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Agronomic response of subsurface versus surface drip irrigation in Nagpur mandarin (*Citrus reticulata* Blanco) on Indian Vertisol

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Introduction: Citrus is a highly water- and nutrient-demanding crop, with several previous efforts focusing on improving water productivity (WP) and nutrient use efficiency (NUE). However, studies highlighting the performance of subsurface drip irrigation (SDI) versus drip irrigation (DI) in black clay soil (Vertisol) for Nagpur mandarin are limited.

Methods: This study evaluated six treatments: T_1 (SDI with double inline laterals at 100 cm radially from the trunk and 30 cm vertically placed into the soil, drippers spaced 30 cm apart); T_2 (SDI with double inline laterals at 100 cm radially from the trunk and 30 cm vertically placed into the soil, drippers spaced 40 cm apart); T_3 (SDI with double inline laterals at 100 cm radially from the trunk and 30 cm vertically placed into the soil, drippers spaced 50 cm apart); T_4 (SDI with double inline laterals at 100 cm radially from the trunk and 30 cm vertically placed into the soil, drippers spaced 60 cm apart); T_5 (DI with double online laterals at 100 cm from the trunk with 6 drippers spaced 60 cm apart; control as farmers' practice); and T_6 (DI with ring-type online laterals at 10 cm from the trunk with 12 drippers tree-1 placed 60 cm apart). These treatments were for their effects on growth performance, fruit yield, fruit quality, WP, and leaf nutrient composition.

Results and discussion: Significantly higher WP and lower water requirement were observed with SDI (7.96–10.73 kgm^{-3} and 13,260 L $plant^{-1}$ $year^{-1}$) compared with DI treatments (2.79–3.04 kg m^{-3} and 32,670 L $plant^{-1}$ $year^{-1}$). These observations were associated with a 25.29% higher fruit yield in SDI over DI treatments. Similarly, fruit quality parameters, viz., juice content and total soluble solids (TSS), were 6.65% and 1.17°Brix higher, respectively, in SDI than in DI treatments. Consequently, SDI treatments registered higher leaf N, P, K, Ca, Mg, Fe, Mn, and Zn contents by 4.81%, 15.68%, 6.60%, 17.51%, 3.18%, 7.70%, 5.04%, and 15.67%, respectively, over DI treatments. Thus, SDI treatments saved.

Conclusion: The T3 treatment was the most effective SDI treatment, registering 47.32% higher fruit yield and 64.87% higher WP than DI treatments, along with significantly improved leaf and fruit nutrient composition.

KEYWORDS

agronomic efficiency, crop coefficient, fruit yield, fruit quality, Nagpur mandarin, subsurface drip irrigation, surface drip irrigation, nutrient content

1 Introduction

Nagpur mandarin (*Citrus reticulata* Blanco), a globally recognized commercial citrus cultivar, is highly valued for its unique taste, nutritional benefits, and adaptability to varied climatic conditions. The cultivar is extensively grown on black clay soils (Entisols, Inceptisols, and Vertisols) in the Vidarbha region of Maharashtra and the Jhalawad/Sriganganagar districts of Rajasthan, India, with strong consumer preference due to its excellent taste and high economic returns (Ladaniya et al., 2021).

Despite the cultivar's prominence, sustaining its high productivity is severely challenged by water scarcity (Panigrahi, 2023a) and by improper irrigation management, particularly in the absence of information on crop phenology-based drip irrigation (DI) scheduling (Puig-Sirera et al., 2021). Previous studies have highlighted the adverse effects of suboptimal irrigation at any critical growth stage on fruit yield and quality (Panigrahi et al., 2014; Panigrahi, 2023a, b). DI scheduling has provided considerable impetus for sustaining optimum productivity worldwide (Shirgure et al., 2004; Panigrahi and Srivastava, 2017; Jamshidi et al., 2020) compared with conventional basin irrigation (Panigrahi et al., 2012a), resulting in water and nutrient savings (Panigrahi et al., 2012b; Martínez-Gimeno et al., 2018) and superior fruit quality attributes (Robles et al., 2016).

In this context, optimizing irrigation water for improved water productivity (WP) by aligning water requirements with critical growth stages, along with enhancing nutrient use efficiency (NUE), is an essential component of profitable citrus cultivation (Shirgure and Srivastava, 2013; Kadam, 2020).

Combining, WP, and NUE has given rise to the concept of fertigation—an irrigation method that has created a strong niche across crops and agroclimates, significantly reducing nutrient leaching losses while enhancing nutrient uptake efficiency to as high as 90% compared with 40%–60% in traditional basin irrigation (Sravani et al., 2020; Pimpale et al., 2022). As in many leading citrus-growing countries, the extensive adoption of DI in citrus orchards in India has transformed water and nutrient management, lowering input costs and improving both yield and quality (Shirgure et al., 2016; Panigrahi and Srivastava, 2016).

More recently, as a further advancement of DI, SDI has emerged as a more advanced micro-irrigation technique, offering the additional advantages of delivering water directly into the root zone, minimizing evaporation losses, and further enhancing and WP (Martinez and Reca, 2014; Robles et al., 2016; Meshram et al., 2019; Franco et al., 2019). SDI has been successfully applied to many woody perennial crops, improving yield, WP, and NUE, while also reducing alternate bearing (Consoli et al., 2014; Ayars et al., 2015; Martínez-Gimeno et al., 2018). Other studies (Robles et al., 2016; Zhang et al., 2017) have demonstrated that SDI increases and WP by reducing water losses compared with surface DI, without compromising fruit yield, and enhances NUE by decreasing water losses by up to 43% (Camp, 1998; Bonachela et al., 2001; Provenzano et al., 2014; Martinez and Reca, 2014).

Despite these clear advantages, effective implementation of SDI is often limited by high initial costs and potential challenges such as emitter clogging and rodent damage (Phene, 1995; Sinobas et al., 2012; Yao et al., 2021; Muhammad et al., 2022; Wang et al., 2024), which may be more prevalent in the black clay soils typical of Vertisols supporting Nagpur mandarin or lemon trees (Robles et al., 2016). Unlike surface DI, where lateral pipes are placed above ground, SDI involves burying these pipes below the soil surface, thereby reducing canopy humidity and weed prevalence (Singh and Rajput, 2007; Camp and Lamm, 2003; Cahn and Hutmacher, 2024).

In India, knowledge about SDI—especially in mandarin cultivation—remains limited. Given its potential to enhance, WP, and NUE, SDI is increasingly being adopted in row-crop agriculture (Gao et al., 2014; Ardenti et al., 2022), offering strong potential for value-added application in citriculture. Previous research has indicated that SDI can save 60%–70% of water and increase fruit yield by 40%–50% compared with surface DI (Meshram et al., 2019). Considering the persistent challenge of water scarcity, coupled with the growing need for efficient irrigation practices in citrus orchards—particularly for Nagpur mandarin—this study was conducted to compare the efficacy of DI and SDI, focusing on yield attributes, water productivity, and nutritional responses of index leaves and fruit. The outcomes of such a study would be useful in providing some useful insights for sustainable citrus farming in central India's hot, subhumid tropical climate.

2 Materials and methods

2.1 Description of experimental site

The field experiment was carried out during 2021–2023 on 12-year-old bearing Nagpur mandarin (*Citrus reticulata* Blanco) budded onto Rough lemon (*Citrus jambhiri* Lush.) rootstock 6.0 × 6.0 m at ICAR–Central Citrus Research Institute (ICAR-CCRI) in Nagpur (21^0 08" N latitude, 79^0 01" E longitude at an altitude of 349 m MSL), India. The soil was taxonomically classified as alkaline and calcareous Typic Haplustert (soil pH 7.73, EC 0.23 dS m^{-1}, sand 22%, silt 25.9%, clay 52.2%, field capacity 35.50%, permanent wilting point 16.34%, available water content 15.66%, organic carbon 0.55%, bulk density 1.35 g cm^{-3}, hydraulic conductivity 2.03 cm h^{-1}, alkaline $KMnO_4$–N 115.63 mg kg^{-1}, Olsen P 11.25 mg kg^{-1}, NH_4OAc-K 274.25 mg kg^{-1}, DTPA Fe 14.17 mg kg^{-1}, DTPA Mn 10.92 mg kg^{-1}, DTPA-Zn 0.62 mg kg^{-1}, and DTPA-Cu 2.58 mg kg^{-1}) showing the occurrence of multiple nutrient constraints in the form of N, P, Fe, Mn, and Zn.

The experiment was set up through six treatments *viz.*, T_1 (SDI with double inline laterals placed at 100 cm from tree trunk at 30 cm soil depth with 30 cm dripper spacing), T_2 (SDI with double inline laterals placed at 100 cm from tree trunk at 30 cm soil depth with 40 cm dripper spacing and 30 drippers tree^{-1} area); T_3 (SDI with double inline laterals placed at 100 cm from tree trunk at 30 cm soil depth with 50 cm dripper spacing and 26 drippers tree^{-1} area); T_4 (SDI with double inline laterals placed at 100 cm from tree trunk at 30 cm soil depth with 60 cm dripper spacing and 20 drippers tree^{-1} area); T_5 (DI with double online laterals placed 100 cm from tree trunk with 6 drippers tree^{-1} area, as control, a common farmers' practice); and T_6 (DI with ring-type online laterals placed at 100 cm from tree trunk with 12 drippers tree^{-1} area). The experiment was carried out in a randomized block design consisting of 6 treatments with 4 trees for each treatment and a total of 24 experimental units replicated four times (location of experimental site and micro-irrigation layout map shown schematically through Figure 1). All the experimental trees were maintained under uniform cultural and management practices. The physical, hydraulic, and chemical characteristics of the soil profile (Supplementary Tables), along with mean monthly meteorological parameters during the study period at the experimental site (ICAR-CCRI, Nagpur, Maharashtra, India) (Supplementary Figure 1), are presented in the Supplementary Files.

Growing citrus in central India is characterized by two flowering seasons, January-February bloom with flowering taking place in winter and June-July bloom with flowering taking place with initial showers of monsoon rains, the former is more

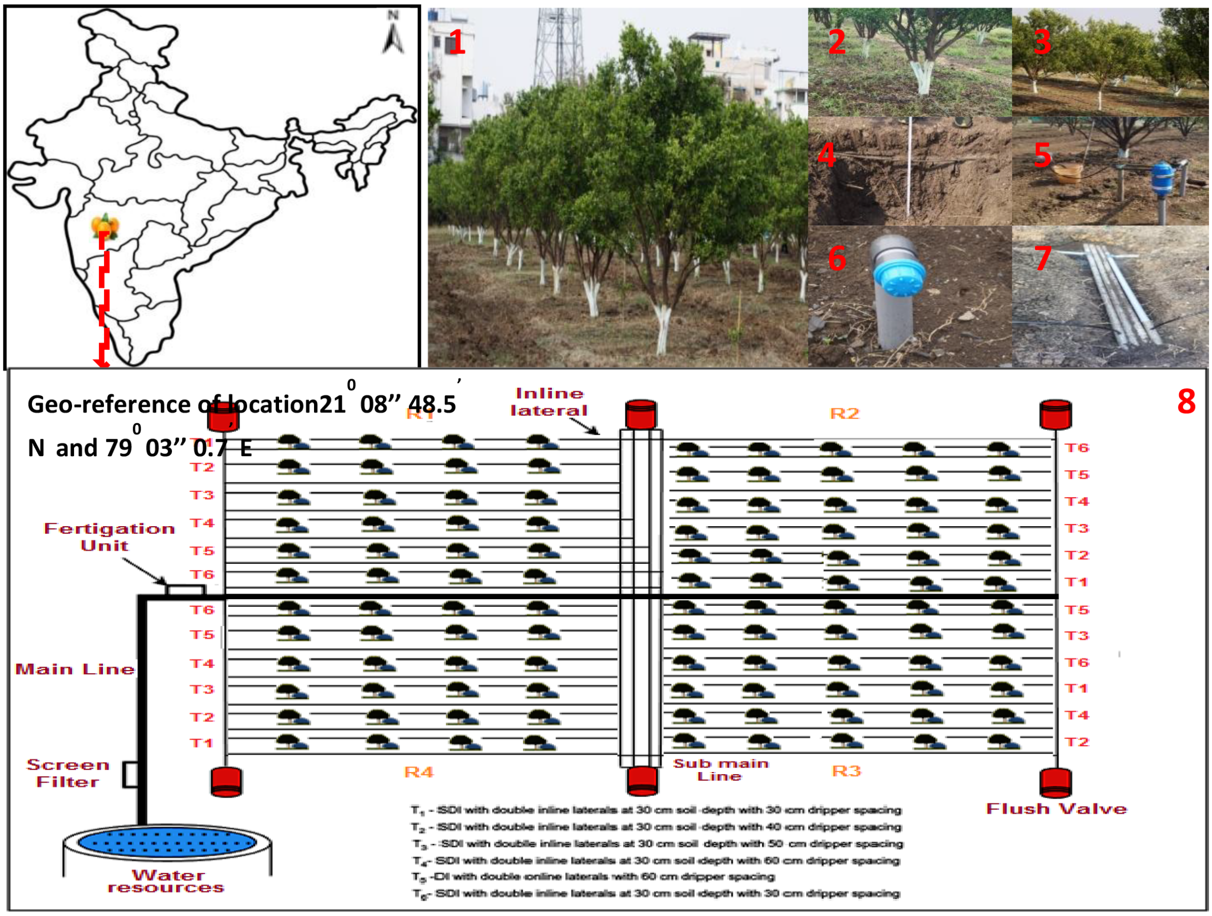

FIGURE 1
Location map and block diagram of SDI and DI irrigation setup at the experimental site.

dependent on water availability than latter (Srivastava et al., 1998; Huchche et al., 1999; Wilkie et al., 2008). In our experiment, we experimented with January-February bloom, induced by withholding irrigation water for 40–50 days during November–December followed by resumption of irrigation at water holding capacity of soil for flowering to take place. The frequency of fertigation was administered on 2nd and 16th day of each month starting from February to June and September to October (August–September as peak rainy days). The recommended doses of nutrients (600 N: 400 P_2O_5: 200 K_2O: 50 borax: 100 $FeSO_4$: 100 $MnSO_4$: 100 $ZnSO_4$, g $plant^{-1}$ $year^{-1}$) (Srivastava, 2013) as recommended doses of fertilizers using conventional fertilizers (N as urea, P as phosphoric acid, and K as muriate of potash). These fertilizers were applied at critical phenological growth stages viz., initiation of leaf flush (250 N:100 P_2O_5:50 K_2O: 25 $FeSO_4$: 25 $MnSO_4$: 25 $ZnSO_4$: 25 Borax, g $plant^{-1}$), fruit development period (250 N: 200 P_2O_5: 100 K_2O: 50 $FeSO_4$: 50 $MnSO_4$: 50 $ZnSO_4$: 25 borax, g $plant^{-1}$) and 10-days before fruit maturity (100 N: 100 P_2O_5: 50 K_2O: 25 $FeSO_4$: 25 $MnSO_4$: 25 $ZnSO_4$, g $plant^{-1}$) through fertigation.

2.2 Irrigation setup

The drip irrigation system and fertigation unit were installed in the experimental block, which accommodated 96 plants, with four plants per replication per treatment. In-line and on-line laterals with 2L and 4 L h^{-1} discharge rate were equipped with SDI and DI drip lines, respectively. The sub-surface drip lines were installed at 30 cm depth, as recommended by Leskovar et al. (2001). In-line (2 L h^{-1}) and online (4 L h^{-1}) pressure-compensating drippers were positioned 100 cm away from the tree trunk (Panigrahi et al., 2008). The daily irrigation scheduling for Nagpur mandarin plants was based on crop evapotranspiration (ET_{NM}) of dry days, while fertigation was applied using a liquid fertilizer injector based on venturi principle.

The water quantity for SDI and DI was determined based on reference crop evapotranspiration (ET_r). The crop coefficient (K_c), ranging from 0.30 to 1.10, was estimated at various phenological stages through the shaded area approach at solar noon hour. ET of crop was calculated using the Penman–Monteith method, varying between 2.56 to 10.47 mm day^{-1}. The daily water requirement (ET_{NM}) and irrigation time for mandarin plants were calculated (Meshram et al., 2019) using the following formulas.

$$ET_{NM} = ET_r \text{ x } K_c \text{ x WA x } A/IE$$

where, ET_{NM} is water requirement (L day^{-1} $tree^{-1}$); ET_r is reference crop evapotranspiration (mm); K_c is crop coefficient, fraction; WA is wetted area, fraction; A is area occupied by each tree (m^2); and IE is irrigation efficiency of the micro-irrigation system, fraction.

$$IT = ET_{NM}/DC$$

where, IT is irrigation time (hr); ET_{NM} is water requirement (L day^{-1} $tree^{-1}$); and DC is dripper discharge capacity (L h^{-1}).

2.3 Estimation of ET_r and K_c

ET_r, as the key factor influencing evapotranspiration, represents the water transpired by vegetation during growth, retain in the plant tissue, and the reduction in water evaporated from the soil and vegetation surface. ET_r was calculated using the Penman–Monteith method with daily, weekly, and monthly datasets. ET_r was calculated based on daily climatic data from January 2021 to December 2023 as per the procedure suggested by Allen et al. (1998). The following equation estimates daily ET_r values:

$$ET_r = \frac{0.408\Delta(R_n - G) + \gamma(\frac{900}{T+273})u_{2(e_s-e_a)}}{\Delta + \gamma(1 + 0.34u_2)}$$

where, ET_r refers to reference ETc (mm day^{-1}); G is soil heat flux density (MJ m^{-2} day^{-1}); R_n is net radiation (MJ m^{-2} day^{-1}); T is mean daily air temperature (^{0}C); γ is psychometric constant (kPa $^0C^{-1}$); Δ is slope of saturation vapor pressure function (kPa $^0C^{-1}$); e_s is saturation vapor pressure at air temperature T (kPa); e_a is actual vapor pressure at dew point température (kPa); and u is average daily wind speed at 2 m height (m sec^{-1}).

K_c values for various crop phenophases (initiation of new leaf start, development, maturity, and harvesting) were determined using shaded area techniques. The following equation, designed for deciduous fruit crops (Ayars et al., 2003; Gorantiwar et al., 2011), was employed:

$$K_c = 0.014x + 0.08$$

where, K_c represents the crop coefficient and x represents the percentage of shaded area (%). Water demand for Nagpur mandarin was estimated using K_c, wetted area (WA), and 90% irrigation efficiency (IE) (Kisekka et al., 2010; Gorantiwar et al., 2011; Meshram et al., 2019).

2.4 Estimation of wetted area (WA), WP, SWC, and θv

The wetted area factor is the proportion of effective root zone. Canopy area was measured weekly, and wetted area was computed using the following equation: Wetted area (WA)=SA/A, where, SA represents the shaded area (m²) and A as the area occupied by each tree (m²) according to Gorantiwar et al. (2011). The yield and daily water requirement were determined from the observed data; while WP was computed using formula: WP= Yield (kg)/WU (m^3) The WP was calculated under different treatments as the ratio of yield in kg ha^{-1} to water used in m^3 ha^{-1}, and expressed in kg m^{-3}. The root zone of Nagpur mandarin trees typically extends up to 120 cm, making this depth of soil profile suitable for studying soil moisture dynamics (Panigrahi and Srivastava, 2016). To assess soil water suction, four tensiometers were installed as per treatment depths viz., 15 cm, 30 cm, 60 cm, and 100 cm, allowing for a detailed evaluation of soil water availability throughout the active root zone. Simultaneously, SWC was monitored daily in the morning at the same depths using a neutron moisture meter (Troxler Model 4300, USA) before initiating irrigation. It was measured directly using the neutron moisture meter, which provided rapid and depth-specific readings by detecting hydrogen atoms in soil water. The volumetric water content (θv) was calculated based on the formula: θv = soil water content × bulk density of soil Monitoring θv enables precise irrigation by identifying moisture depletion zones and aligning water application with crop demand.

2.5 Observations on growth-contributing parameters

Growth-contributing parameters such as stock girth diameter (stem diameter measured at 0.01 m above the bud union), canopy diameter (mean of canopy spread diameter measured in N-S and E-W direction), plant height (distance from the ground surface to the top of the plant crown), and stem height (distance from the ground surface to the base of the first branch) were measured using a metric tape. The canopy volume was calculated using the formula developed by Panigrahi (2023a): $Vc = 0.5238HW^2$, where V_c denotes canopy volume (m^3); H is the difference between tree height and stem height (m), and W is the mean canopy width (m) measured in the north–south and east–west direction.

2.6 Leaf physiological parameters

The leaf physiological parameter relative leaf water content (RLWC) was calculated according to the procedure suggested by Turner (1988). Leaf water use efficiency (LWUE) was estimated as the ratio of the net photosynthesis rate to transpiration rate of leaves (Garcia Sanchez et al., 2007). The net photosynthesis rate (Pn), transpiration rate (Tr), and stomatal conductance (gs) were measured fortnightly on clear days using a CO_2 (Model 301PS, CID Bio-Science, USA) during the period from 9:00 a.m. to 5:00 p.m. at one-hour intervals.

2.7 Yield and fruits analysis data

Fruit weight (g) and number of fruits per tree were observed in each treatment, and mean yield per tree was calculated. Yield (t ha^{-1}) was calculated, and the total yield (t ha^{-1}) based on yield per tree was computed considering 277 trees ha^{-1}. The weekly fruit growth was recorded using a digital slide caliper. Ten random fruits per plant (4 plants $treatment^{-1}$) were tagged immediately after fruit set (mid-April). The fruit quality parameters such as fruit length (mm), fruit diameter (mm), fruit axis diameter (mm), rind thickness (mm), number of segments, juice content (%), TSS (^{0}Brix), acidity (%), and TSS: acid ratio were recorded as per standard procedures described by Ranganna (2001). The yield increase percentage was calculated as per the method suggested by Abd El-Naby et al. (2019) using the equation:

$$\text{Yield increase}\,(\%) = (\text{Yield}\,(\text{Treatment}) - \text{Yield}\,(\text{Control}))/\text{Yield}\,(\text{Control}) \times 100$$

The fruit size distribution observations, based on the percentage of graded fruits, were also recorded in all six treatments. Fruit samples from each treatment were used to measure the fruit diameters for this purpose using a Vernier caliper (0.01 mm accuracy). Grading of Nagpur mandarin fruits was done on the basis of fruit size grades (A, B, C), with Grade A for fruits with a diameter greater than 80 mm, Grade B for fruits with a diameter between 70 and 80 mm, and Grade C for fruits with a diameter less than 70 mm.

2.8 Determination of leaf and fruit nutrients composition

Three- to five-month-old Nagpur mandarin leaves (3rd and 4th leaf from the tip of non-fruiting branches) at a height of 1.5 m from the ground surface surrounding the plant canopy were collected in paper bags from different treatments at the end of October (Srivastava et al., 1998; Srivastava and Singh, 2009). The collected leaf samples were thoroughly washed (Bhargava, 2002; Huchche et al., 2001), initially dried under shade, followed by drying at 65°C in an oven to constant weight, and finally ground to obtain a homogeneous sample ready for acid digestion. Likewise, ten mature, fresh, and undamaged Nagpur mandarin fruits were randomly selected from each treatment, washed thoroughly with distilled water to remove dirt, air-dried, followed by drying at 65°C in an oven to constant weight, and finally ground to obtain a homogeneous sample ready for acid digestion. Both leaf and fruit samples were digested in a di-acid mixture of 2 parts HNO_3 and 1 part H_2SO_4 until clear digests were obtained. They were then analyzed for macronutrients (N, P, K, Ca, and Mg), expressed as percentages, and micronutrients (Fe, Mn, Cu, and Zn), expressed as ppm, following standard procedures (AOAC, 1995).

2.9 Statistical analysis

The data from the experimentation were analyzed statistically using analysis of variance (ANOVA). The F-test was employed to assess the significance of the treatments at the 5% significance level. Principal component analysis (PCA) and development of the regression equation for prediction of fruit yield were carried out using IBM-SPSS statistical software (version 27). The multivariate analysis, including correlation matrix and PCA, and multiple linear regression analysis correlating fruit yield to other plant-based parameters were also performed using the software. The correlation matrix (using PROC CORR) was prepared to determine the strength of the linear relationship among the variables, whereas regression analysis (using PROC REG) was conducted to establish the mathematical relationship between the dependent variable (yield) and the independent variable having maximum variability in the dataset. PCA was performed using the PROC PRINCOMP procedure to determine the variables with maximum variability. Data for different years were tested by comparing treatment means using the t-test.

3 Results and discussion

3.1 Climatic analogues vis-à-vis crop phenology

The agro-met observatory at ICAR–Central Citrus Research Institute, Nagpur, Maharashtra (India) was used to generate mean monthly meteorological parameters (averaged over three years). Cooler December temperatures with lower humidity (26.04°C max., 11.09°C min., and 61.21% RH) compared to November (27.88°C max., 15.13°C min., and 69.41% RH) aided in developing plant stress under no-irrigation scenarios. Rising temperature, humidity, and long sunshine hours during January–February favored the induction of new flush and, consequently, fruit set.

The fruit development phase experienced high temperatures, elevated evaporation rates, and low humidity, especially during April–May, when temperatures sometimes reached up to 47.8°C. Substantial June rainfall reduced temperatures, aiding in comparatively faster fruit development.

The initial growth phase (January–February) saw a rise in maximum temperatures (30.34°C–33.24°C) and low minimum temperatures (10.11°C–12.33°C), with high relative humidity (68.58%–70.85%) and extended sunshine hours (8.72–10.08 h). These conditions, along with minimal rainfall during January (15.10 mm), favored early vegetative growth, floral induction, and subsequent anthesis.

The fruit development phase coincided with April–May (peak temperatures of 47.8°C in May), a period known for high temperatures, high evaporation, and low humidity, which began to decline from June onwards due to substantial rainfall, aiding faster fruit development. July recorded the highest monthly rainfall (563 mm), followed by September (363 mm) and August (256 mm), collectively supporting fruit growth towards the mid-development stage.

This was followed by comparatively cooler temperatures and reduced evaporation during September–October (2.41–3.25 mm day^{-1} evaporation; temperature range 19.12°C–30.78°C). The fruit maturity period featured moderate temperatures, humidity, and sunshine hours, leading into the color-break stage, when both temperature and humidity were lower (temperature range 10.11°C –42.41°C; humidity 40.25%–85.71%), allowing the final color change in the peel (Supplementary Tables).

3.2 ET_{NM}, K_c, and WA vis-à-vis crop phenology

ET_r is an important parameter in understanding the crop water requirement, computed from weather data (Pereira et al., 2015; Latief et al., 2017). The ET_r data (Figure 2) revealed that the highest ET_{NM} coincided with the pea-size fruitlet stage, increasing along with rising temperatures and longer daylight hours, which further enhanced evaporation and transpiration rates. The lowest ET_{NM} occurred towards the completion of the fruit development stage in September. Beyond this stage, the occurrence of cooler temperatures and shorter days aided in reducing water loss. The average ET_r values were 1,812.30 mm, with daily minimum and maximum values ranging from 2.56 to 10.47 mm, respectively. The K_c values and wetted area values for different growth stages of 12-year-old Nagpur mandarin trees varied in the ranges of 0.20–1.10 and 0.30–1.20, respectively. The K_c values showed four distinct phases, initially with values of 0.60 at the flowering–fruit set stage, reaching stable values between 1.10 and 1.20 during the fruit development stage, and then declining towards crop maturity and

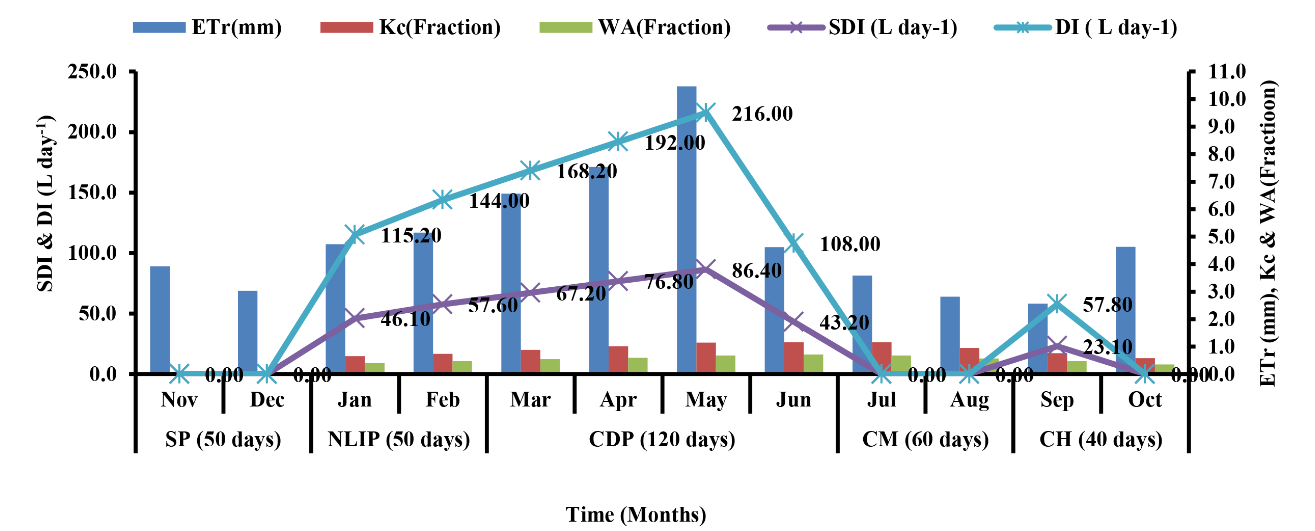

FIGURE 2
Reference crop evapotranspiration (ET_r) in mm, Crop coefficient (K_c), Wetted area (WA) in fraction, Water applied through SDI and DI in Lday^{-1} during study period (Pooled data of two seasons). (*SP, Stress period; NLIP, New leaf initiation period; CDP, Crop development phase; CM, Crop maturation; CH, Crop harvesting).

the color-break stage. These K_c values at various growth stages of Nagpur mandarin are comparable with previous studies (Petillo and Castel, 2007; Bhantana and Lazarovitch, 2010; Gorantiwar et al., 2011; Jamshidi et al., 2020) on other fruit crops such as pomegranate, peach, and Citrus. Phenophase-wise wetted area of Nagpur mandarin showed average values ranging from 0.20 to 0.70, 0.30 to 0.80, and 0.40 to 1.10 during the 12th and 13th years of orchard age, respectively.

3.3 Soil moisture variation under SDI versus DI

Daily water applied through SDI and DI treatments (Figure 2) showed an increasing trend from January–February (46 and 115 L day^{-1}) to May–June (86 and 216 L day^{-1}), indicating 60.00% less water with the former treatments. The water used by mandarin trees varied considerably compared with Valencia trees grown in Florida, USA, due to differences in age, climate, nature of citrus cultivars, type of irrigation system, and method of scheduling irrigation (Fares and Alva, 1999).

The total water applied through SDI and DI during the crop production cycle of Nagpur mandarin showed a contrasting variation from 13,260 to 32,670 L tree^{-1} with the former using 60% less water. These observations indicated that SDI-irrigated trees used a higher quantity of stored soil moisture in the root zone than DI. The mean (θv) observed at different soil depths (15, 30, 60, and 100 cm) in SDI and DI (Supplementary File with Figures 1a–d) further supported these observations. The θv decreased progressively from the onset of stress until the end of the stress period (45 days of stress) in both years of the experiment. The fortnightly estimated soil water content (SWC) was highest r SDI, 1.72% to 14.40%, and accompanied θv values, ranging 2.24% to 16.91%, considering different soil depths (Turner, 1988). The maximum SWC was observed at a 30 cm soil depth, followed by 15 cm, indicating the most active root zone (effective root depth) of mandarin trees between 15 and 30 cm. Earlier findings reported a shallow active root zone of 15 cm for drip-irrigated Nagpur mandarin budded on Rangpur lime grown on Vertisol in central India (Autkar et al., 1988; Panigrahi et al., 2008) and 30 cm for sweet orange budded on Rangpur lime in red sandy clay loam soil in South India (Iyengar and Shivananda, 1990). This difference was due to variation in citrus cultivars and rootstocks used under different pedoclimatic conditions. The SWC value at 30 cm depth under SDI was significantly higher than under DI due to greater root activity up to 60 cm soil depth under water stress conditions with SDI treatments.

3.4 Response on canopy volume and fruit quality

The effects of SDI and DI on canopy volume varied among treatments (Table 1). A 29.19% higher canopy volume was observed with SDI over DI, with treatment T_3 consistently outperforming the others. Earlier studies (Abo-Taleb et al., 1998; Ibrahim and Abd El-Samad, 2009) also reported maximum canopy volume with various SDI treatments.

Fruit quality, on the other hand, responded significantly to micro-irrigation treatments. Treatment T_3 exhibited the highest juice content, TSS, acidity, and TSS:acid ratio. These results indicated that T_3 was more effective in enhancing fruit quality compared with other treatments. Greater canopy light interception in T_3 likely improved photosynthetic activity, thereby aiding the development of superior fruit quality parameters. These findings emphasize the importance of selecting optimal micro-irrigation treatments to improve the quality and marketability of Nagpur mandarin fruits.

3.5 Response on fruit yield

Fruit yield was more influenced by SDI than by DI treatments (Table 2). The highest yield and yield increase (%) were obtained with treatment T_3 (56.23%), followed by T_4 (35.56%), and the lowest yield with T_1 (15.86%) and T_2 (29.16%) among the SDI treatments.

Among the DI treatments, and considering T_5 as the control (farmers' practice), SDI treatments registered 15.86–56.23% higher fruit yield. Compared with T_6 (a DI treatment), SDI treatments recorded 6.95–47.32% higher fruit yield. The significantly superior response of Nagpur mandarin to SDI treatments over DI treatments

TABLE 1 Effect of micro-irrigation treatments on growth characteristics and fruit quality parameters (Pooled data of two seasons).

Treatments	Canopy volume (m^3)	Leaf area (cm^2)	Juice content (%)	TSS (^{0}Brix)	Acidity (%)	TSS: acid ratio	No. of segments fruit^{-1}
T_1	28.31^{bc}	22.45^{cd}	38.60^{ab}	9.24^{c}	0.785	11.94	10.13
T_2	31.17^{ab}	23.44^{ab}	39.95^{a}	9.55^{bc}	0.795	12.42	10.13
T_3	38.06^{a}	24.63^{a}	41.68^{a}	10.61^{a}	0.853	12.59	10.38
T_4	32.36^{ab}	23.63^{bc}	41.21^{a}	9.80^{b}	0.810	12.31	10.75
T_5	20.30^{c}	20.78^{e}	33.06^{c}	8.53^{d}	0.700	10.79	10.25
T_6	26.55^{bc}	21.80^{de}	34.37^{bc}	8.74^{d}	0.750	11.21	10.00

Within each column, different letters indicate significant differences at $p \leq 0.05$ (n=32).

TABLE 2 Effect of micro-irrigation treatments on yield attributes and water productivity of Nagpur mandarin (pooled data of two seasons).

Treatments	Fruit $tree^{-1}$ (Nos.)	Fruit weight (gm)	Yield ($kgtree^{-1}$)	Yield increase (%)	WU (m^3)	WP (kgm^{-3})
T_1	649.75^{c}	162.80^{bc}	105.56^{c}	15.86^{c}	13.26	7.96^{c}
T_2	701.63^{b}	167.81^{ab}	117.76^{b}	29.16^{bc}	13.26	8.88^{b}
T_3	805.00^{a}	176.61^{a}	142.28^{a}	56.23^{a}	13.26	10.73^{a}
T_4	718.63^{b}	171.97^{ab}	123.58^{b}	35.56^{b}	13.26	9.32^{b}
T_5	585.63^{d}	155.63^{c}	91.10^{d}	00.00^{e}	32.67	2.79^{d}
T_6	615.62^{cd}	161.18^{bc}	99.25^{cd}	8.91^{d}	32.67	3.04^{d}

Within each column, different letters indicate significant differences at $p \leq 0.05$ (n = 32).
(T_1 – SDI with double inline laterals at dripper spacing 30 cm; T_2 – SDI with double inline laterals at dripper spacing 40 cm; T_3 – SDI with double inline laterals at dripper spacing 50 cm; T_4 – SDI with double inline laterals at dripper spacing 60 cm; T_5 – DI with double online laterals (6D); and T_6 – DI with single online laterals with ring-type inline laterals (12D)).

was attributable to reduced water losses, which translated into higher water- and nutrient-use efficiency.

Similarly, Ayars et al. (2003) reported a 30.0% saving in water over alternate-day irrigation using drip irrigation in a lysimetric study.

An improved yield was directly associated with the number of fruits $tree^{-1}$, with treatment T_3 recording the highest number (718.75 fruits $tree^{-1}$) among SDI treatments, compared to 600.62 fruits $tree^{-1}$ under DI (Table 2), showing the lesser effectiveness of the latter. Fruit size distribution is another indicator of improved fruit yield. A higher percentage of B-grade fruits was recorded with treatment T_3 (64%), statistically on par with treatments T_4 and T_2, compared to the rest of the treatments. A similar pattern was observed with respect to A-grade fruit size, with T3 as the best treatment followed by T4 and T_2. Hence, implementing SDI could be a highly remunerative strategy to increase the proportion of A-grade fruits over B- or C-grade fruits, alongside fruit size, thereby enhancing marketability (Figure 3).

3.6 Improvements in WP and NUE

Use efficiency of applied nutrients and water provided strong clues towards the magnitude of crop response. WU was observed to be quite consistent in treatments such as T_1 and T_4 (13.26 m^3). However, T_5 and T_6 showed significantly higher WU (32.67 m^3), indicating a 60% water saving with SDI over DI treatments on account of restricted deep percolation losses below the root zone (Table 2). WP, measuring the efficiency of water use in producing higher fruit yield, was highest with treatment T_3 (73.99%) compared to T_1 (69.94%), T_2 (65.58%), or T_4 (70.06%) among SDI treatments, and to T_6 as a DI treatment (8.22%), considering T_5 as the control treatment. This highlighted the greater effectiveness of SDI over DI. Water stress at any growth stage adversely affects fruit yield; the role of SDI in this regard was not only to ensure uniform delivery of water but also to maintain uniform water distribution within the effective root zone, thereby keeping the plants in a water-friendly mode—an agro-pedological condition necessary for elevated WP.

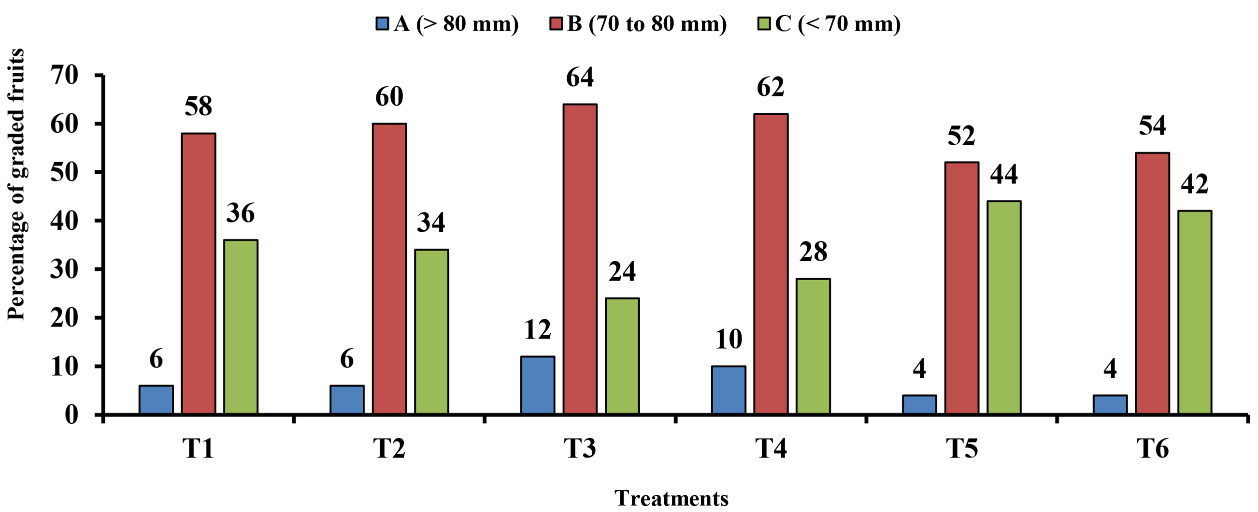

FIGURE 3
Percentage distribution of fruit size in response to among various treatments (Pooled means of two harvesting seasons).

The WP values in our study were lower than some previously reported under more humid tropical environments (Howell, 2001). These differences could be explained by the fact that our study was conducted in a more semi-arid environment.

3.7 Changes in leaf nutrients composition

Treatments expressed a differential response in leaf nutrient composition, except for leaf P content (Figure 4). The highest concentrations of leaf nutrients were recorded with treatment T_3, followed by T_4. However, in all treatments, regardless of SDI or DI, the leaf macro- and micronutrient contents were higher than the suggested optimum concentrations for Nagpur mandarin. Treatment T_3 was the most effective, with the highest leaf nutrient concentrations. In contrast, treatments T_5 and T_6 exhibited the lowest nitrogen and potassium contents, indicating their reduced efficacy compared to other treatments. Phosphorus levels in the leaves remained unaffected by the different treatments. Despite the lack of significant differences, T_3 still demonstrated the highest phosphorus content, implying slightly better phosphorus uptake.

Micronutrients play a vital role in photosynthesis and nutrient transport, thereby increasing yield and nutrient content. Treatment T_3 had the highest Fe, Mn, Cu, and Zn contents, making it the most effective in enhancing micronutrient accumulation. Treatments T_5 and T_6 exhibited progressively lower concentrations of different micronutrients. These observations underscore the importance of selecting an optimal micro-irrigation system to enhance nutrient accumulation and improve both fruit yield and quality (Shirgure et al., 2001; Srivastava, 2013; Kuchanwar et al., 2017).

The correlation between fruit yield and other plant-based variables (CV, canopy volume; nutrient content in leaves and fruits [N, P, K, Ca, Mg, Fe, Mn, Cu, and Zn]; and physiological parameters [RLWC, Pn, gs, Tr, LWUE]) (Figure 5) showed notable patterns. Fruit yield was positively correlated with leaf nutrients such as N (r = 0.94**), K (r = 0.88**), Ca (r = 0.91**), Fe (r = 0.93**), Mn (r = 0.78**), Cu (r = 0.79**), and Zn (r = 0.91**), indicating that higher leaf nutrient content contributed significantly to yield. Similarly, yield was positively correlated with fruit nutrients such as N (r = 0.89**), P (r = 0.87**), K (r = 0.79**), Ca (r = 0.90**), Mg (r = 0.81**), Fe (r = 0.74**), and Zn (r = 0.79*), highlighting the importance of nutrient-rich fruits for better yield outcomes. The physiological parameters, including CV (r = 0.57), RLWC (r = 0.83*), Pn (r = 0.92**), gs (r = 0.91**), Tr (r = 0.95**), and LWUE (r = 0.93**), also showed positive correlations with yield.

The strong relationship of fruit yield with Tr and gs was earlier reported by Dzikiti et al. (2010) in citrus under micro-irrigation treatments. Principal component analysis (PCA) using 23 variables indicated that the first three PCs explained 87% of the variability under micro-irrigation (Figure 6). Therefore, the variables involved in these three PCs were considered for further analysis. Variables from PC1 (Leaf-N, Leaf-P, Leaf-K, Leaf-Fe, Leaf-Mn, Leaf-Cu, Leaf-Zn, RLWC, LWUE, Pn, gs, and Tr), PC2 (Fruit-N, Fruit-P, Fruit-K, Fruit-Ca, Fruit-Na, Fruit-Fe, Fruit-Mn, Fruit-Cu, Fruit-Zn, RLWC, LWUE, Pn, gs, and Tr), and PC3 (CV, RLWC, LWUE, Pn, gs, and Tr) were retained for interpretation, considering their eigenvalues > 1.

However, due to the strong correlations among gs, Tr, and Leaf-K; between Pn and CV (r = 0.87–0.89**); and between Leaf-N and SD (Figure 5), CV, RLWC, LWUE, Pn, gs, and Tr were not considered for the PCRAA multiple regression model. A regression model (Figure 7) developed between yield and other selected plant variables (Leaf-N, Leaf-P, Leaf-K, Leaf-Fe, Leaf-Mn, Leaf-Cu, and Leaf-Zn, RLWC, LWUE, Pn, gs, and Tr) is proposed as:

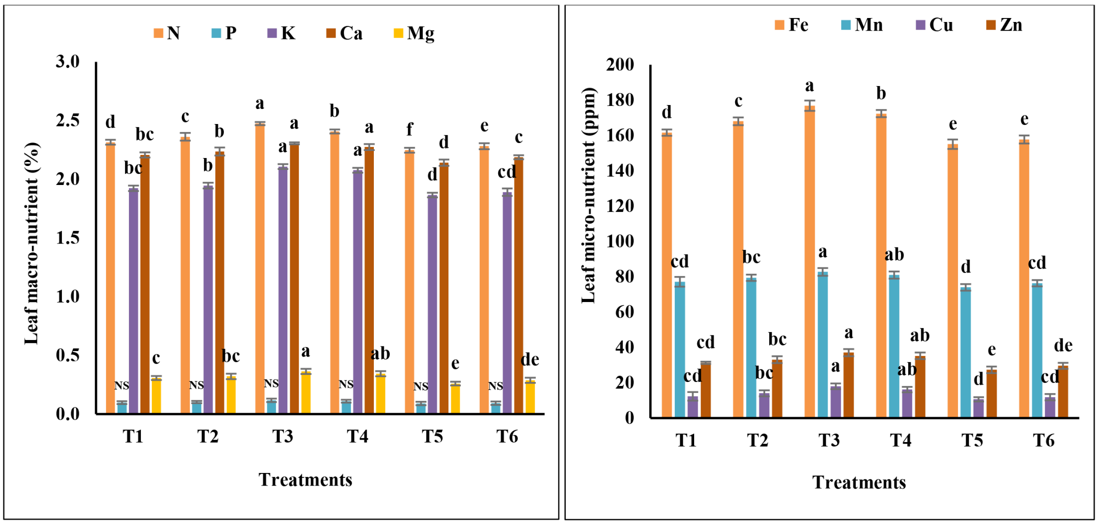

FIGURE 4
Response of micro-irrigation treatments on leaf macro-nutrients (N, P, K, Ca, and Mg) and micro-nutrients (Fe, Mn, Cu, and Zn).

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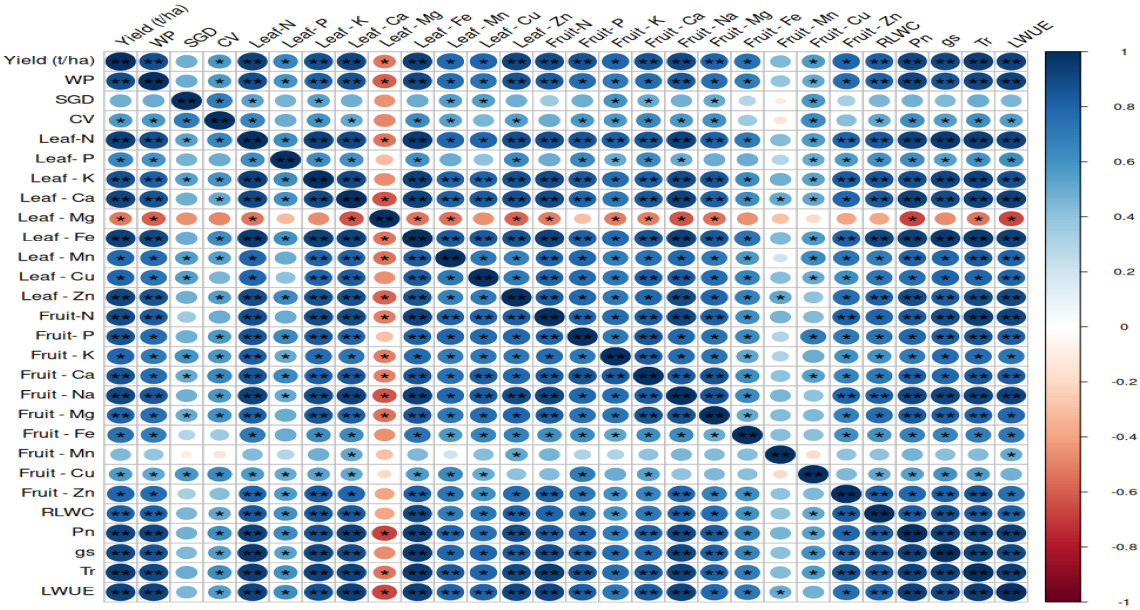

FIGURE 5
Correlation matrix (Pearson's) for plant-based observations (leaf nutrients, fruit nutrients, and physiological parameters) and fruit yield using the pooled data of two seasons. Data followed by "*" indicate a significant correlation at $p < 5$, and data followed by "+" indicate a significant correlation at $P<1$.

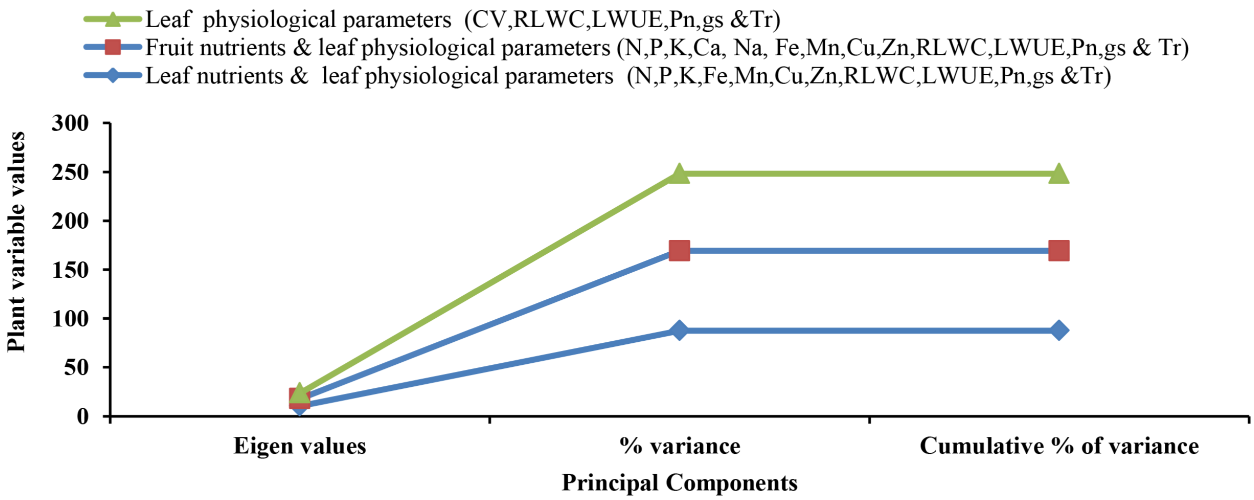

FIGURE 6
Principal components (PCs) for plant-based variables (leaf nutrients, fruit nutrients, and physiological parameters) with Eigen values in response to different treatments in EFGP.

$$\text{Fruit yield} = -49.99 + 23.46*(\text{Leaf} - \text{N}) - 28.35*(\text{Leaf} - \text{K}) + 0.14*(\text{Leaf} - \text{Fe}) + 0.13*(\text{Leaf} - Mn) + 0.28*(\text{LeafCu}) + 0.65*(\text{Leaf} - Zn) - 0.006*\text{RLWC} - 0.15*\text{LWUE} + 1.29*Pn - 0.0024*gs + 11.05\text{Tr}; (p < 0.05; R^2 = 0.956; \text{RMSE}0.9825\,\%)$$

3.8 Fruit nutrients composition

The concentration of different nutrients in fruits is considered crucial for both plant health and nutritional quality. The analysis of fruit nutrient composition showed that all nutrients except P, Mn, and Cu were significantly affected by different treatments involving SDI and DI (Figure 8). The highest concentration of N was observed

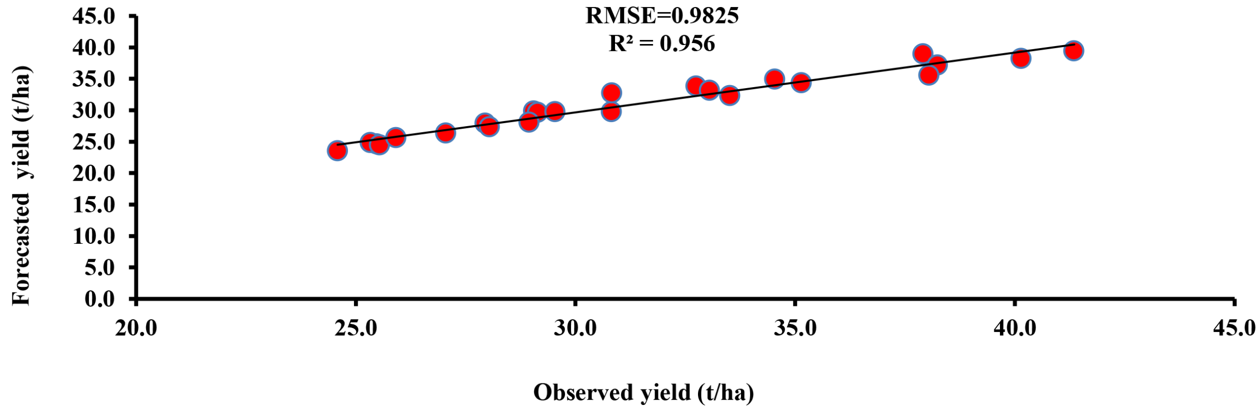

FIGURE 7
Predicated fruit yield versus observed fruit yield of Nagpur mandarin under various micro-irrigation treatments.

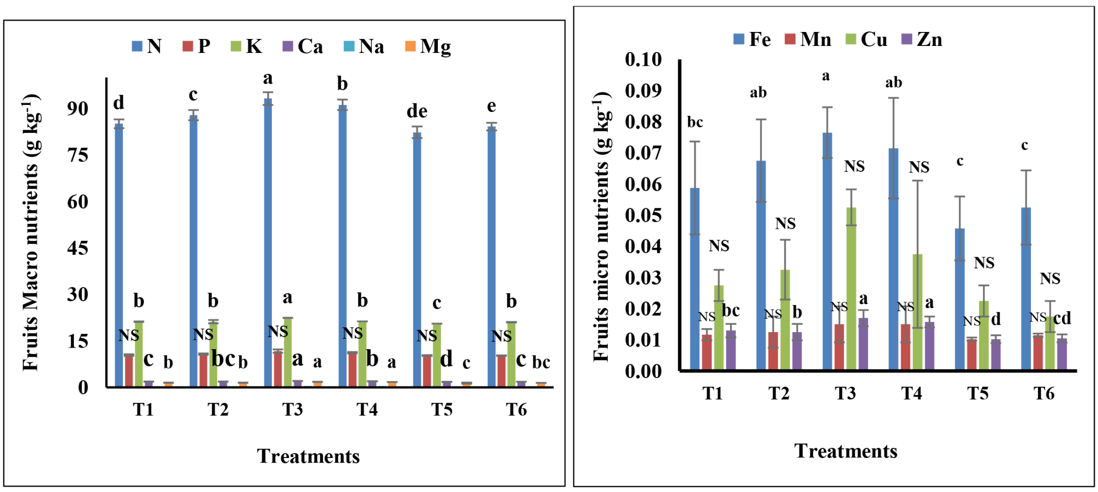

FIGURE 8
Comparative response of SDI versus DI treatments on fruit nutrients composition (Pooled mean of two harvesting seasons).

with treatment T_3, followed by T_4, T_2, T_1, T_6, and T5 in decreasing order. Treatment T_3 also showed the highest K concentration, followed by T_5 and T_6. Ca levels were relatively low across all treatments. Like macronutrients, noticeable differences in the concentration of micronutrients in response to irrigation treatments were observed. The concentration of Fe and Mn in fruits was maximum with T_3 compared to the rest of the treatments. On the other hand, Zn concentration was highest with treatments T_1 and T_2. SDI treatments maintained optimum soil moisture content, thereby increasing root activity and nutrient uptake, which ultimately increased the leaf nutrient content and improved yield and quality. Optimizing irrigation practices, therefore, played a pivotal role.

4 Conclusion

Irrigation water is a precious commodity in citriculture that demands innovative research. Our studies in this direction showed that SDI outperformed DI in terms of quality production of Nagpur mandarin, coupled with improvement in soil fertility and leaf nutrient composition, with an edge in nutritional quality of fruits. SDI ensured higher WP and NUE, suggesting far better utilization efficiency of important inputs like water and nutrients. These studies are expected to provide better insights by scheduling nutrients such as N, K, and Zn during the fruit developmental growth stage, coupled with their partitioning and mobilization/remobilization, to develop a demand-driven fertilization strategy.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

DM: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing. AS: Data curation, Funding acquisition, Methodology, Project administration, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing. AT: Data curation, Supervision, Writing – review & editing. NM: Investigation, Supervision, Writing – review & editing. PJ: Resources, Software, Visualization, Writing – review & editing. AU: Data curation, Formal Analysis, Resources, Validation, Visualization, Writing – review & editing. CP: Data curation, Formal Analysis, Investigation, Resources, Validation, Visualization, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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