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ORIGINAL ARTICLE

# Growth, Yield and Water Productivity of Tomato as Influenced by Deficit Irrigation Water Management

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## Abstract

The deficit irrigation offers water savings potential that is becoming popular in arid and semi-arid regions reducing freshwater use over time. A two-year factorial experiment was conducted to evaluate growth, yield and water productivity of tomato under water deficit irrigation of the drip and furrow method. The experiment was carried out in a split-plot design with drip irrigation and furrow irrigation as main plot treatments, and soil moisture regimes (0, -10, -20, -30 kPa) as subplots. Data were collected on growth parameters, physiological traits, yield and water productivity of tomato. The results showed that physiological traits, yield, and water productivity were significantly influenced by irrigation system and soil moisture regime. The drip irrigation system with -10 kPa soil moisture regime reduced total water input by 22.6% and 19.8% and gave 28% and 22% higher fruit yields in 2020 and 2021, respectively, compared with furrow irrigation system. Plant growth was higher and flowering occurred earlier (3 days) with drip irrigation system than with furrow irrigation. When the soil water content was -10 kPa, drip irrigation performed significantly better than for other soil moisture regimes by improving physiological and phenological attributes, and thereby, advancing tomato growth and fruit yield. Thus, a drip irrigation system with soil moisture regime -10 kPa could reduce total water input through precise irrigation, maximizing tomato yield and water productivity.

## Highlights

- Average total water input was reduced by about 21.2% using drip irrigation system.
- Soil moisture regime was more affected by furrow irrigation system.
- Flowering occurred earlier (3 days) in the drip irrigation system.
- Drip irrigation with a -10 kPa soil moisture regime upgraded average tomato yield by 25%.

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## 1 Introduction

Climate change and agricultural malpractices rising groundwater depletion are major concerns globally and more acute in the developing countries of Asia (Ahmed et al. 2014; Neupane et al. 2021) resulting in water scarcity for crop production, especially in dry seasons (Jahan et al. 2010; Hasan et al. 2018). Freshwater scarcity through groundwater depletion is an acute environmental phenomenon threatening global food safety by unfavorably impacting justifiable crop production (Ullah et al. 2017; Ilyas et al. 2021). Agriculture is the largest freshwater consumer globally; the reduced freshwater availability due to vast population growth, industrialization, climate change, and unproductive water loss is a key challenge to address for sustainable agricultural production (Chareesri et al. 2020; Das et al. 2021b). Water scarcity tempts the downregulation of various physioco-chemical processes in plants causing severe oxidative damage to cellular activities and subsequent significant yield loss (Ullah et al. 2019; Panda et al. 2021). Water scarcity and food safety are strongly connected because agricultural systems are probably the first and direct victims of climate change-mediated groundwater depletion. These demands finding water-saving methods to decrease water use in agriculture while boosting yield to assist a rising population (Carrijo et al. 2017). Future climate forecasts direct towards more uncertainties regarding irrigation water accessibility; regular incidents of drought will aggravate sustainable and precise application of irrigation water (Gosling and Arnell 2016; Neupane et al. 2021). In Bangladesh, total rainfall during the tomato growing season is irregular, ranging from 150 to 500 mm in total. In fact, in the last couple of years, there has been a trend of decreasing precipitation during the tomato growing season. It has been reported that climate change may be exacerbating many countries' experiences of groundwater depletion, water stress, and constraining the accessibility of irrigation water (Yan et al. 2015). Hence, water savings irrigation through a deficit irrigation system might be a potential avenue for enhancing yield and water use efficiency of horticultural commodities. Efficient water distribution has become a growing concern for sustainable agricultural production (Al-Faraj et al. 2016). Climate change and water scarcity are posing new challenges to irrigation management. Water demand gradually increases whereas crop yield reduces due to climate change. Efficient irrigation management approaches could be helpful in counteracting the detrimental effect of climate change and sustainable use of water resources (El-Nashar and Elyamany 2022). Different strategies have been taken worldwide for rational use of available water resources. Deficit irrigation (DI) management is one of the strategies that save 12% total water input and improved water productivity when compared to full irrigation (Tsakmakis et al. 2018). DI uses limited water resources to achieve desirable crop yield according to the migration law of production attributes during crop growth (Li et al. 2022).

Deficit irrigation is a water-saving irrigation strategy that is becoming popular in arid and semi-arid areas. Under DI, irrigation water is applied at lower amounts than the full crop water requirement (i.e., ET), thus increasing water productivity. It has been postulated that the level of irrigation water supplied under DI should be between 60% and 100% of ET (Mabhaudhi et al. 2021). Water productivity (WP) under DI improves significantly in comparison to full irrigation because small amounts of irrigation increase crop ET linearly up to a point maximizing yield, while additional amounts of irrigation do not further increase yield. Actually, farmers are used to over-irrigate their crops to obtain better yields which aggravates unproductive water loss towards freshwater scarcity globally (Liu et al. 2022). Some research claimed furrow irrigation causes 10–18% water loss in greenhouse (GH) tomato production (Qiu et al. 2017). It is possible to reduce excess irrigation by 20–50% through the drip irrigation method without yield loss (Yang et al. 2017). Currently, the drip irrigation system is widely used in different countries for growing tomatoes, cucumbers, melons, peppers, etc. in GH in the winter offering various benefits (Wang et al. 2019a, b; Liu et al. 2022). Past research has reported that the conventional furrow irrigation system relies on more irrigation water than drip irrigation. Also, crop yields were lowered with furrow irrigation compared to the drip irrigation system (Sun et al. 2019; Li et al. 2021a, b). Conventional crop production using a furrow irrigation system is water-intensive overexploiting freshwater resources and should be operated with water-saving schemes to uphold efficiency and preserve the environment without negotiating crop yield and quality (Ruiz-Sanchez et al. 2011). In GH tomato production, drip irrigation dropped the irrigation amount by 17–30% compared to furrow irrigation systems without yield loss (Li et al. 2020). Drip irrigation systems preserved proper soil moisture, and greatly reduced evaporation losses resulting in the highest water use efficiency over furrow irrigation leading to good crop response for tomato production (Musa et al. 2014; Chen et al. 2018; Chakma et al. 2021). In the case of strawberries, drip irrigation maintained more uniform soil moisture, plant growth and fruit yield compared to the furrow irrigation system in Bangladesh (Dash et al. 2020). Although drip irrigation systems provides more efficient use of water, their upsurge in installation and maintenance costs prohibit their wide-scale adoption by low-income farmers in many developing countries (Fathel 2020). These necessitate the development of a consistent low-cost drip irrigation system that fits the desires of low-income farmers. Government subsidies for agriculture may be available to offset the cost of drip irrigation systems through the National Agricultural Technology Project, which is projected to upsurge agricultural output and farm income (World Bank 2014).

Tomato is the most popular vegetable growing at different parts of the world but it is sensitive to soil water deficit (Yang et al. 2017; Hou et al. 2020). Therefore, use of suitable irrigation systems and maintaining optimum soil moisture conditions are crucial to get a higher return and water productivity for tomato production in open field conditions. Tomato yield and water productivity were significantly affected due to soil moisture deficit at 50% field capacity (FC) compared to 100% FC (Chakma et al. 2021). Marketable fruit yield of tomatoes decreased by 53–83% and water use efficiency by 17% under 50% of full irrigation supply and rainfed conditions, respectively (Cantore at al. 2016). When the plant consumption of irrigation water reduced from 100 to 50%, stomatal conductance decreased by 45% in the Ikram genotype of tomatoes resulting in a cut assimilation rate of this genotype (Giuliani et al. 2018). Similarly, tomato fruit yield was reduced by 86 − 94% and water productivity by 79–92% at 50% FC assessed with 100% FC (Chakma et al. 2022). Due to less frequent irrigation in furrow irrigation systems, soil rapidly dries out and it is showing cracking symptoms at the soil surface. Also, roots are straggling getting through the soil and absorbing moisture and nutrients from the soil. Drip irrigation systems allow irrigation water to soak in and spread out properly in the root zone.

Most previous studies show the potentialities of drip irrigation systems in greenhouse conditions, not in the open field situation. As a result, this study focuses on the potentialities of drip irrigation systems in field conditions under optimized soil moisture level under deficit irrigation. To confront the changing climate and conserve groundwater, it is primarily necessary to optimize water requirement of irrigation systems for tomato production.

Plenty of literature is available on different aspects of tomatoes but to the best of our knowledge, limited literature is available regarding the water savings potential between drip and furrow irrigation methods and fine twinning of soil moisture regime for tomato production. Therefore, the objective of this study was to evaluate growth, yield and water productivity of tomato under a deficit irrigation management system of drip and furrow methods under various soil moisture regimes.

## 2 Materials and Methods

### 2.1 Experimental Setup

Field experiments were conducted at Professor Dr. Purnendu Gain field laboratory of Agrotechnology Discipline, Khulna University, Bangladesh (22°47’ N; 89°34’ E) during the dry seasons of 2020 and 2021. The soil was collected from the research farm of Khulna University containing 16% sand, 36% silt, 51% clay and 2.4% organic matter. It was reported that soil is slightly acidic (pH = 6.2) with inherent exchangeable P, K, Ca, and Mg contents of 2.1 Cmol $kg^{-1}$, 0.5 Cmol $kg^{-1}$, 15.5 Cmol $kg^{-1}$, and 10.5 Cmol $kg^{-1}$ soil, respectively (SRDI 2009). The field capacity of the soil was computed according to Datta et al. (2009) where 44.8% soil moisture content was determined at 100% field capacity corresponding to 0 kPa soil water potential. The temperature in the experimental field ranged from 22 to 34 °C, and the relative humidity ranged from 70 to 86% throughout the growing period.

### 2.2 Experimental Treatment, Design and Water Management

Two years (2020 and 2021) of field experiments were conducted which investigated two factors using a split-plot design in which the main plot was the irrigation system and the subplot was soil moisture regime settled in a randomized complete block design with four replications. The factorial experiments contained two irrigation systems (drip and furrow) placed in a block design with confined randomization and four soil moisture regimes (0, -10, -20, -30 kPa) randomly allocated to the subplots (Fig. 1). In the drip irrigation system, totally impermeable black plastic mulch (0.09-mm thickness) film was applied on the surface of beds prior to transplanting and a single drip tape line (Claber; 7.5 L/30 m, 0.03-mm thickness, 140-mm diameter, 0.6-m emitter spacing, Pordenone, Italy) was positioned along the middle of the bed during the placing of the mulch film (Dash et al. 2020). A tensiometer (Model 2725ARL Jet Fill Tensiometer, Soil moisture Equipment Corp., CA, USA) was fitted into the soil per treatment basis at a depth of 0.2 m and the soil moisture regimes were maintained according to the treatments. In clay loam texture soil, the drip irrigation (0.002 $m^3$ $min^{-1}$ 30 $m^{-1}$) was run daily as per tensiometer reading using a slightly modified protocol of Sanchez (2018). The irrigation time for the soil to return to the field capacity was assessed by computing the ratio of the water replacement slide and the dripper flow rate, assuming 90% application efficiency (Liu et al. 2019). Soil water potential was maintained at 0, -10, -20, and −30 kPa, respectively, in which irrigation water was delivered when soil water potential touched the anticipated level of the treatments. The soil water regime of −30 kPa designates approximately 30% reduction of the maximum amount of water held in the soil whereas 0 kPa refers to the maximum amount of water held in the soil after gravitational water drainage stops, according to Das et al. (2021a). Water was delivered from an elevated water tank which was filled by an electric

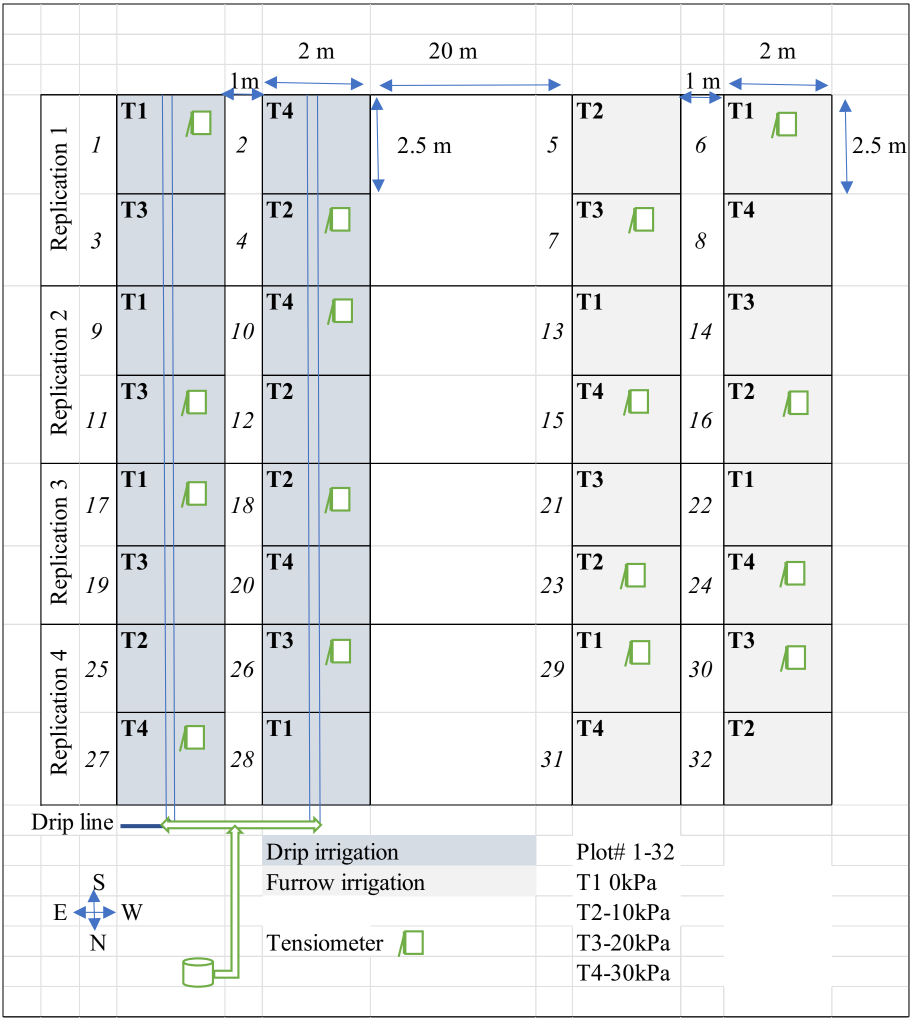


**Fig. 1** Layout of the experimental plot

pump. The water input of drip irrigation system was measured by the water meter (DLJ; Daniel L Jerman Co. Hackensack, NJ, USA). On the contrary, the water input of furrow irrigation system was recorded by the amount of water per minute should supply through the system (Dash et al. 2020).

## 2.3 Crop Husbandry and Nutrient Management

Mintoo Super (HYV) tomato seeds were used as experimental materials which were grown at the nursery of Agrotechnology Discipline, Khulna University, Bangladesh. The life cycle of this variety ranges from 80 to 90 days. The tomato transplant was set on November 12, 2020, and November 9, 2021, respectively. Seeds were treated with 10% $H_2O_2$ for 10 min, rinsed followed by washing thoroughly with distilled water (Dash et al. 2020). Seeds were sown into the plastic cell tray containing coco peat (pH-6.5, water holding capacity 70%) growing media (RIOCOCO, Ceyhinz Link International, Inc., TX, USA) and sprayed 20-20-20: % N-P-K (Balwan Fertilizer and Chemicals, Ahmedabad, Gujrat, India) fertilizer once per week starting from 2-weeks after germination, and 28 days after sowing, one healthy and vigor seedling was transplanted at 0.6-m apart in double staggered rows with a 0.8-m spacing between rows into each hole of the bed. Beds were prepared manually on 2-m centers with approximate bed height and width of 0.2 and 0.7 m for drip irrigation system and 0.1 and 0.7 m for furrow irrigation system, respectively. The individual plot size was 2.5 m×2.0 m, and the gap between plots was 1.0 m. Mixed fertilizer 20-20-20: % N-P-K (Balwan Fertilizer and Chemicals, Ahmedabad, Gujrat, India) at 8.65 kg $ha^{-1}$ was applied weekly up to fruiting as liquid form throughout the season.

## 2.4 Data Collection

Data were collected on plant height (cm), leaf number, leaf area ($cm^2$), leaf area index (LAI), shoot dry matter (g $plant^{-1}$), root dry matter (g $plant^{-1}$), leaf relative water content (LRWC) (%), electrolyte leakage (%), canopy temperature (°C), leaf greenness (SPAD value), number of flower clusters $plant^{-1}$, number of fruit clusters $plant^{-1}$, days required to first and 50% flower, total water input, fruit yield and total water productivity (kg $m^{-3}$). Plant height was measured by meter scale during the flowering stage. ImageJ software (Martin et al. 2020) was used to compute leaf area ($cm^2$ $plant^{-1}$) which is widely used software for leaf area measurement. To compute leaf area, this software utilizes a threshold-based pixel count procedure described by Easlon et al. (2014). The leaf area index (LAI) was measured nondestructively using an application of a smartphone (Pocket LAI) (Maneepitak et al. 2019). Shoot dry matter (g $plant^{-1}$) and root dry matter (g $plant^{-1}$) were evaluated by calculating the oven-dried (80 °C) weight of tomato shoot and root until a constant weight was found. The canopy temperature was measured using an infrared thermometer (Fluke 572-2 High-Temperature infrared thermometers, TEquipment, TX, USA). The leaf greenness was recorded using SPAD 502 Plus chlorophyll meter (Spectrum Technologies, Aurora, IL, USA) and four readings from each plot were averaged to represent a single observation.

For measuring leaf relative water content (LRWC), leaf samples were collected from the fully extended leaf of the plant and were weighed for their fresh weight (FW) instantly after sampling. After collecting FW, leaves were cut into small segments (2 cm), deep in distilled water in test tubes, and kept overnight in the laboratory and the turgid weight (TW) of the samples was recorded. Then, turgid leaves were oven-dried at 70 °C until the constant weight was attained, and dry weight (DW) was documented. Leaf relative water content was computed using the following formula presented by Jones and Turner (1978):

$$\mathrm{LRWC}\ (\%) = \frac{\mathrm{FW} - \mathrm{DW}}{\mathrm{TW} - \mathrm{DW}} \times 100 \tag{1}$$

Electrolyte leakage (EL) was computed as follows. The leaf samples were cut into six discs and washed with deionized water a couple of times to remove adhered debris. The discs were inserted into the test tube and filled with 20 mL deionized water and kept for 20 h. The electrical conductivity ($EC_1$) of the solution was recorded using a conductivity meter (CON 150, Thermo Scientific, Singapore). Then, the samples were boiled for 15 min and followed by room cooling and the final electrical conductivity of the solution ($EC_2$)

was measured. Then, EL was computed using the following formula presented by Camejo et al. (2005) and Chakma et al. (2021):

$$\text{EL } (\%) = \frac{\text{EC1}}{\text{EC2}} \times 100 \tag{2}$$

Data on fruit yield was recorded during harvesting and total yield was calculated. The total irrigation water productivity (kg $m^{-3}$) was computed as the total fruit yield (kg) divided by total irrigation input ($m^3$) as mentioned by Das et al. (2022).

### 2.5 Statistical Analysis

Data were subjected to a three-way analysis of variance (ANOVA) and were investigated using the analytical software SAS following the general linear model procedure. Means with significant treatment effects were recognized by the F-test and separated by Tukey's honest significant difference test at $p < 0.05$ (SAS software Version 9.4, SAS Institute Inc., Cary, NC, USA). Data with significant treatment effects are described based on the highest order of factorial combination that was significant in the ANOVA. The graph was illustrated using Origin 2020 (OriginLab Corporation, Version 9.6.5, Massachusetts, USA). To determine the relations between the variables and treatments, and to visualize the trends and patterns of variables, principal component analysis and cluster analysis were performed using the raw data.

## 3 Results

### 3.1 Growth Parameters

The interaction effect of irrigation systems and soil moisture regimes was significant ($p < 0.05$) for plant height (Table 1). The three-way interaction effect among seasons, irrigation systems and soil moisture regimes were not statistically significant for plant height. The plant height decreased in excess moisture conditions as well as when the soil contained less water. The highest plant height (99.2 ± 0.8 cm) was obtained in drip irrigation system with a -10 kPa soil moisture regime (Table 2). Similarly, the interaction effect of irrigation systems as well as soil moisture regimes were significant ($p < 0.05$) for leaf number, while no statistical differentiation was noticed between growing seasons. Under excess moisture and low soil water conditions, a smaller number of leaves emerged compared to well soil water content conditions in drip irrigation systems. The maximum leaf number was found in drip irrigation with a -10 kPa soil moisture regime (118.4 ± 2.5) whereas the minimum in furrow irrigation with a 0 kPa soil moisture regime (75.8 ± 1.4) trailed by drip irrigation with a 0 kPa soil moisture regime. Also, the interaction effect of irrigation systems and soil moisture regimes were significant ($p < 0.05$) for leaf area. But, the irrigation systems, soil moisture regimes and growing season three-way interaction did not influence leaf area (LA). LA significantly decreased in both low and excess soil water content conditions. The drip irrigation system with a -10 kPa soil moisture regime combination resulted in 48.76% higher LA than the furrow irrigation system with a 0 kPa soil moisture regime.

In the case of the leaf area index (LAI), the drip irrigation system dominated the furrow irrigation system and caused 14% higher LAI than furrow irrigation (Table 3).

**Table 1** Significance levels in three-way ANOVA of the effect of the growing season, irrigation systems and soil moisture regime on growth parameters, physiological parameters, yield components, fruit yield and water productivity of tomato

| Items | Growing seasons (S) | Irrigation systems (A) | Soil moisture regimes (B) | S × A | A × B | B × S | S × A × B |
|---|---|---|---|---|---|---|---|
| Plant height (cm) | $1.4^{ns}$ | $28.9^{***}$ | $31.9^{***}$ | $6.3^{ns}$ | $21.6^{*}$ | $5.9^{ns}$ | $6.1^{ns}$ |
| Leaf number | $1.9^{ns}$ | $34.1^{***}$ | $38.3^{***}$ | $7.4^{ns}$ | $24.5^{*}$ | $9.2^{ns}$ | $3.8^{ns}$ |
| Leaf area (cm$^2$) | $3.1^{ns}$ | $35.2^{***}$ | $27.6^{***}$ | $4.2^{ns}$ | $25.2^{*}$ | $7.1^{ns}$ | $4.9^{ns}$ |
| Leaf area index | $5.5^{ns}$ | $30.3^{***}$ | $19.8^{**}$ | $6.1^{ns}$ | $1.3^{ns}$ | $8.2^{ns}$ | $6.7^{ns}$ |
| Shoot dry matter (g) | $1.3^{ns}$ | $18.4^{***}$ | $29.3^{***}$ | $1.5^{ns}$ | $3.1^{ns}$ | $2.7^{ns}$ | $3.9^{ns}$ |
| Root dry matter (g) | $1.4^{ns}$ | $15.8^{***}$ | $22.7^{***}$ | $3.2^{ns}$ | $1.3^{ns}$ | $1.9^{ns}$ | $1.1^{ns}$ |
| SPAD value | $1.6^{ns}$ | $25.7^{**}$ | $37.5^{***}$ | $2.8^{ns}$ | $2.5^{ns}$ | $3.2^{ns}$ | $1.7^{ns}$ |
| Number of the flower cluster plant$^{-1}$ | $2.3^{ns}$ | $33.4^{***}$ | $28.2^{**}$ | $2.8^{ns}$ | $4.5^{ns}$ | $3.1^{ns}$ | $2.5^{ns}$ |
| Number of the fruit cluster plant$^{-1}$ | $1.2^{ns}$ | $36.4^{***}$ | $21.6^{**}$ | $3.3^{ns}$ | $5.5^{ns}$ | $4.2^{ns}$ | $3.1^{ns}$ |
| Days required to first flower | $3.5^{ns}$ | $24.1^{***}$ | $7.3^{ns}$ | $2.1^{ns}$ | $4.4^{ns}$ | $3.5^{ns}$ | $6.3^{ns}$ |
| Days required to 50% flower | $2.9^{ns}$ | $26.5^{***}$ | $4.8^{ns}$ | $5.2^{ns}$ | $6.1^{ns}$ | $8.3^{ns}$ | $1.9^{ns}$ |
| Leaf relative water content (%) | $1.3^{ns}$ | $28.1^{***}$ | $23.2^{***}$ | $3.9^{ns}$ | $5.0^{ns}$ | $2.1^{ns}$ | $3.3^{ns}$ |
| Electrolyte leakage (%) | $1.8^{ns}$ | $14.7^{*}$ | $20.6^{**}$ | $1.7^{ns}$ | $1.1^{ns}$ | $2.3^{ns}$ | $1.4^{ns}$ |
| Canopy temperature (ºC) | $1.1^{ns}$ | $26.5^{***}$ | $7.6^{ns}$ | $3.8^{ns}$ | $2.9^{ns}$ | $4.7^{ns}$ | $8.2^{ns}$ |
| Total water input (m$^3$ha$^{-1}$) | $41.1^{***}$ | $34.5^{***}$ | $39.3^{***}$ | $4.3^{ns}$ | $6.2^{ns}$ | $5.1^{ns}$ | $7.7^{ns}$ |
| Fruit yield (kg ha$^{-1}$) | $7.4^{ns}$ | $27.6^{***}$ | $48.8^{**}$ | $7.3^{ns}$ | $29.7^{***}$ | $2.9^{ns}$ | $2.9^{ns}$ |
| Total water productivity (kg m$^{-3}$) | $6.7^{ns}$ | $21.2^{***}$ | $39.4^{***}$ | $6.8^{ns}$ | $35.2^{***}$ | $4.7^{ns}$ | $2.3^{ns}$ |

*ns*: non-significant; *** $p < 0.001$; **$p < 0.01$; *$p < 0.05$

**Table 2** Interaction effect of irrigation systems and soil moisture regimes on plant height, leaf number and leaf area of tomato

| Irrigation system (A) | Soil moisture regime (B) | Plant height (cm) | Leaf number | Leaf area (cm$^2$) |
|---|---|---|---|---|
| Drip | 0 kPa | 61.7 ± 0.3 c | 77.6 ± 1.4 c | 8,658 ± 61 cd |
| | -10 kPa | 99.2 ± 0.8 a | 118.4 ± 2.5 a | 16,569 ± 125 a |
| | -20 kPa | 79.7 ± 0.6 b | 95.4 ± 1.8 b | 12,393 ± 98 b |
| | -30 kPa | 67.6 ± 0.5 bc | 82.4 ± 1.6 bc | 9,298 ± 75 bcd |
| Furrow | 0 kPa | 59.9 ± 0.3 c | 75.8 ± 1.4 c | 8,489 ± 57 c |
| | -10 kPa | 73.1 ± 0.6 bc | 94.6 ± 1.8 b | 11,763 ± 105 bc |
| | -20 kPa | 73.0 ± 0.6 bc | 89.4 ± 1.7 bc | 10,94 ± 82 bcd |
| | -30 kPa | 64.7 ± 0.4 bc | 81.9 ± 1.5 bc | 9,253 ± 72 bcd |

Means followed by the same letters within a column do not differ significantly whereas means having dissimilar letters differ significantly as per Tukey's HSD test at $p \leq 0.05$, Data are mean ± standard error

The soil moisture regime −10 kPa, as well as the −20 kPa, led to better LAI over other soil moisture regimes. The two and three-way interactions did not influence LAI. Shoot dry matter (SDM) was significantly ($p < 0.001$) affected because of irrigation systems and soil moisture regime variations. SDM was significantly higher under the drip irrigation system than in furrow irrigation. SDM was reduced by 14.66% in the furrow irrigation system. The soil moisture regime −10 kPa had the highest SDM trailed by -20 kPa whereas the lowest was for 0 kPa which was statistically similar to -30 kPa for SDM. A consistent positive trend was observed for root dry matter (RDM) in both growing seasons. The maximum RDM was found in the drip irrigation system as well as the −10 kPa soil moisture regime compared to the other treatments. RDM was reduced by 17.24% in the furrow irrigation system.

The drip irrigation system resulted in a higher SPAD reading than the furrow irrigation system with no seasonal statistical differences (Table 3). The plants grown in the drip irrigation system had 6.15% more SPAD readings than those grown in the furrow irrigation system. SPAD reading was the highest (50.4 ± 0.5) at soil moisture regime (-10 kPa), whereas it was the lowest (44.9 ± 0.2) at 0 kPa soil moisture regime followed by statistically alike SPAD reading at -20 kPa soil moisture regime. The drip irrigation system resulted in a 15.5% number of flower clusters per plant, 8.2% number of fruit clusters per plant, 2.5 and 3.2 days less time required for first and 50% flowering, respectively, than the furrow irrigation system. The soil moisture regime −10 kPa exhibited better than other soil moisture regimes for the number of flower clusters per plant and the number of fruit clusters per plant, whereas the two and three-way interaction effects among seasons, irrigation systems and soil moisture regimes were not statistically significant.

### 3.2 Physiological Parameters

The irrigation systems and soil moisture regimes had a highly significant ($p < 0.001$) effect on leaf relative water content for LRWC with no seasonal statistical differentiation (Table 4). Out of two irrigation systems and four soil moisture regimes, LRWC remained statistically higher in drip irrigation and 0 kPa soil moisture regime compared to other treatments. The drip irrigation system had 3.82% more LRWC compared to the furrow irrigation system. The furrow irrigation system revealed more electrolyte leakage (EL) than the drip irrigation system as well as -30 kPa soil moisture regime had significantly more EL than the 0 kPa soil moisture regime. Furrow irrigation had 11.5% more EL than the drip irrigation system. Canopy temperature was maximum (31.0 °C) when the plants received furrow irrigation compared to drip irrigation system (28.6 °C) whereas canopy temperature was not affected by the soil moisture regime differences. The plants grown in the furrow irrigation system experienced > 2 °C more canopy temperature compared to the drip irrigation system.

### 3.3 Total Water Input

More consistent soil moisture was detected with drip irrigation than with furrow irrigation systems throughout the season (Fig. 2a). Total water input (TWI) was significantly inclined by the effect of the irrigation system ($p < 0.001$) while two and three-way interaction effects of seasons, irrigation types and soil moisture regimes were non-significant

**Table 3** Main effect of irrigation systems and soil moisture regimes on leaf area index, shoot and root dry matter, SPAD value, number of flower and fruit clusters, days required to first and 50% flower of tomato

| Treatments | Leaf area index | Shoot dry matter (g) | Root dry matter (g) | SPAD value | Number of the flower cluster plant$^{-1}$ | Number of the fruit cluster plant$^{-1}$ | Days required to first flower | Days required to 50% flower |
|---|---|---|---|---|---|---|---|---|
| Irrigation systems (A) | | | | | | | | |
| Drip | 5.0 ± 0.3 a | 30.7 ± 1.2 a | 2.9 ± 0.2 a | 48.8 ± 0.5 a | 24.5 ± 0.6 a | 15.9 ± 0.5 a | 19.5 ± 0.2 b | 24.5 ± 0.3 b |
| Furrow | 4.3 ± 0.1 b | 26.2 ± 0.8 b | 2.4 ± 0.1 b | 45.8 ± 0.3 b | 20.7 ± 0.4 b | 14.6 ± 0.4 b | 22.0 ± 0.4 a | 27.7 ± 0.5 a |
| Soil moisture regimes (B) | | | | | | | | |
| 0 kPa | 4.2 ± 0.1 b | 25.3 ± 0.4 b | 2.3 ± 0.1 b | 44.9 ± 0.2 b | 21.9 ± 0.2 b | 14.5 ± 0.3 b | 21.0 ± 0.2 | 26.2 ± 0.3 |
| -10 kPa | 5.2 ± 0.3 a | 32.7 ± 0.9 a | 3.2 ± 0.3 a | 50.4 ± 0.5 a | 23.8 ± 0.5 a | 16.5 ± 0.6 a | 20.2 ± 0.1 | 25.6 ± 0.2 |
| -20 kPa | 4.8 ± 0.2 ab | 28.9 ± 0.7 ab | 2.8 ± 0.2 b | 47.4 ± 0.3 ab | 22.7 ± 0.3 ab | 15.5 ± 0.5 ab | 20.5 ± 0.1 | 25.8 ± 0.2 |
| -30 kPa | 4.3 ± 0.1 b | 27.0 ± 0.5 b | 2.5 ± 0.1 b | 46.7 ± 0.3 b | 22.2 ± 0.2 b | 14.7 ± 0.3 b | 21.5 ± 0.2 | 26.8 ± 0.3 |

Means followed by the same letters within a column do not differ significantly whereas means having dissimilar letters differ significantly as per Tukey's HSD test at $p \leq 0.05$, Data are mean ± standard error

**Table 4** Main effect of irrigation systems and soil moisture regimes on leaf relative water content, electrolyte leakage, and canopy temperature of tomato

| Treatments | Leaf relative water content (%) | Electrolyte leakage (%) | Canopy temperature (°C) |
|---|---|---|---|
| Irrigation systems (A) | | | |
| Drip | 65.4 ± 0.8 a | 20.0 ± 0.3 b | 28.6 ± 0.4 b |
| Furrow | 62.9 ± 0.6 b | 22.6 ± 0.5 a | 31.0 ± 0.6 a |
| Soil moisture regimes (B) | | | |
| 0 kPa | 68.0 ± 0.5 a | 21.3 ± 0.1 b | 30.0 ± 0.3 |
| -10 kPa | 63.6 ± 0.3 b | 22.5 ± 0.2 ab | 29.3 ± 0.2 |
| -20 kPa | 65.4 ± 0.4 b | 22.0 ± 0.2 ab | 29.5 ± 0.2 |
| -30 kPa | 59.5 ± 0.2 c | 23.1 ± 0.2 a | 30.5 ± 0.3 |

Means followed by the same letters within a column do not differ significantly whereas means having dissimilar letters differ significantly as per Tukey's HSD test at $p \leq 0.05$, Data are mean ± standard error

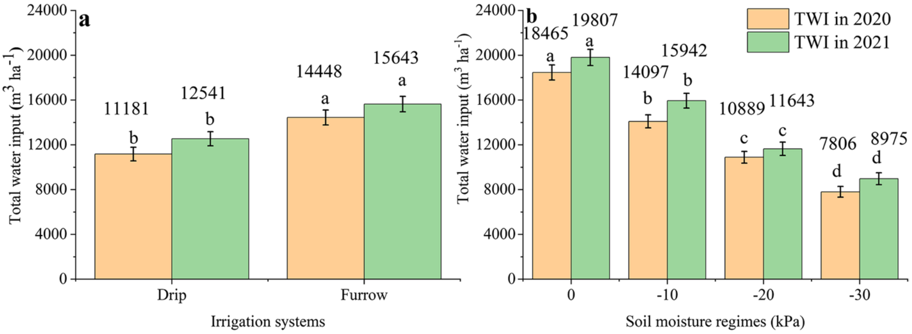


**Fig. 2** Effect of irrigation systems (**a**) and soil moisture regimes (**b**) on total water input of tomato. The vertical bar represents standard error, bar graph having dissimilar letter are statistically significantly different whereas bars sharing the same letter are statistically similar as per Tukey's HSD test at $p < 0.05$

(Fig. 2a and b). However, total water input varied between the 2020 and 2021 field trials. The plots kept under the furrow irrigation system had the highest total water input in both tomato growing seasons. In 2020, the drip irrigation system distributed a more precise use of water with 3267 ± 55 m$^3$ ha$^{-1}$ less water compared to the furrow irrigation system. Also, the 0 kPa soil moisture regime consumed more water compared to the other soil moisture regimes (Fig. 2b). Similarly, the drip irrigation system supplied more effective water use with 3102 ± 60 m$^3$ha$^{-1}$ less water used than the furrow irrigation system in the 2021 growing season. The drip irrigation system lowered total water input by 22.6% and 19.8% in 2020 and 2021, respectively, compared with the furrow irrigation system. The drip irrigation technique saves water by reducing total water input in both growing seasons with a subsequent upsurge of TWP.

## 3.4 Fruit Yield and Total Water Productivity

Fruit yield was highly influenced by the two-way interaction between the irrigation systems and soil moisture regimes ($p < 0.001$); the effect of the irrigation system and soil moisture regime were also highly significant ($p < 0.001$) for fruit yield, while no statistical differentiation was noticed between field trials of 2020 and 2021 (Fig. 3). A higher fruit yield was gained from plants maintained under a drip irrigation system with a soil moisture regime of -10 kPa than under a furrow irrigation system with a soil moisture regime of 0 kPa. The drip irrigation system with the – 10 kPa soil moisture regime had 28% and 22% higher fruit yields in the 2020 and 2021 growing seasons, respectively, than the furrow irrigation system with 0 kPa soil moisture regime. However, the total water productivity was significantly ($p < 0.001$) higher under drip irrigation with a -30 kPa soil moisture regime than furrow irrigation with a 0 kPa soil moisture regime (Fig. 4). The soil moisture regime (-30 kPa) consumed less water during production compared to other treatments although it gave less fruit yield. As a result, drip irrigation systems with – 30 kPa soil moisture regime had 75.4% and 69% higher TWP in 2020 and 2021, respectively, than furrow irrigation systems with a 0 kPa soil moisture regime.

### 3.5 Principal Component Analysis (PCA) and Cluster Analysis

PCA was performed on all 16 studied variables of the experiment to determine the significance of gross erraticism and to recognize the main variables contributing to experimental modification. Of all the PCAs, the first two essentials PCA1 and PCA2 accounted

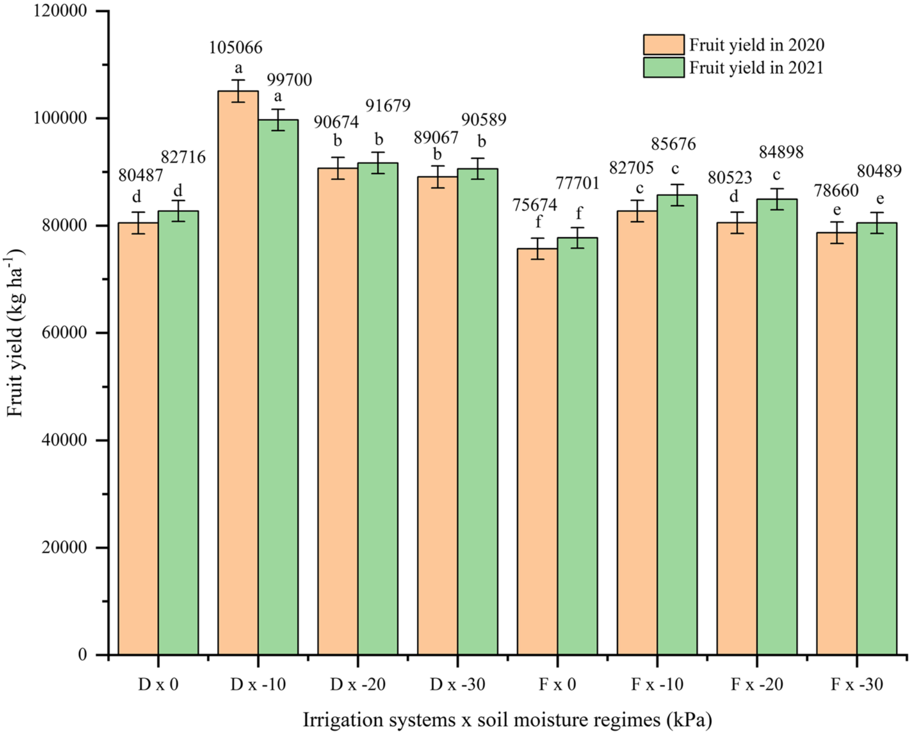


**Fig. 3** Interaction effect of irrigation systems and soil moisture regime on fruit yield of tomatoes. The vertical bar represents standard error, $p$ value indicates level of significance, bar graph having dissimilar letter are statistically significantly different whereas bars sharing the same letter are statistically similar as per Tukey's HSD test at $p < 0.05$, D: drip irrigation, F: Furrow irrigation

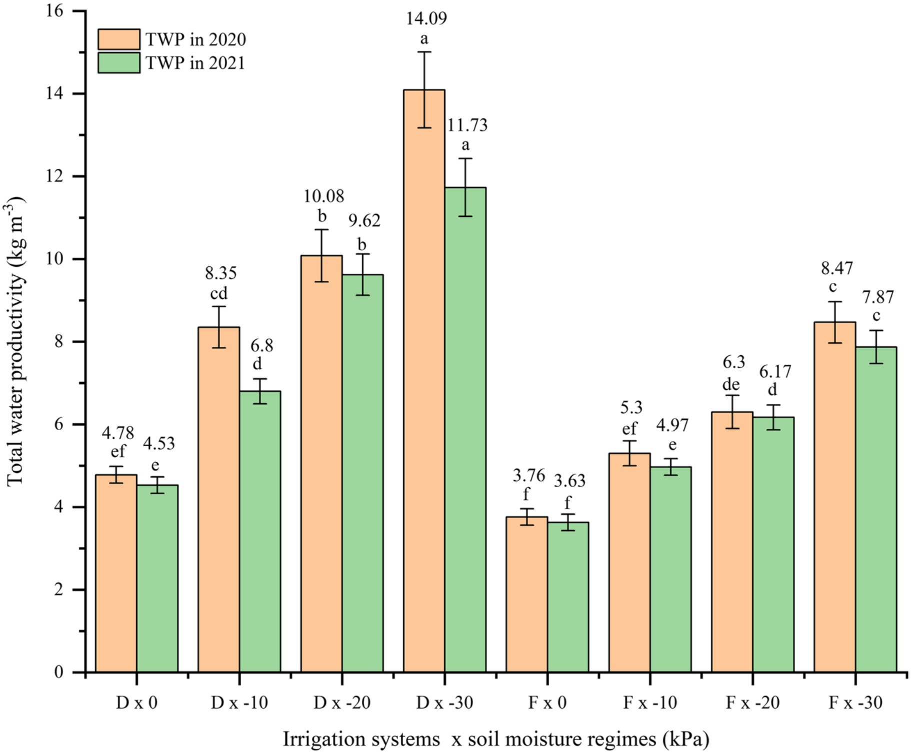
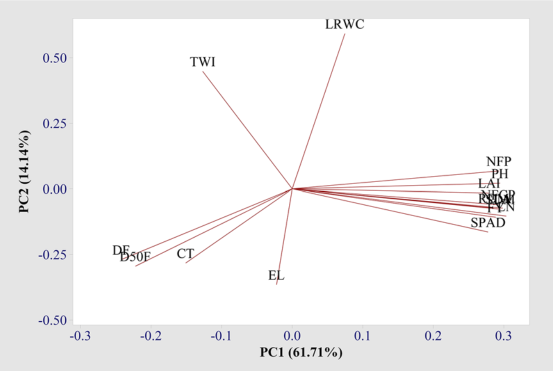


**Fig. 4** Interaction effect of irrigation systems and soil moisture regime on total water productivity of tomatoes. The vertical bar represents standard error, *p* value indicates level of significance, bar graph having dissimilar letter are significantly statistically different whereas bars sharing the same letter are statistically similar as per Tukey's HSD test at $p < 0.05$, D: drip irrigation, F: Furrow irrigation

for 61.7% and 14.1% of the total dissimilarity, respectively (Fig. 5). The biplot is a suitable way to depict the results from PCA that presents the principal component scores and the loading vectors in a single graph. The biplot elucidated fruit yield, plant height, leaf number, leaf area, leaf area index, shoot and root dry matter, SPAD value, relative leaf water content, number of flowers and fruit cluster plant$^{-1}$ are positively correlated but total water input, electrolyte leakage, canopy temperature, days required to first and 50% flower variables are not likely to be linked. According to the results, all the examined variables had a variable effect on understanding the experimental variance, either positive or negative. Among the 16 variables in PCA1, leaf number, leaf area (cm$^2$), shoot dry matter (g), plant height (cm), number of fruit and flower cluster plant$^{-1}$, fruit yield (kg ha$^{-1}$), root dry matter (g), SPAD value, leaf area index, and leaf relative water content (%) were recognized with positive loadings on experimental dissimilarity while days required to first and 50% flower, canopy temperature (°C), total water input (m$^3$ ha$^{-1}$), and electrolyte leakage (%) had the highest negative loadings (Fig. 5). Apart from that, growth attributes were more influenced to save water, and improve the yield and total productivity of tomatoes. However, PC2 does not explain the experimental variation too much. Similarly, cluster analysis broadly divided the total studied variables into two distinct major classes according to the similarity matrix (Fig. 6). One was a cluster of growth, development, yield and



| Experimental Variables | PC1 |
|---|---|
| Total water input (TWI) | -0.132 |
| Fruit yield (FY) | 0.285 |
| Plant height (PH) | 0.295 |
| Leaf number (LN) | 0.304 |
| Leaf area (LA) | 0.299 |
| Leaf area index (LAI) | 0.282 |
| Shoot dry matter (SDM) | 0.296 |
| Root dry matter (RDM) | 0.285 |
| Relative leaf water content (RLWC) | 0.071 |
| Electrolyte leakage (EL) | -0.016 |
| Canopy temperature (CT) | -0.151 |
| SPAD | 0.277 |
| Number of flower cluster plant$^{-1}$ (NFP) | 0.292 |
| Number of fruit cluster plant$^{-1}$ (NFCP) | 0.293 |
| Days required to first flower (DF) | -0.242 |
| Days required to 50 % flower (D50F) | -0.222 |
| Eigenvalue | 9.874 |
| Variation | 61.71 % |

**Fig. 5** PCA biplot (Principal component-1 PC1 vs. Principal component-2 PC2) visualizing the correlations among the growth and physiological parameters affected by the irrigation systems and soil moisture regimes of tomatoes

yield-contributing variables encompassing plant height, leaf number, leaf area, leaf area index, shoot and root dry matter, SPAD value, number of flowers and fruit cluster plant$^{-1}$ and fruit yield; and another was water associated variables involving relative leaf water content, total water input, electrolyte leakage, canopy temperature, days required to first and 50% flower. The first cluster of the dendrogram highlighted those variables that aid in the enhancement of tomato growth and yield, while the variables of the second cluster

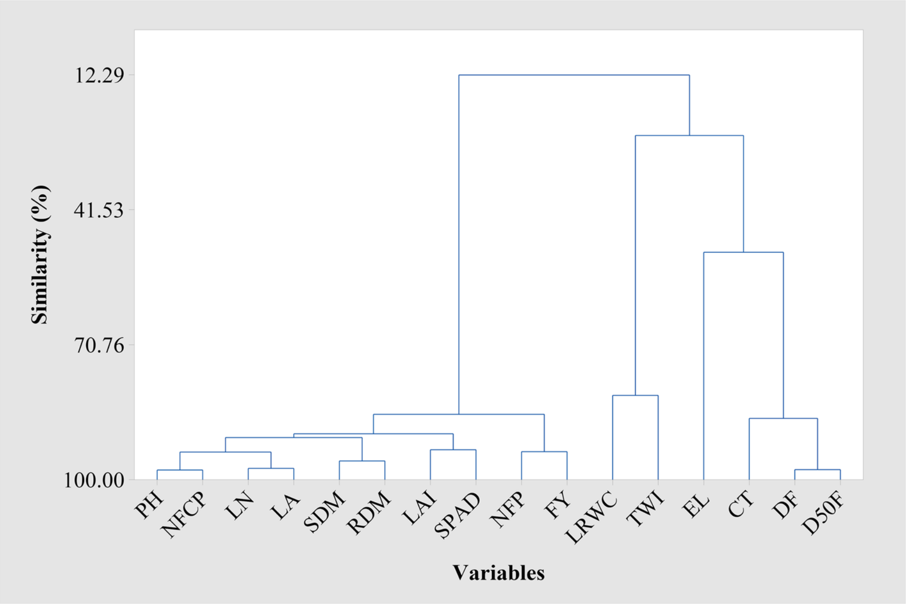


**Fig. 6** Cluster analysis displaying the alliance of studied variables; one cluster associated with growth, development, yield and yield-contributing variables and another cluster concerned the relationship between water shortage and their impact on the physiology of tomato plants

concerned the relationship between water shortage and their impact on the physiology of tomato plants. Among the 16 studied variables, electrolyte leakage and canopy temperature were found to sit distinctly from others. Therefore, the PCA and cluster analysis established the fact that water productivity is mainly modulated by growth, yield and yield-contributing variables, which were rigorously affected by total water input, relative leaf water content, electrolyte leakage and canopy temperature richness.

## 4 Discussion

Deficit irrigation system and soil moisture regimes had a significant impact on tomato plant growth, physiological, and fruit yield parameters in the current study. In furrow irrigation, water was applied less frequently, potentially causing a water deficit in the soil. An interruption in cell division and cell elongation (Ilyas et al. 2017; Ullah et al. 2018; Chakma et al. 2021) which might be accountable for the diminution of plant height and leaf area. Maham et al. (2020) stated that water deficit condition adversely impacts microenvironments around the tomato plants and leads to a reduction in vegetative growth. Under a controlled shortage irrigation level of 0.6 ETc, Nangare et al. (2016) discovered a significant decrease in growth variables such as plant height and LAI, root attributes, and chlorophyll content of tomatoes. In the present study, it was reported that an upsurge in SPAD value in plants due to optimum irrigation conditions evidently reveals an improvement in photosynthetic rate resulting in increase in plant growth and fruit yield (Nazar et al. 2015). Electrolyte leakage was properly responded due to the irrigation system and soil moisture regime variations. Water efficiency was reduced with the furrow irrigation system resulting in fruit yield reduction and vegetative growth being impaired while EL was increased in the furrow irrigation system where a lower moisture regime was observed. Furrow irrigation induces percolation water losses towards soil moisture stress that affect leaf electrolyte leakage and leaf chlorophyll content. Drought stress causes many hostile effects on tomatoes like turgor loss, chlorophyll degradation, down-regulation of net assimilation rate, and lowering of inter-cellular $CO_2$ concentration resulting in decreased leaf expansion, root and shoot development, biomass production, and thus, fruit yield is also affected (Sousaraei et al. 2021; Zhou et al. 2017). Under severe water deficit conditions, EL was highly increased due to $K^+$ efflux from the plant cells, which is mediated by the cation conductance of the plasma membrane (Sousaraei et al. 2021; Demidchik et al. 2010). Our findings also illustrated that irrigation methods influenced the leaf water content as exhibited in both irrigation systems. The plants grown in drip irrigation systems had higher LRWC, which indicates that these plants have the ability to absorb water from the soil and conserve water inside the leaf, and maintain plant physiological activities accurately. Aliniaeifard and Van Meeteren (2014) described that in water stress conditions, LRWC was reduced significantly, causing the reduction of stomatal conductance and inter-cellular $CO_2$ concentration into the leaf and diminishing of net photosynthesis. The net assimilation rate, stomatal conductance and transpiration rate was reduced significantly under water deficit conditions in potatoes and the opposite occurred under well-water conditions (Li et al. 2021a, b).

In the drip irrigation system, less time for flowering and a higher number of flowers and fruit clusters were observed compared to the furrow irrigation system. This may be due to the drip irrigation system ensuring water availability in the soil, especially in the flowering stage, which is a sensitive phenological stage of tomato plants. Several studies have found that flowering and fruiting stages of tomatoes are more sensitive to water stress (Nangare et al. 2016; Ripoll et al. 2016). However, canopy temperature had a significant effect to modulate plant growth and development. The drip irrigation system maintained a cool environment around the plants by confirming water availability in the soil resulting in a lower temperature in the canopy zone of the tomato plants. The growth and development of tomato plants were greatly influenced by temperatures reported by Shamshiri et al. (2018). The microclimate within the crop canopy area and near the soil surface is seriously affected due to irrigation systems (Xu et al. 2017). The different irrigation methods could generate a specific environment for the plants that regulate cell division, expansion, plant growth and development, other physiological events within plants, which could have determined the yield and productivity of tomato plants (Toscano et al. 2019; Bertin and Genard 2018).

It is distinct from the current study that the growth and fruit yield attributes of tomato plants were significantly reduced when they were grown in a furrow irrigation system with reduced soil moisture regimes (-30 kPa). With the decrease in water supply from well-watered (100% ETc) to acute water stress (50% ETc), a significant yield (13.16%) reduction was observed in greenhouse tomatoes (Wu et al. 2022; Lu et al. 2019) reported a decline in aboveground biomass due to water deficit conditions resulting in reduced tomato yield. Alternatively, Wu et al. (2022) stated that under optimum irrigation conditions, tomato plants produced more fruits than those grown in deficit irrigation. Previous studies claimed that under water deficit conditions, tomato plants reduced their ability to absorb and metabolize nutrients effectively which may lead to a decrease in fruit yield (Wang et al. 2019a, b). In the current study, the decrease in fruit yield in the furrow irrigation system might be due to the overall decline of growth and physiological attributes (SPAD value, LRWC and EL) (Hayat et al. 2008).

Irrigation water use was lower with drip than furrow irrigation systems in both seasons, which was projected. Actually, drip irrigation could be regulated more accurately than furrow irrigation in which water was supplied precisely drop by drop near the roots of plants. In 2021, total water input was higher than in 2020 because of the lack of precipitation and high temperatures. As a result, irrigation water was supplied at a greater frequency in 2021. In South Asia, extreme heat and precipitation conditions have compounding effects on crops and a complex relationship exists between extreme heat and precipitation reported by Fan et al. (2022). Likewise, Qi et al. (2022) described that extremely high temperatures and drought events had interactive effects on crop growth and yield. However, water was supplied drop by drop in the root zone of the plants at the drip irrigation system without irrigating the non-cropped area, resulting in a significant proportion of water saved, maintaining optimum soil moisture content and lower crop evapotranspiration compared with furrow irrigation system, as reported by Li et al. (2021a, b). Yang et al. (2019) reported that appropriate irrigation application strategies could improve the water productivity of tomatoes. However, some studies indicated that water deficit conditions have no effect on the water productivity of tomatoes (Yang et al. 2020; Zheng et al. 2013), which is opposite to our findings. Drip irrigation dropped the irrigation amount by 17–30% to those under furrow irrigation systems and a boost in fruit yield (Li et al. 2020; Yang et al. 2017) described that it is possible to reduce excess irrigation by 20–50% through the drip irrigation method without sacrificing fruit yield. Tagar et al. (2012) reported that the drip irrigation system not only saves irrigation water (56.4%) but also gave 22% more yield compared to the furrow irrigation system. Similarly, Panigrahi et al. (2019) reported that drip irrigation with mulching saved 19% of irrigation water and improved water use efficiency (89%)

and mean fruit yield of tomatoes (53%). Jha et al. (2017) reported that tomato yield was raised by 58.7% in drip irrigation systems over furrow irrigation, which supports our results. The long-season deficit irrigation (50% ETc) and the short-season full irrigation (100% ETc) received a more or less similar quantity of irrigation water, but fruit yield decreased by 46% in the case of long-season deficit irrigation (50% ETc) (Lovelli et al. 2017). However, few studies have suggested that higher soil moisture regimes maximize tomato productivity and − 35 kPa is suggested to guide tomato irrigation under greenhouse conditions (Yang et al. 2022) which matches the present findings where deficit irrigation through drip irrigation with − 10 kPa soil moisture regime produced maximum fruit yield.

PCA analysis illustrated the main variables affecting and enhancing tomato growth, yield and water productivity. Dendrogram supported the PCA analysis by clustering the studied variables into two distinct groups according to the similarity matrix where water-related attributes are positioned opposite to growth and yield-promoting variables. This research developed a distinct relationship among the studied variables regarding how total water input, electrolyte leakage, and canopy temperature impacted tomato growth, yield and water productivity as displayed in PCA analysis.

## 5 Conclusion

Growth, yield and water productivity were significantly influenced by the irrigation system and deficit soil moisture regime. When compared to furrow irrigation, drip irrigation produced better results in terms of growth, physiological traits, yield and water productivity of tomatoes. Soil moisture regime -10 kPa outperformed other soil moisture regimes in terms of plant growth and fruit yield. Drip irrigation system with -10 kPa soil moisture regime received less total water input by 22.6% and 19.8% and resulted in 28% and 22% higher fruit yields over furrow irrigation system during 2020 and 2021, respectively. Furthermore, a reduced soil moisture regime (-30 kPa) showed maximum water productivity for both drip and furrow irrigation irrespective of the growing season but checked normal growth and yield. Drip irrigation with reduced soil moisture regimes (-10 kPa) could be a potential approach for promoting tomato growth, yield and water productivity under field conditions, especially where irrigation water is scarce.

**Author Contributions** Sangeeta Mukherjee: Performing field experiments, collecting data, and writing the draft manuscript; Prosanta Kumar Dash: Design, analysis of data and supervision of the experiments, and review of the manuscript; Debesh Das: Supervision of the experiments and review of the manuscript; Shimul Das: Prepared Figs. 1, 2, 3, 4, 5 and 6 and reviewed the manuscript.

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**Data Availability** Data is available for sharing and will be provided based on request.

## Declarations

**Competing Interests** The authors have no competing interests.

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