 15 April 2018 and harvesting was completed on 23 February 2017, 18 February 2018 and 20 February 2019, respectively.*

Water-yield production function

The relationship between green rhizome yield (*Y*) and *I* and *Y* and ETa for the three growing seasons and their overall values was analysed through linear regression. Green rhizome yield (*Y*) was plotted against the independent variables *I* and ETa, to derive best-fit mathematical functions (Fig. 3). There were strong linear relationships between *Y* and *I* and between *Y* and ETa during the second and third seasons, as well as the overall 3-year data, with $R^2 > 0.92$. These relationships indicate that the yield increased linearly with a concomitant increase in seasonal irrigation and ETa, and the magnitudes differed variably in each experimental year. *I* has a greater contribution to yield maximization than the Re and PWC components of ETa. These predictive equations can serve as yield harnessing guidelines under variable irrigation water supply. These findings align with Yazar et al. (2009), who found a similar linear relationship between corn grain yield and seasonal irrigation water under Mediterranean climatic conditions in Southern Turkey. Bhowmik et al. (2020) also noticed a significant linear function between cowpea seed yield and irrigation water in the humid sub-tropical climate of India.

Crop yield response factor (Ky)

The mathematical relationship between (1 – ETa/ETm) and (1 – Ya/Ym) for the ginger plant is portrayed in Fig. 4. The average seasonal Ky value for the entire growing season was 0.77, with a high R^2 value of 0.92, which explained an average slope of 0.77% yield decline for every 1% reduction in seasonal ETa. Table 4 showed that high Ky was observed in I_2 followed by I_1, indicating the plant will incur a substantial yield decline if soil water deficit is not replenished at the correct times. According to Patra et al. (2022), if Ky < 1.0, the decrease in yield is proportionally lower with increasing soil water deficit. As the test crop is shallow-rooted and highly sensitive to soil water deficit, optimising the water regime in the root zone by adopting proper irrigation scheduling based on the IW/CPE ratio at all physiological stages of the ginger plant is thus imperative (Nwaogu, 2014).

Nutrient uptake of ginger

The pooled data of 3 cropping years for nutrient uptake showed that the ginger plant's N, P and K contents at harvest were significantly affected by imposed irrigation scheduling and nutrient management and their mutual combinations (Table 5). Mean maximum uptake of 134.36, 44.78 and 142.45 $kg \cdot ha^{-1}$ for N, P and K, respectively, was obtained with I_4, which was significantly on par with that of I_3. Both treatments were superior to the remaining two irrigation treatments. On the other hand, mean minimum N, P and K uptake were noted for I_1. The results indicate that zero and mild soil water stress due to higher irrigation (I_4)

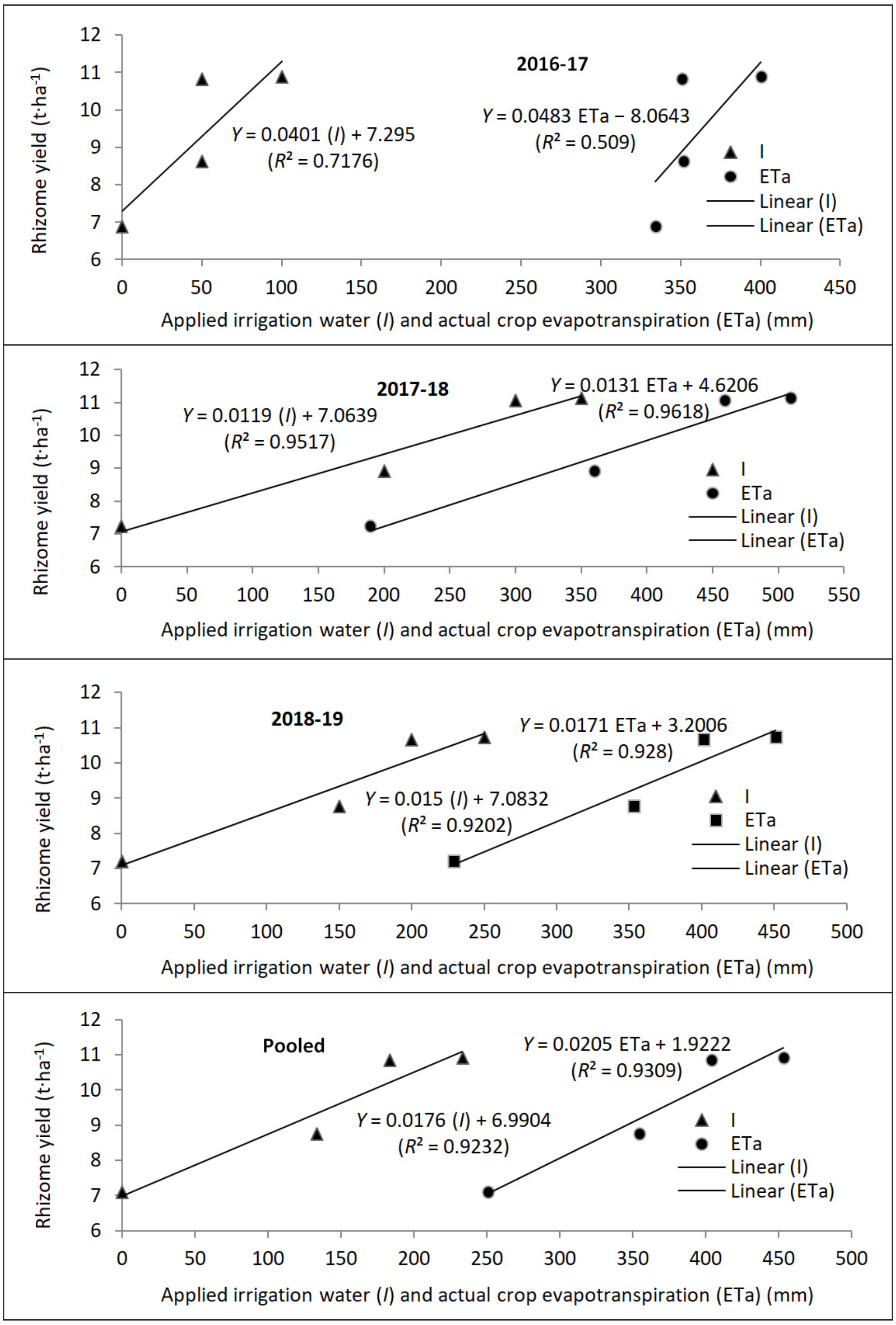

Figure 3. Relationships between ginger green rhizome yield (Y) with seasonal irrigation water (I) and actual crop evapotranspiration (ETa) during growing seasons. Seed rhizomes were planted on 19 April 2016, 12 April 2017 and 15 April 2018 and harvesting was completed on 23 February 2017, 18 February 2018 and 20 February 2019, respectively.

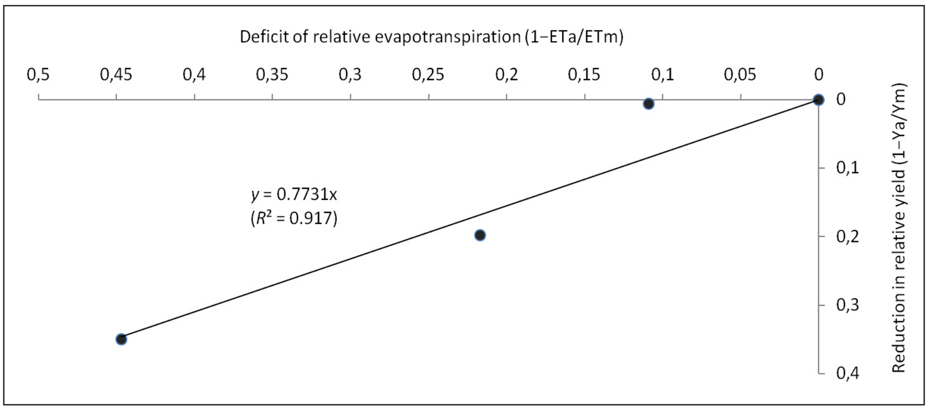

Figure 4. Relationship between the relative yield deficit and relative evapotranspiration deficit for ginger plant

Table 4. Relationship between the deficit of relative actual evapotranspiration (1 − ETa/ETm) and deficit in relative yield (1 − Ya/Ym) for ginger (pooled data of 3 years)

Irrigation	ETa (mm)	ETm (mm)	(1 − ETa/ETm)	Ya ($Mg \cdot ha^{-1}$)	Ym ($Mg \cdot ha^{-1}$)	(1 − Ya/Ym)	Ky
I_1	250.9	453.6	0.447	7.10	10.92	0.350	0.778
I_2	355.0	453.6	0.217	8.76	10.92	0.198	0.904
I_3	404.1	453.6	0.109	10.85	10.92	0.006	0.054
I_4	453.6	453.6	0	10.92	10.92	0	0

I_1: rainfed, I_2: irrigation at 0.6 IW/CPE, I_3: irrigation at 0.9 IW/CPE, I_4: irrigation at 1.2 IW/CPE; IW: irrigation water, CPE: cumulative pan evaporation, ETa: actual crop evapotranspiration, ETm: maximum crop evapotranspiration, Ya: actual yield, Ym: maximum yield; Ky: crop yield response factor.

Table 5. Effect of different irrigation scheduling and nutrient management on nutrient uptake by ginger plants (pooled data of 3 years)

Treatment	Nutrient uptake ($kg \cdot ha^{-1}$)		
	N	P	K
Irrigation (I)			
I_1	86.73	26.12	101.85
I_2	106.64	30.73	113.19
I_3	127.29	41.20	137.44
I_4	134.36	44.78	142.45
LSD ($p = 0.05$)	7.87	3.92	5.85
Nutrient management (N)			
N_1	115.82	35.77	119.49
N_2	122.42	42.18	145.23
N_3	103.02	29.18	106.47
LSD ($p = 0.05$)	4.92	2.26	3.05
Interaction (I × N)			
I_1N_1	87.31	24.75	97.17
I_1N_2	93.75	31.08	116.59
I_1N_3	79.14	22.52	91.78
I_2N_1	108.62	29.67	109.42
I_2N_2	113.46	37.10	131.35
I_2N_3	97.83	25.43	98.81
I_3N_1	127.95	41.72	133.24
I_3N_2	138.68	48.27	163.85
I_3N_3	115.23	33.61	115.22
I_4N_1	139.41	46.95	138.13
I_4N_2	143.77	52.26	169.14
I_4N_3	119.89	35.14	120.08
LSD ($p = 0.05$)	5.42	4.30	6.03

I_1: rainfed, I_2: irrigation at 0.6 IW/CPE, I_3: irrigation at 0.9 IW/CPE, I_4: irrigation at 1.2 IW/CPE; N_1: 100% RDF as fertilizers, N_2: 75% RDF as fertilizers + 25% RDF as vermicompost, N_2: 50% RDF as fertilizers + 50% RDF as vermicompost; RDF (recommended dose of fertilizer): 75:50:50 kg N, P_2O_5, $K_2O \cdot ha^{-1}$.

and marginal deficit irrigation (I_3) recorded higher growth and yield contributing parameters on account of higher NPK uptake by plants, and, consequently, promoted green rhizome yield. The adequate moisture availability in the root zone across the growing period might have caused more solubilization and accessibility of nutrients in the soil, increased root mass growth and spread, caused higher absorption and transmission of nutrients from soil to leaves, a high photosynthetic rate and subsequent translocation of assimilates to different plant organs (Padbhushan and Kumar, 2014). Conversely, plants exposed to frequent and higher soil water stress (I_1) and higher levels of deficit irrigation (I_2), had inhibited growth and yield constituents and rhizome yield as a result of low soil availability and absorption of nutrients by plants (Nybe and Raj, 2016). The increase in soil moisture tension due to reduced water application exerts an adverse physiological effect on root elongation, turgidity and number of root hairs, which might cause lower N, P and K uptake by the ginger plants and decreased rhizome yield (Arjun, 2009). The soil water-stress condition resulted in lower nutrient availability in soil, restricted root growth, low plant nutrient uptake, poor assimilate production and consequent migration from leaves to plant parts (Halder et al., 2022).

Likewise, the highest average uptake of 122.42, 42.18 and 145.23 $kg \cdot ha^{-1}$ for N, P and K, respectively, was found with N_2 which was significantly superior to N_1 and N_3. The combined application of inorganic fertilizers and organic VC at a 3:1 ratio, where inorganic fertilizers release available nutrients more readily during initial growth stages, whereas VC releases both the macro- and micronutrients more slowly throughout the growing period, which together resulted in higher nutrient accumulation resulting into the highest growth and development of plants and maximum yield (Puli et al., 2017; Srinivasan et al., 2019). Besides, incorporation of well-decomposed organic manure in the form of VC in the RDF could improve the physicochemical and hydrophysical conditions of the soil, which influence the development and yield of the rhizome as a result of higher nutrient uptake (Yanthan et al., 2010). The addition of RDF alone might satisfy the nutritional demand of the plant during the early stages, but the plant then suffers nutrient insufficiency in later developmental stages, resulting in moderate nutrient uptake and moderate yield. These findings are similar to Arjun (2009) and Shaikh et al. (2010) who recorded maximum yield and uptake of N, P and K for ginger in India's semi-arid tropics by application of 75:50:50 NPK kg·ha^{-1} + FYM at 25 t·ha^{-1}. In sandy loam soil under foothill agro-climatic conditions, maximum uptake of N was found with a treatment combination of 50% NPK + 50% pig manure. In contrast, maximum P and K uptake were recorded with 50% NPK + 50% FYM which was on par with 50% NPK+ 50% pig manure (Yanthan et al. 2010). The increased N uptake in N_2 could be attributed to the direct addition of nutrients in the soil through highly soluble inorganic fertilizers and slow and continual supply of the nutrients from the vermicompost coupled with reduced denitrification or leaching losses of N (Reddy and Reddy, 1998; Tilahun et al., 2013). The higher P uptake could be due to the release of organic acids from VC, altered soil pH towards neutrality, and boosted solubility and availability of P (Puli et al., 2017). The higher uptake of K by the plant due to the application of organic VC could be ascribed to the blocking effect of organic manure on the cation exchange surface of the clay particles, reducing K fixation (Smith, 2015).

The interaction effects showed that N_2 demonstrated relatively higher uptake of N, P and K at each irrigation treatment by the ginger plant, followed by N_1 and N_3. However, mean maximum uptake, of 143.77, 52.26 and 169.14 kg·ha^{-1} for N, P and K, respectively, were found with I_4N_2. These results were statistically on par with those for I_3N_2. The greater nutrient uptake by plants at marginal deficit to higher irrigation scheduling, complemented by conjoint application of nutrients through 75% RDF as inorganic fertilizer and 25% RDF as organic manure, could be attributed to the better water and nutrient availabilities in soil, higher nutrient absorption by proliferated and extensive root mass growth, greater transport via xylem to leaves, higher photosynthetic rate and translocation of assimilates produced in leaves to plant parts on remobilization. The lowest N, P and K uptake was recorded in I_1N_3. The lower uptake of N, P and K in nutrient management treatments under the rainfed condition and higher deficit irrigation scheduling was probably due to frequent and continuous episodes of higher soil water stress. These resulted in a decline in nutrient availability in the soil, adverse physiological effects on root growth and elongation, lower photosynthetic rate, and stunted growth characteristics, which ultimately reduced the yield (Tayel and Sabreen, 2011; Arjun, 2009).

CONCLUSION

Studies to monitor the response of ginger to irrigation and nutrient management have not been seriously undertaken in the past. The present study suggests that irrigation at 0.9 IW/CPE accompanied by 75% RDF as inorganic fertilizers + 25% RDF as vermicompost was the best treatment combination for achieving higher ginger rhizome yield, quality parameters and maximum water productivity in the Indo-Gangetic Inceptisols. The study also revealed a high impact on the ginger rhizome yield owing to soil water stress and an imbalance of soil available nutrients. Thus, well-managed irrigation and nutrient scheduling is the key to future promising ginger production, as well as marketability of the crop for better remuneration to its growers under sole cropping or even intercropping conditions.

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CONFLICT OF INTEREST

There exists no conflict of interest among the authors.

AUTHOR CONTRIBUTIONS

All authors contributed towards the final make-up of the paper. Expressing in terms of author initials, SKP obtained the fund, conceived the idea of the experiment as well as created the original draft; SS, RP and KB proofread, edited and compiled the final manuscript.

REFERENCES

ARJUN SD (2009) Effect of irrigation systems and integrated nutrient management on growth, yield and quality of ginger (*Zingiber officinale* Rosc.). PhD dissertation, Agricultural College, Mahatma Phule Krishi Vidyapeeth, Rahuri-413722, India.

AYALEW A and DEJENE T (2012) Combined application of organic and inorganic fertilizers to increase yield of barley and improve soil properties at fereze in southern Ethiopia. *Innov. Syst. Des. Eng.* **3** (1) 25–35.

BANDYOPADHYAY PK, MALLICK S and RANA SK (2005) Water balance and crop coefficients of summer-grown peanut (*Arachis hypogaea* L.) in a humid tropical region of India. *Irrig. Sci.* **23** 161–169. https://doi.org/10.1007/s00271-005-0104-7

BEKEKO Z (2014) Effect of enriched farmyard manure and inorganic fertilizers on grain yield and harvest index of hybrid maize (bh-140) at Chiro, eastern Ethiopia. *Afr. J. Agric. Res.* **9** (7) 663–669. https://doi.org/10.5897/AJAR12.2241

BHOWMIK A, KHAWAS S, DUTTA G, RAY R and PATRA SK (2020) Response of summer cowpea to growth, yield and water use efficiency under different irrigation and nutrient management in lower Indo-Gangetic Plains. *Int. J. Curr. Microbiol. Appl. Sci.* **9** (8) 900–911. https://doi.org/10.20546/ijcmas.2020.908.098

DAS A, LAYEK J, BABU S, KUMAR M, YADAV GS, PATEL DP, IDAPUGANTI RG, LAL R and BURAGOHAIN J (2020) Influence of land configuration and organic sources of nutrient supply on productivity and quality of ginger (*Zingiber officinale* Rosc.) grown in Eastern Himalayas, India. *Environ. Sustainability.* **3** (1) 59–67. https://doi.org/10.1007/s42398-020-00098-x

DASGUPTA S, SENGUPTA S, SAHA S, SAHA N, BHATTACHARYYA K and DEY P (2021) Predicting the response of soil potassium to broccoli (*Brassica oleracea* var. *italica*) in a Gangetic Inceptisol of West Bengal, India through suitable chemical extractants. *J. Plant Nutr.* **44** (7) 931–945. https://doi.org/10.1080/01904167.2020.1867580

DINESH R, SRINIVASAN V, HAMZA S, MANJUSHA A and KUMAR PS (2012) Short-term effects of nutrient management regimes on biochemical and microbial properties in soils under rainfed ginger (*Zingiber officinale* Rosc.). *Geoderma.* **173** 192–198. https://doi.org/10.1016/j.geoderma.2011.12.025

GATABAZI A, MARAIS D, STEYN MJ, ARAYA HT, MOFOKENG MM and MOKGEHLE SN (2019) Evaluating growth, yield, and water use efficiency of African and commercial ginger species in South Africa. *Water.* **11** (3) 548. https://doi.org/10.3390/w11030548

GOMEZ KA and GOMEZ AA (1984) *Statistical Procedure for Agricultural Research* (2nd edn). John Wiley and Sons, New York.

HALDER A, PODDAR R, DEY A, KUNDU R and PATRA SK (2022) Frequency of irrigation and boron on growth, yield, water use efficiency and economics of summer green gram in humid subtropical climate. *Commun. Soil Sci. Plant Anal.* **53** (2) 180–198. https://doi.org/10.1080/00103624.2021.1984514

HIMANSHU SK, SINGH AK, KUMAR S and KALURA P (2013) Response of broccolli to irrigation scheduling and methods under drip, sprinkler and surface irrigation. *Int. J. Eng. Adv. Technol.* **2** (4) 2249–2258.
ISLAM MA, RAHIM MA and IQBAL TMT (2015) Effect of irrigation and mulching on growth and yield of ginger. *Bangladesh Agron. J.* **18** (1) 27–36. https://doi.org/10.3329/baj.v18i1.25564
KALLAPPA N, RAVIRAJA SHETTY G, NAGARAJ G, RAVI P, SUDEEP HP and SHIVAKUMAR HJ (2015) Performance of ginger (*Zingiber officinale* Rosc.) varieties for yield and quality attributes under hill zone of Karnataka. *Ecol. Environ. Conser.* **21** (3) 259–262.
KANG Y, KHAN S and MA X (2009) Climate change impacts on crop yield, crop water productivity and food security–A review. *Prog. Nat. Sci.* **19** (12) 1665–1674. https://doi.org/10.1016/j.pnsc.2009.08.001
LORDWIN GKJ, TAYAL Z and ABINEET R (2007) Yield, irrigation production efficiency and economic return of broccoli (*Brassica oleracea* var. italica) under different irrigation methods and schedules. *Ethiopian J. Sci. Technol.* **4** (2) 47–60.
MOMIN BG, RAY R and PATRA SK (2018) Assessment of saturated hydraulic conductivity of red and lateritic soils under diverse land topography and vegetation using classical statistical analysis. *Int. J. Curr. Microbiol. Appl. Sci.* **7** (10) 963–972. https://doi.org/10.20546/ijcmas.2018.710.107
NAIR KP (2019) Ginger nutrition. In: Nair KP (ed.) *Turmeric (Curcuma longa L.) and Ginger (Zingiber officinale* Rosc.*) – World's Invaluable Medicinal Spices.* Springer, Cham. 433–440. https://doi.org/10.1007/978-3-030-29189-1_20
NWAOGU EN (2014) Soil fertility changes and their effects on ginger (*Zingiber officinale* Rosc.) yield response in an ultisol under different pigeon pea hedgerow alley management in South Eastern Nigeria. *Afr. J. Agric. Res.* **9** 2158–2166. https://doi.org/10.5897/AJAR2013.7291
NYBE EV and RAJ NM (2016) Ginger production in India and other South Asian countries. In: Ravindran PN and Nirmal Babu K (eds) *Ginger.* CRC Press, Boca Raton. 231–260. https://doi.org/10.1201/9781420023367-9
PADBHUSHAN R and KUMAR D (2014) Influence of soil and foliar applied boron on green gram in calcareous soils. *Int. J. Agric. Environ. Biotechnol.* **7** (1) 129–136. https://doi.org/10.5958/j.2230-732x.7.1.018
PANDA R and PATRA SK (2018) Quantity-intensity relations of potassium in representative coastal soils of eastern India. *Geoderma.* **332** 198–206. https://doi.org/10.1016/j.geoderma.2018.07.014
PATRA SK, PODDAR R, PRAMANIK S, GABER A and HOSSAIN A (2022) Crop and water productivity and profitability of broccoli (*Brassica oleracea* L. var. italica) under gravity drip irrigation with mulching condition in a humid sub-tropical climate. *PLoS ONE.* **17** (3) e0265439. https://doi.org/10.1371/journal.pone.0265439
PATRA SK and SENGUPTA S (2022) Effect of gravity-fed drip irrigation and nitrogen management on flowering quality, yield, water and nutrient dynamics of gladiolus in an Indian inceptisol. *J. Plant Nutr.* 1–19. https://doi.org/10.1080/01904167.2022.2057327
PAWAR DD, DINGRE SK and KALE KD (2020) Productivity, storability and economics of microsprinkler fertigation for winter onion (*Allium cepa* L.) in semi-arid conditions. *Int. J. Curr. Microbiol. Appl. Sci.* **9** (6) 1096–1109. https://doi.org/10.20546/ijcmas.2020.906.136
PEREIRA JRD, CARVALHO JA, PAIVA PDO, SILVA DJS, SOUZA AMG and SOUZA KJ (2009) Growth and production of gladiolus floral stems under different soil water tensions. (In Portuguese.) *Cien. Agrotecnol.* **33** (4) 965–970. https://doi.org/10.1590/S1413-70542009000400004
PEREIRA DA SILVA AJ, COELHO EF and DE MIRANDA JH (2013) Efficiency of water application of irrigation systems based on microsprinkling in banana plantations. *Sci. Agric.* **70** (3) 139–146. https://doi.org/10.1590/S0103-90162013000300001
PULI MR, PRASAD PRK, JAYALAKSHMI M and RAO BS (2017) Effect of organic and inorganic sources of nutrients on NPK uptake by rice crop at various growth periods. *Res. J. Agric. Sci.* **8** (1) 64–69.
REDDY BG and REDDY MS (1998) Effect of organic manures and nitrogen levels on soil available nutrient status in maize-soybean cropping system. *J. Indian Soc. Soil Sci.* **46** 474–476.
ROY SS and HORE JK (2007) Influence of organic manures on growth and yield of ginger. *J. Plantation Crops.* **35** (1) 52.
SADASIVAM VB and MANICKAM A (1996) *Biochemical Methods* (2nd edn). New Age International Publication, Calcutta. 22 pp.
SAHA C, BHATTACHARYA P, SENGUPTA S, DASGUPTA S, PATRA SK, BHATTACHARYYA K and DEY P (2021) Response of cabbage to soil testbased fertilization coupled with diferent levels of drip irrigation in an inceptisol. *Irrig. Sci.* 1–15. https://doi.org/10.1007/s00271-021-00761-z
SENGUPTA S, BHATTACHARYYA K, MANDAL J, BHATTACHARYA P, HALDER S and PARI A (2021) Deficit irrigation and organic amendments can reduce dietary arsenic risk from rice: Introducing machine learning-based prediction models from field data. *Agric. Ecosyst. Environ.* **319** 107516. https://doi.org/10.1016/j.agee.2021.107516
SEYIE A, NARUKA IS, SINGH PP and KUSHWAH SS (2013) Nutrient management and its effect on growth, yield and quality of ginger cultivars. *Indian J. Hort.* **70** (1) 65–70.
SHAIKH AA, DESAI MM, SHINDE SB and TAMBE AD (2010) Yield and nutrient uptake of ginger (*Zingiber officinale* Rosc.) as affected by organic manures and fertilizers. *Int. J. Agric. Sci.* **6** (1) 28–30.
SHARMA HD and SHARMA V (2012) Production technology of ginger under changing climate. In: Bhardwaj ML, Dev Sharma H, Kumar M, Kumar R, Kansal S, Thakur K, Singh SP, Kumar D, Kumari S, Gupta M and Sharma V (eds). *Vegetable Production Under Changing Climate Scenario.* 44–52.
SIMSEK M, TONKAZ T, KACIRA M, COMIEKCIOGLU N and DOGAN Z (2005) The effects of different irrigation regimes on cucumber (*Cucumbis salivus* L.) yield and yield characteristics under open field conditions. *Agric. Water Manage.* **73** 173–191. https://doi.org/10.1016/j.agwat.2004.10.013
SINGH AK, GAUTAM US and SINGH J (2015) Impact of integrated nutrient management on ginger production. *Bangladesh J. Bot.* **44** (2) 341–344. https://doi.org/10.3329/bjb.v44i2.38528
SINGH R, SHARMA RR, KUMAR S, GUPTA RK and PATIL RT (2008) Vermicompost substitution influences growth, physiological disorders, fruit yield and quality of strawberry. *Biores. Technol.* **99** 8507–8511. https://doi.org/10.1016/j.biortech.2008.03.034
SINGH VB and SINGH AK (2007) Effect of types of organic manures and method of nitrogen application on growth, yield and quality of ginger. *Environ. Ecol.* **25** 103–105.
SMITH N (2015) The role of soil organic matter on potassium fixation. *Symposium on Undergraduate Research and Creative Expression on Agronomy and Environmental Science*, Iowa State University, Department of Agronomy. 19 pp.
SRINIVASAN K, ADHYA P and SHARMA SS (2019) Nutraceutical potential of ginger. In: Gupta RC, Srivastava A and Lall R (eds) *Nutraceuticals in Veterinary Medicine.* Springer, Cham. 51–70. https://doi.org/10.1007/978-3-030-04624-8_4
SRINIVASAN V, THANKAMANI CK, DINESH R, KANDIANNAN K, HAMZA S, LEELA NK and ZACHARIAH TJ (2018) Variations in soil properties, rhizome yield and quality as influenced by different nutrient management schedules in rainfed ginger. *Agric. Res.* **8** (8) 1–15.
TAHERI N, HEIDARI SAH, YOUSEFI K and MOUSAVI SR (2011) Effect of organic manure with phosphorus and zinc on yield of seed potato. *Aus. J. Basic Appl. Sci.* **5** 775–780.
TAYEL MY and SABREEN KHP (2011) Effect of irrigation regimes and phosphorus level on two *Vica faba* varieties: 1 – growth characters. *J. Appl. Sci. Res.* **7** (6) 1007–1015.
TILAHUN TF, NIGUSSIE DR, WONDIMU B and SETEGN G (2013) Effect of farm yard manure and inorganic fertilizers on the growth, yield and moisture stress tolerance of rainfed lowland rice. *Am. J. Res. Commun.* **1** (4) 274–301.
TOLOSSA TT (2021) Onion yield response to irrigation level during low and high sensitive growth stages and bulb quality under semi-arid climate conditions of Western Ethiopia. *Cogent Food Agric.* **7** 1859665. https://doi.org/10.1080/23311932.2020.1859665
YANTHAN L, SINGH AK and SINGH VB (2010) Effect of INM on yield, quality and uptake of N, P and K by ginger. *Agropedology* **20** (1) 74–79.
YAZAR A, GOKÇEL F and SEZEN MS (2009) Corn yield response to partial root zone drying and deficit irrigation strategies applied with drip system. *Plant Soil Environ.* **55** (11) 494–503. https://doi.org/10.17221/96/2009-PSE

APPENDIX

Table A1. Climatological parameters during the three ginger growing seasons

Growing season	Month									
	April (25–30)	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan (1–21)
Mean maximum relative humidity (%)										
2016-17	88.5	91.5	90.9	94.8	96.4	96.4	92.8	93.0	96.1	95.9
2017-18	87.4	90.6	90.6	94.3	95.7	96.6	93.1	92.7	94.6	93.6
2018-19	87.7	90.1	94.0	95.2	96.5	95.3	96.9	84.0	84.8	85.8
Mean minimum relative humidity (%)										
2016-17	51.6	65.0	71.1	78.9	81.7	81.0	63.4	56.2	56.3	63.0
2017-18	49.6	54.7	66.2	79.2	79.2	76.5	58.6	57.1	56.8	49.5
2018-19	42.4	67.2	78.2	81.1	81.6	76.2	78.9	55.3	58.6	63.0
Mean maximum air temperature (°C)										
2016-17	34.0	35.0	34.0	32.3	31.4	31.8	33.3	30.3	25.1	23.8
2017-18	36.1	36.8	35.6	33.0	32.3	32.9	33.5	30.1	26.5	24.8
2018-19	37.7	35.1	34.4	33.6	33.0	34.0	31.6	30.1	26.8	24.2
Mean minimum air temperature (°C)										
2016-17	23.7	25.5	26.6	26.2	26.1	25.8	24.8	18.4	13.2	13.4
2017-18	25.4	26.5	27.7	26.8	26.4	25.9	22.9	18.5	11.9	9.9
2018-19	24.2	25.7	26.4	26.5	26.0	26.0	24.4	22.5	12.4	10.5
Wind speed ($km \cdot h^{-1}$)										
2016-17	0.5	0.3	0.5	0.2	0.1	0.0	0.0	0.0	0.0	0.0
2017-18	0.2	0.3	0.7	0.6	0.1	0.1	0.0	0.0	0.0	0.0
2018-19	0.3	1.6	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bright sunshine (h)										
2016-17	8.7	7.8	5.9	4.5	4.0	4.5	7.4	7.6	6.1	5.3
2017-18	8.4	8.8	5.1	4.0	5.2	5.5	7.4	6.5	5.6	5.6
2018-19	8.4	5.5	4.9	5.4	4.5	5.2	4.6	8.2	6.2	5.7
Total rainfall (mm)										
2016-17	63.7	144.1	195.1	413.1	646.8	288.9	68.9	0.0	0.0	57.0
2017-18	20.8	93.5	184.0	264.0	203.3	278.8	29.0	50.2	7.3	1.9
2018-19	11.0	1308	1595	180.3	314.5	228.4	240.5	0	0	0
Mean open pan evaporation ($mm \cdot day^{-1}$)										
2016-17	3.69	3.97	3.33	1.98	2.02	2.15	2.38	1.60	1.04	0.91
2017-18	4.78	4.60	3.35	2.46	2.08	2.28	2.48	1.64	1.01	0.99
2018-19	4.59	3.57	2.53	2.53	2.07	2.20	1.64	1.69	1.03	0.95

Table A2. Quantity of irrigation water applied under different irrigation scheduling during the three ginger growing seasons

Plant growth stages	Days after planting	2016-17				2017-18				2018-19			
		Irrigation scheduling (IW:CPE ratio)											
		RF	0.6	0.9	1.2	RF	0.6	0.9	1.2	RF	0.6	0.9	1.2
		Irrigation water supply (mm)											
Germination	0–30	0				0		50	50	0			50
Vegetative	31–90	0				0	50	50	100	0	50	50	50
Rhizome initiation	91–135	0				0	50	50	50	0		50	
Rhizome development	136–225	0		50	50	0	50	100	100	0	50	50	100
Maturity	226–270	0	50		50	0	50	50	50	0	50	50	50

RF: rainfed. The seed rhizomes were planted on 19 April 2016, 12 April 2017 and 15 April 2018 and harvesting was completed on 23 February 2017, 18 February 2018 and 20 February 2019, respectively.