agronomy

MDPI

Article

Improving Water Productivity Using Subsurface Drip Irrigation in the Southwest Monsoon Area in Yunnan Province of China

Long Wan [1,2], Yi Jian [1,3], Mei Zhang [2,4], Jing Tong [5], Ansa Rebi [1,2] and JinXing Zhou [1,2,*]

[1] School of Soil and Water Conservation, Beijing Forestry University, Beijing 100083, China; wanlong255@sina.com (L.W.); 2013ag3549@uaf.edu.pk (A.R.)
[2] Jianshui Research Station, Beijing Forestry University, Beijing 100083, China
[3] Jiangsu Huizhi Engineering Technology Co., Ltd., Nanjing 210036, China
[4] Jianshui Forestry and Grassland Technology Extention Station, Jianshui 654300, China
[5] Beijing Vegetable Research Center, Beijing Academy of Agriculture and Forestry Science, Beijing 100097, China; tongjing@nercv.org
* Correspondence: zjx9277@126.com

Abstract: Due to the influence of the Asian southwest monsoon, seasonal drought is serious and water resources are scarce in the Yunnan province of Southwest China. More effective water-saving irrigation methods should be developed to solve the problem of water scarcity in the dry season. In this study, a subsurface drip irrigation method was used to improve the water productivity of tomato cultivation. Deficit irrigation was conducted. We controlled the lower limit of soil moisture at three different levels (55~65%, 65~75%, and 75~85% of the field capacity). The results indicated that the subsurface drip irrigation treatment significantly increased tomato height in the later stage of tomato growth. Due to the buried pipes, the root/shoot ratio was 8~18% higher for subsurface drip irrigation than for surface drip irrigation methods. Though the yields using subsurface drip irrigation methods were slightly lower than those obtained using surface drip irrigation methods, the tomato quality and water productivity improved significantly. The subsurface drip irrigation methods improved the water productivity by 8.5~21.8% at different soil moisture levels and improved the chlorophyll content by 9.1~17.3%. The VC, soluble sugar, soluble solids, and the ratio of sugar to acid increased by 6.5~15.2%, 7.3~21.6%, 4.1~6.6%, and 3.2~20.8%. This study also indicated that by optimizing the irrigation methods and patterns, water productivity and fruit quality could be improved by more than 50%. This research will be helpful for guiding irrigation during the drought season in the southwest monsoon area in Asia.

Keywords: subsurface drip irrigation; deficit irrigation; water productivity; fruit quality; southwest monsoon area

check for updates

Citation: Wan, L.; Jian, Y.; Zhang, M.; Tong, J.; Rebi, A.; Zhou, J. Improving Water Productivity Using Subsurface Drip Irrigation in the Southwest Monsoon Area in Yunnan Province of China. *Agronomy* **2024**, *14*, 679. https://doi.org/10.3390/agronomy14040679

Academic Editor: Maria do Rosário Cameira

Received: 20 February 2024
Revised: 14 March 2024
Accepted: 21 March 2024
Published: 26 March 2024

1. Introduction

The southwest monsoon has great impacts on the climate of the Yunnan province of China [1], which frequently results in seasonal drought, especially in winter and spring. The precipitation is 600~800 mm in this area, which is concentrated from June to August. Evapotranspiration can be more than 2000 mm. The drought season lasts 8~9 months in this region. In the drought season, water resources cannot meet the needs of vegetable production [2]. Because this region belongs to a karst graben basin landform [3], water withdrawn from rivers, springs, and underground aquifers is the main resource for the irrigation of vegetables.

As a result of its low latitude, the southwest monsoon area in China has the advantages of high insolation and high heat [4]. Vegetables are widely planted in this region, including tomato, eggplant, and cabbage, which can be planted 2~3 times per year. However, with the karst graben landform in this region, the mountains fluctuate greatly [5]. The water in the river in the basin and valley cannot be supplied to the high mountain area [6]. Low rainfall in the dry season has produced few water resources. Drought has resulted in severe water scarcity, which limits vegetable production. Traditional irrigation, including sprinkling irrigation and surface drip irrigation (SDI), is widely used to improve water use efficiency, but the shortage of water is still serious. More efficient water-saving irrigation methods should be developed and applied.

Subsurface drip irrigation (SSDI) is a kind of irrigation technique with a low quota that is being researched globally. In 1913, American researcher House published the first study on drip irrigation technology [7], but due to technical limitations at that time, it was too expensive for practical use. Later, the subsurface irrigation method was developed based on surface drip irrigation. After the 1980s, research on subsurface drip irrigation technology focused on improving the quality of emitters and optimizing system design parameters [8]. In the twenty-first century, the water use efficiency of the subsurface drip irrigation method improved quickly [9]. Many studies have shown that SSDI can decrease evapotranspiration and improve water production. The subsurface drip irrigation method has been used in the irrigation of sorghum, alfalfa, and vegetables [10,11]. For tomato cultivation, Incrocci et al. (2006) found that subirrigation can be a tool to reduce water consumption. They concluded that subsurface drip irrigation increased the yield and water use efficiency of a tomato crop, which resulted in the saving of applied irrigation water by creating a good moisture distribution at the root zone depth [12]. Al-Omran et al. (2010) concluded that the subsurface drip irrigation increased the yield and the WUE of the tomato crop and resulted in the saving of applied irrigation water by creating a good moisture distribution in the root zone depth [13]. The most important problem when using the subsurface irrigation technique was the anti-clogging performance of the emitters [14].

Deficit irrigation, which involves the application of irrigation water to a lesser extent than the full vegetation evapotranspiration, is emerging as an important technique to enhance water productivity [15]. Deficit irrigation is a water-saving technology that has been developed in recent years. It has the advantages of saving water and improving the quality of vegetables and fruits [16]. Deficit irrigation technology has been widely applied in the growing of pomegranates, grapes, tomatoes, etc. A study integrated the deficit irrigation method and the subsurface drip irrigation method, which proved to be efficient for saving water in sandy soil in arid areas [17]. The integrated irrigation method has the potential to optimize water productivity, but it has rarely been applied in clay soil developed from limestone.

Tomato is one of the most important vegetables worldwide, and its production is increasing in China [18]. Because of its high-light and high-temperature conditions, tomato production accounts for 30~40% of vegetable production in the Yunnan province of Southwest China. Tomatoes are very sensitive to drought stress, not only initially during vegetative development but also when the tomatoes are in the reproductive stage [19]. Water is scarce in the southwest monsoon area and is not sufficient for tomato production. In this area, the soil is a limestone clay soil. New water-saving methods like subsurface drip irrigation have not been applied in this region. Farmers are unaware of the effects of subsurface drip irrigation. Therefore, new water-saving irrigation methods like subsurface irrigation should be studied to improve water productivity.

The objectives of this study were to (1) evaluate whether subsurface irrigation can be adapted to the drought climate in the southwest monsoon limestone area and improve water efficiency and (2) evaluate how integrated deficit irrigation and subsurface drip irrigation methods improve the productivity, physiology, and quality of tomatoes.

2. Materials and Methods

2.1. Site Description

The present work was carried out at Jianshui Research Station (102°54′00″~102°54′55″ E, 23°36′50″~23°37′30″ N), Yunnan, China, at an altitude of 1394 m. The experimental area is shown in Figure 1. The research area is in a typical karst graben basin that experiences severe water shortages. The climate belongs to the southwest subtropical monsoon climate.

Seasonal drought is serious here. In the dry season (November to May of the next year), evapotranspiration is high and rainfall is rare. Rainfall is concentrated in the rainy season from June to September [20]. The annual average temperature is 19.8 °C, the annual average sunshine duration is 2322 h, and the annual average rainfall is 805 mm. The frost-free period averages 307 days throughout the year.

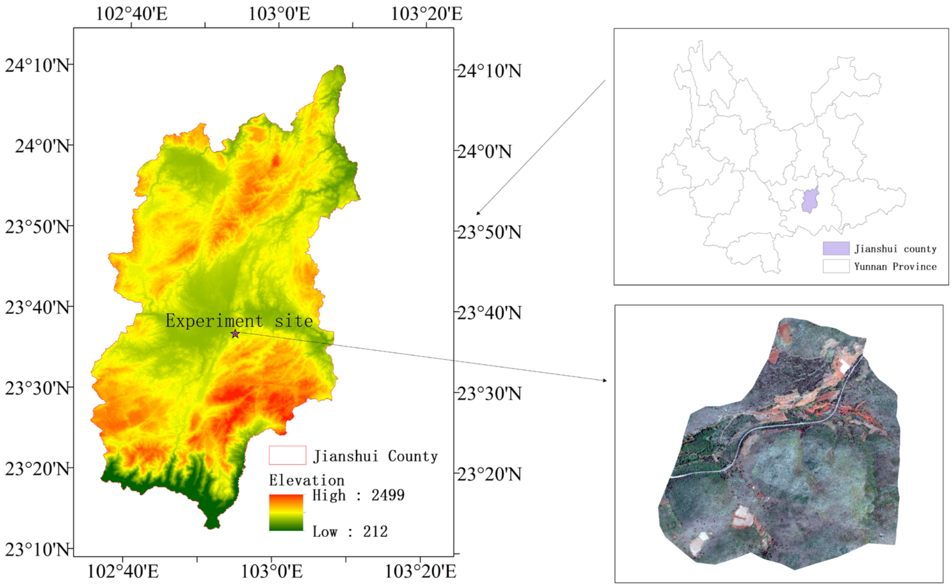

Figure 1. Location of the experimental area.

2.2. Experimental Design

The experiment was carried out in a greenhouse in Jianshui County, Yunnan province. The geographical coordinates were 102°54′11″ E, 23°37′13″ N. Figure 1 shows the location of the experimental area. The experimental area was on farmland. Tomatoes were cultivated in the greenhouse on the farmland. The roof covering was plastic film, but it had no occlusion on the east or west sides. Wind could blow into the greenhouse. We used steel as a greenhouse scaffolding material. Rainwater could not feed the soil in the greenhouse. The plastic film material for the greenhouse was transparent and made of polyvinyl chloride. First, seeds were germinated in trays in the greenhouse. After 30 days, the seedlings were transplanted into the soil in the greenhouse according to the design. Tomato was completely artificially irrigated in the greenhouse.

The cultivated variety of tomato used in this experiment was Mantian 2199 produced by Beijing Mantian Seeds Co., Ltd. Infinite (Beijing, China). Its growth type is medium maturity with vigorous plant growth. The fruit is apple-shaped, with a thick pericarp, good hardness, good storage, and transportation resistance. It has strong resistance to yellow leaf curl virus disease and is suitable for greenhouse sowing in hot areas of Yunnan. A base fertilizer was applied before planting, and the quantity of each treatment in the growth period was the same as that in the topdressing period.

The soil in this experiment was red soil rich in calcium carbonate. The parent material of this soil formation is limestone. The texture of the soil was clayey, and the sand, silt, and clay fractions were 4.5%, 52.8%, and 42.7%, respectively. The field water capacity of the experimental soil was measured to be 38.2% (volume moisture content), and the soil bulk density was 1.27 g/cm^3. The irrigation water was underground water from a well about 60 m below the ground. The EC, NH_4^+-N, total P, and COD concentration of the irrigation water were 412 µs/cm, 0.047 mg/L, 0.009 mg/L, and 9.1 mg/L. The basic physical and chemical properties of the soil are shown in Table 1.

Table 1. The basic physical and chemical properties of the soil before the test.

Index	Value
Soil bulk density (g/cm^3)	1.27
Total nitrogen (g·kg^{-1})	2.878
Ammonium nitrogen (mg·kg^{-1})	144.88
Nitric nitrogen (mg·kg^{-1})	18.506
Total phosphorus (g·kg^{-1})	0.533
Rapidly available phosphorus (mg·kg^{-1})	29.769
Fast-acting potassium (mg·kg^{-1})	46.793
Organic matter (g·kg^{-1})	8.487
pH	7.24

Two irrigation methods were used: surface drip irrigation under film and subsurface drip irrigation. The film was transparent, with a thickness of 0.015 mm and a transmittance greater than 90%. Different deficit irrigation methods were used for SDI and SSDI. There were three irrigation water levels. When the soil moisture reached the lower limit of 75~85% (HS treatment), 65~75% (MS treatment), or 55~65% (LS treatment) of the field water capacity, irrigation began, and the soil was irrigated to its field water capacity. A total of 6 treatments were tested, as shown in Table 2. Three rows were planted in each treatment as a plot. Eight tomato seedlings were cultivated in each row, and the tomato plant spacing was 1.5 m × 2 m. The buried depth of the plastic film was 50 cm to isolate the transmission of water and nutrients between different plots. Drip irrigation pipes with a dripper spacing of 35 cm were used in the drip irrigation treatment. Trace irrigation pipes were used for the subsurface irrigation method. They were buried at a depth of 20 cm underground according to the previous research, with a dripper spacing of 35 cm [21]. The trace irrigation pipes were designed with a double-layer membrane structure. The structure separated the water control function and the filtration function, resulting in a low effluent flow rate below 1 L/h per meter of the pipes. It has been proven by researchers to have good anti-clogging performance in pipelines [22]

Table 2. The irrigation patterns and soil moisture control.

Treatment	Irrigation Methods	Lower Limit of Soil Moisture
A1	Drip irrigation under film (A treatments)	75~85
A2		65~75
A3		55~65
C1	Subsurface drip irrigation (C treatments)	75~85
C2		65~75
C3		55~65

2.3. Measurements

2.3.1. Growth of Tomato Plants

The tomato plants were transplanted into the field on 10 September. After 10 days of tomato planting, growth indexes such as plant height and stem diameter were determined every 7 days. Three plants with similar growth were randomly selected from each irrigation plot for observation replication. After the fruiting period, the observation plants were dug out to measure their root systems and biomass. Next, 10~20 random roots were selected to measure the average diameter of the root system, and the root volume was measured using the dosage cylinder overflow method. The length of the roots was determined by the height of the cylinder. The plant root length and root surface area were calculated using Formulas (1) and (2).

$$L = 4V/\pi d^2 \tag{1}$$

$$S = 4V/d \tag{2}$$

where L is the root length (cm); V is the root volume (cm^3); d is the root diameter (cm); and S is the root surface area (cm^2).

The plants that were dug out were divided into roots, stems, and leaves. The fresh roots, stems, and leaves were dried at 105 °C for 30 min and at 85 °C for about 24 h. Then, the dry weight of each part was determined. The soil moisture was measured using a CS616 soil moisture sensor buried 20 cm underground, which was produced by Campbell Scientific, Inc. (Logan, UT, USA) The CS616 soil moisture sensor used highly sensitive time-domain reflectometry to measure the moisture content of the soil. The data were corrected using the soil drying method. Irrigation was carried out according to the measured lower limit of soil moisture.

2.3.2. Tomato Yield, Quality, and Water Productivity

In the fruiting period, the fruit weight and fruit number were determined 8 times to derive the total weight. The irrigation water productivity (IWP, kg/m^3) was calculated as the ratio between the fruit yield and the applied irrigation volume. Fruit quality was measured in the full bearing period and the later fruiting period by sampling 5 fruits randomly collected from the sampled trees from each treatment. The fruit juice titratable acidity was determined via titration with 0.1 N NaOH (Potentiometric Titrator, Metrohm, 785 DMP Titrino, Herisau, Switzerland), and the juice's total soluble solids content was measured with a temperature-compensated digital refractometer (Digital Refractometer, Atago, Palette PR-101, Tokyo, Japan). The soluble sugar was determined via the enthrone colorimetric method. The 2, 6-dichloroindophenol titration method was used for the determination of vitamin C (VC). The ratio of sugar to acid was calculated as the ratio between soluble sugar and titratable acidity.

2.3.3. Determination of Physiological Indexes

The chlorophyll content was determined using acetone extraction methods. Malondialdehyde (MDA) was determined using the thiobarbituric acid (TBA) reaction, as described by Heath and Packer [23]. Sulfosalicylic acid was used to extract proline (PRO) [24]. Nine leaves were averaged per plant. These indexes were determined in the full bearing period.

2.3.4. Statistical Methods

The normality of the indexes was assessed using the Kolmogorov–Smirnov test. A one-way analysis of variance (ANOVA) of all the data was performed using SPSS 22.0 to compare the effects of surface irrigation and subsurface irrigation. The significance was set to $p < 0.05$, and different lowercase letters or different groups of lowercase letters were used to indicate significant differences.

3. Results

3.1. The Impacts of Different Irrigation Treatments on Tomato Growth

As shown in Table 3, in the first 21 days after transplantation, the lengths of the tomato plants increased fast, and there were no significant differences between the different treatments. From 21 to 42 days, the tomato plants grew faster and reached greater heights in the SDI treatments. The plant height increased with increases in the soil moisture content for all irrigation methods. After 42 days, the tomato height in the C treatments had increased significantly and was highest in the C1 treatment. In addition, the increase in tomato growth in the HS and MS treatments was significantly higher than that of the LS treatments.

For the same lower limit of the soil moisture level, the root length, root volume, and root diameter area had no significant differences between the A and C treatments (Table 4). The root surface area was significantly higher in the C treatments. Reducing the soil moisture via deficit irrigation increased the root volume, diameter, and surface area. These root-related indexes were significantly higher for the LS treatments.

Table 3. Plant heights in different irrigation treatments at different stages.

Days after Transplantation	Plant Height Increases in Different Growth Stages (cm/d)					
	A1	C1	A2	C2	A3	C3
14~21	2.83 a	2.80 a	2.80 a	2.81 a	2.69 a	2.79 a
21~28	4.36 b	4.17 ab	4.32 b	3.94 ab	3.95 ab	3.90 a
28~35	5.57 d	5.29 c	5.10 bc	4.94 b	4.46 ab	4.34 a
35~42	5.14 d	4.80 bc	4.90 c	4.77 bc	5.01 c	4.23 ab
42~49	3.81 c	3.86 c	3.24 b	2.86 ab	2.43 a	2.62 a
49~56	1.43 a	1.76 ab	1.90 b	2.10 b	2.43 c	2.67 d
56~63	0.24 a	0.90 b	0.62 ab	1.52 c	0.52 ab	0.62 ab

Note: different lowercase letters in the same row indicate that the indexes of treatments are significantly different ($p < 0.05$).

Table 4. Root growth indexes of tomato plants under different irrigation treatments.

Treatments	Root Volume (cm^3)	Root Diameter (mm)	Root Length (cm)	Root Surface Area (cm^2)
A1	44.60 a	1.20 abc	3945.1 a	1486.4 a
C1	46.20 ab	1.18 ab	4226.4 bcd	1566.0 bc
A2	48.20 c	1.22 cd	4126.5 abc	1580.4 bc
C2	49.13 c	1.23 cd	4137.9 bc	1597.8 cd
A3	51.43 d	1.25 d	4193.7 bcd	1645.9 e
C3	53.70 e	1.25 d	4383.4 d	1707.3 f

Note: different lowercase letters in the same column indicate that the indexes of treatments are significantly different ($p < 0.05$).

The leaf biomass accounted for 52~57% of the total biomass. Stems accounted for 36~43%, and roots accounted for 4~8% of the total biomass. For the same soil moisture level, there were no significant differences in the leaf and stem biomass between the A and C treatments. The aboveground biomass increased in the higher soil moisture level, but the underground biomass showed an opposite trend. The root/shoot ratios were 8~18% higher in the C treatments than in the A treatments and reached the highest level in the C3 treatment when using deficit irrigation (Table 5).

Table 5. Biomass and root/shoot ratios of tomato plants under different irrigation treatments.

Treatments	Leaf Dry Weight (g)	Leaf Dry Weight Ratio (%)	Stem Dry Weight (g)	Stem Dry Weight Ratio (%)	Root Dry Weight (g)	Root Dry Weight Ratio (%)	Root/Shoot Ratio (%)	Total Dry Weight (g)
A1	95.98 e	52.65 ab	72.78 e	42.94 c	8.05 a	4.41 a	4.614 a	176.81
C1	90.64 de	53.87 ab	68.89 d	40.95 abc	8.68 ab	5.16 bc	5.441 bc	168.21
A2	85.92 cd	54.48 ab	62.99 cd	39.90 ab	8.86 b	5.62 cd	5.951 cd	157.77
C2	82.51 bc	51.96 a	66.94 cd	41.99 c	9.61 cd	6.04 de	6.436 de	159.06
A3	77.37 ab	55.66 ab	51.51 ab	37.04 a	10.15 e	7.30 f	7.875 f	139.03
C3	72.62 a	55.01 ab	48.78 ab	36.87 a	10.69 f	8.12 g	8.841 g	132.09

Note: different lowercase letters in the same column indicate that the indexes of treatments are significantly different ($p < 0.05$).

3.2. Impacts on Plant Physiological Indexes

Drought stress can promote the accumulation of PRO and MDA, which can improve the osmotic pressure of the protoplasm in plant cells so as to prevent or reduce water loss and enable plants to carry out normal metabolic activities. In this experiment, the results indicated that the PRO and MDA contents had no significant difference between the SDI and SSDI irrigation methods. However, deficit irrigation increased water stress significantly. The PRO contents in the HS treatments were 3~4 times higher than those in the LS treatments, and the MDA contents were 2~3 times higher than those in the LS treatments.

There were significant differences in the chlorophyll contents between the A and C irrigation methods (17.3% for the HS treatments and 9.1% for the MS treatments) (Figure 2). The chlorophyll contents could be decreased by 20–25% in the LS treatments.

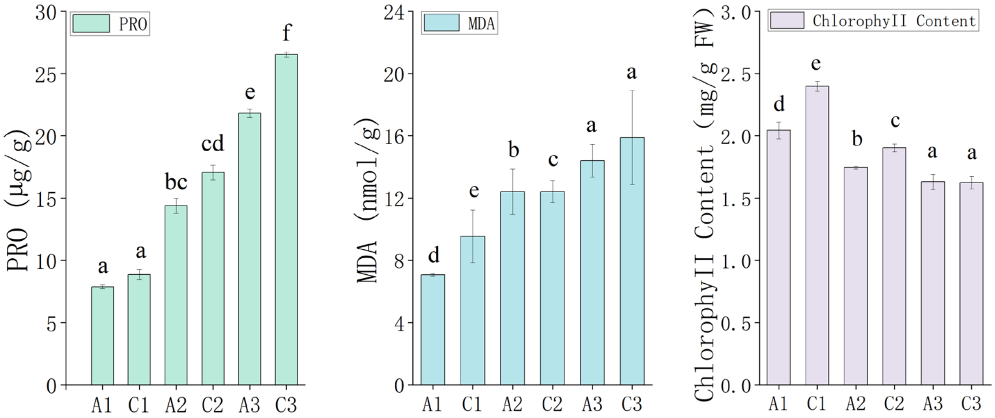

Figure 2. The PRO, MDA, and chlorophyll contents under different irrigation treatments. Note: different lowercase letters in the same column indicate that the indexes of treatments are significantly different ($p < 0.05$).

3.3. Impacts on Fruit Quality Characteristics

As a result of the various irrigation treatments, water stress could significantly improve fruit qualities such as total soluble solids, VC, soluble sugar, and titratable acid (Figure 3). For the same lower limit in the soil moisture treatments, the SSDI methods could improve the VC, soluble sugar, soluble solids, and the ratio of sugar to acid by 6.5~15.2%, 7.3~21.6%, 4.1~6.6%, and 3.2~20.8% compared to the SDI methods. The LS treatments could significantly improve the fruit quality, which was the best in the C3 treatment. The C3 treatment improved the VC, soluble sugar, soluble solids, and ratio of sugar to acid by 43.5%, 52.7%, 17.8%, and 22.6% compared to the A1 treatment.

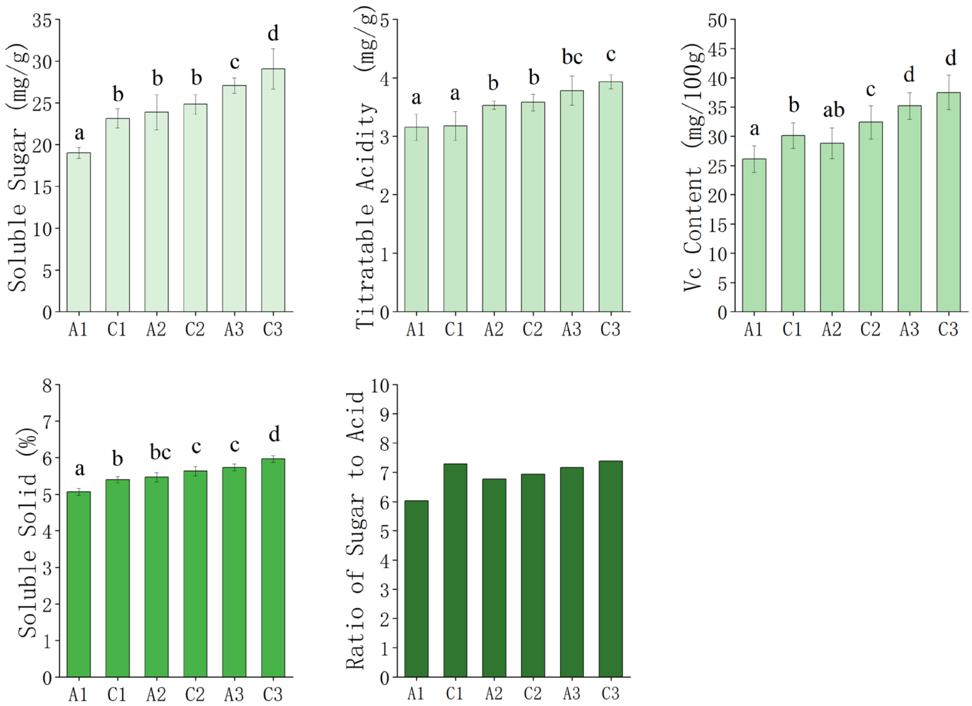

Figure 3. Fruit qualities under different treatments. Note: different lowercase letters in the column indicate that the indexes of treatments are significantly different ($p < 0.05$).

3.4. Impacts on Fruit Yield and Irrigation Water Productivity

Table 6 compares the yields for the two types of irrigation methods. The greatest yields were obtained using the A1 and C1 irrigation treatments. The tomato yields of the SDI methods were slightly higher than those of the SSDI methods. The yields of the A2 and A3 treatments were 3.6% and 5.5% higher than those of the C2 and C3 treatments. In the early period and the full bearing period, the yields were higher in the A treatments. However, in the late fruiting stage, the tomato yields of the C treatments significantly exceeded those of the A treatments. This research also found that the fruiting time lasted longer when using subsurface irrigation methods and lower soil moisture treatments. The single fruit weight significantly increased in the C treatments, especially the C2 treatment, where the average single fruit weight increased 90% more than in the A2 treatment. Deficit irrigation led to a small decrease in production. The production of the HS treatments was higher than that of the MS and LS treatments.

Table 6. Fruit yields and single fruit weights at different stages under different irrigation treatments.

	Fruit Yield in the Early Period (kg/hm^2)	Fruit Yield in the Full Bearing Period (kg/hm^2)	Fruit Yield in the Later Period (kg/hm^2)	Single Fruit Weight (kg)	Total Fruit Yield (kg/hm^2)	Frequency of Irrigation	Irrigation Water Amount (m^3/hm^2)	IWP (kg/m^3)
A1	20,145 d	57,855 de	7560 a	141.29 c	85,560 e	11	2522.1	33.9 e
C1	11,850 b	60,015 e	13,125 b	138.08 bc	84,990 e	13	2056.4	41.3 e
A2	18,735 cd	50,985 d	9885 a	139.24 bc	79,605 d	8	2157.4	36.9 d
C2	10,650 ab	47,355 c	18,780 c	136.75 ab	76,785 c	10	1857.3	41.3 c
A3	16,110 c	42,090 b	15,795 bc	133.18 a	73,995 b	6	1935.3	37.7 b
C3	9555 a	37,725 a	22,830 de	133.48 a	70,110 a	6	1689.2	40.9 a

Note: different lowercase letters in the same column indicate that the indexes of treatments are significantly different ($p < 0.05$).

To keep the soil water content above 75% of the field water capacity, the irrigation frequency needed to increase, but the irrigation amount each time was lower. The irrigation frequencies for the HS, MS, and LS treatments were, respectively, 11~13, 8~10, and 6 times in the tomato growth stage. The irrigation frequencies in the C treatments were slightly higher than those in the A treatments. Overall, the irrigation amounts in the A1, A2, and A3 treatments were 22.6%, 16.2%, and 14.6% higher than those in the C1, C2, and C3 treatments, respectively. As the results show, the irrigation water productivity was significantly improved when using the SSDI methods. The water productivity of the A1 treatment was only 33~38 kg/m^3. However, the water productivity of all C treatments exceeded 40 kg/m^3. The C1, C2, and C3 treatments improved the WUE by 21.8%, 11.9%, and 8.5% compared to the A1, A2, and A3 treatments.

4. Discussion

4.1. Effects of Subsurface Drip Irrigation on Tomato Growth and Physiological Characteristics

According to our study, the SSDI methods can significantly promote root growth because the pipes are buried underground and increase the chlorophyll content. SSDI had a significant water-saving effect. Compared to the common SDI methods, there were no adverse effects on aboveground tomato growth or physiological characteristics when using the SSDI methods. Deficit irrigation greatly impacted growth. The PRO and MDA contents were approximately three~four times greater, respectively, in the HS treatments compared to the LS treatments. Other researchers have also reported higher yields and water use efficiency for tomatoes under subsurface drip irrigation [25]. As a good water-saving measure, subsurface drip irrigation has many advantages for plant growth. Tomato growth was affected by the depth of the subsurface drip irrigation pipes [26]. When using the surface irrigation method, there is a risk of spreading disease by wetting foliage, while subsurface drip irrigation minimizes foliar disease. In surface drip irrigation, there are more chances for salt accumulation near the surface, while subsurface drip irrigation has the ability to make contact directly with the root zone so as to reduce the risk of salinity [27].

4.2. Effects of Subsurface Drip Irrigation on Fruit Production and Fruit Quality

The subsurface drip irrigation technique can efficiently decrease soil evaporation and deep seepage, increase labor savings, optimize water usage, and enhance operation and management effectiveness [28]. In our results, compared to the surface drip irrigation treatments, the subsurface drip irrigation treatments improved the VC, soluble sugar, soluble solids, and the ratio of sugar to acid by up to 15.2%, 21.6%, 6.6%, and 20.8%, respectively. Subsurface drip irrigation supplied less water but did not significantly decrease fruit production at the same soil moisture level. According to a study, subsurface drip irrigation increased tomato yield by 13.48% compared to surface drip irrigation [29]. Optimizing the subsurface drip irrigation technique is necessary to further promote the productivity of vegetables. Deficit irrigation has great impacts on fruit production and fruit quality. Our research showed that with reduced water, deficit irrigation decreased yields but produced much better-quality vegetables. In the pursuit of a high-quality, integrated deficit irrigation method, the subsurface drip irrigation pattern is an effective approach.

4.3. Influence of Subsurface Drip Irrigation on Water Productivity

A global meta-analysis showed that subsurface drip irrigation significantly increased yields and irrigation water productivity by 5.39% and 6.75% relative to surface drip irrigation [30]. In this study, the efficiency of surface water use was just 33–38 kg/m^3. However, water use efficiencies were higher than 40 kg/m^3 in the subsurface irrigation treatments. Our results indicated an increase in water productivity in subsurface drip irrigation. Subsurface drip irrigation reduces water loss through evaporation and seepage, making it evidently more efficient in terms of water productivity when compared to alternative irrigation techniques [31]. It also made it possible to distribute nutrients and manage fertilizers more effectively, which led to higher yield homogeneity, improved crop quality, and reduced plant stress. There is no denying that subsurface drip irrigation has brought about revolutionary advantages. Underground irrigation outperformed surface drip irrigation for eggplants by a margin of 22.9% [32]. Corn irrigation water use was successfully reduced by 35% to 55% in Kansas, USA, after ten years of using subsurface drip irrigation [33]. Water scarcity is a major challenge in Southwest China. To improve water efficiency, subsurface drip irrigation is a possible way to solve the problems of water shortages, sustainable agriculture, and enhanced food security. Deficit irrigation has clearly improved water productivity and will be useful for the area of severe water scarcity in this region.

5. Conclusions

This research compared tomato growth and physiological characteristics for surface and subsurface drip irrigation methods applied in the Asian southwest monsoon area in the Yunnan province of China. The results indicated that the subsurface irrigation methods significantly improved water productivity and tomato fruit quality and did not reduce tomato fruit yield. Optimizing irrigation patterns by integrating deficit irrigation methods is also an effective way to increase water productivity and fruit quality. Subsurface irrigation techniques could be widely applied to solve the agricultural water scarcity in the southwest monsoon area of China.

Author Contributions: Conceptualization, L.W. and J.Z.; methodology, L.W. and J.Z.; software, Y.J. and J.T.; validation, L.W.; formal analysis, L.W. and J.T.; investigation, Y.J. and M.Z.; resources, Y.J.; data curation, Y.J. and J.T.; writing—original draft preparation, L.W. and Y.J.; writing—review and editing, L.W., J.T. and A.R.; visualization, Y.J. and M.Z.; supervision, J.Z.; project administration, L.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Key Research and Development Program of China (2022YFF1302901), the National Natural Science Foundation of China (31700640), and the special fund for low-carbon development guidance in Yunnan province, China, named "Research on the response of degraded grassland ecosystems in Yunnan to climate change".

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to ethical restrictions.

Acknowledgments: We are grateful for the support from Jianshui Research station.

Conflicts of Interest: Author Yi Jian was employed by the company Jiangsu Huizhi Engineering Technology Co., Ltd. The remaining 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.

References

1. Zhang, X.; Zheng, Z.; Huang, K.; Yang, X.; Tian, L. Sensitivity of altitudinal vegetation in Southwest China to changes in the Indian summer monsoon during the past 68000 years. *Quat. Sci. Rev.* **2020**, *239*, 106359. [CrossRef]
2. Yu, Y.; Wang, J.; Cheng, F.; Deng, H.; Chen, S. Drought Monitoring in Yunnan Province Based on a TRMM Precipitation Product. *Nat. Hazards* **2020**, *104*, 2369–2387. [CrossRef]
3. Qiu, J.; Cao, J.; Lan, G.; Liang, Y.; Li, Q. The influence of land use patterns on soil bacterial community structure in the karst graben basin of Yunnan province, China. *Forests* **2020**, *11*, 51. [CrossRef]
4. Zheng, X.; Kang, W.; Zhao, T.; Luo, Y.; Duan, C.; Chen, J. Long-term trends in sunshine duration over Yunnan-Guizhou plateau in Southwest China for 1961–2005. *Geophys. Res. Lett.* **2008**, *35*, 386–390. [CrossRef]
5. Yang, H.; Zhang, P.; Zhu, T.; Li, Q.; Cao, J. The characteristics of soil C, N, and P stoichiometric ratios as affected by geological background in a karst graben area, southwest China. *Forests* **2019**, *10*, 601. [CrossRef]
6. Jiang, Y.; Yuan, D.; Xie, S.; Li, L.; Zhang, G.; He, R. Groundwater quality and land use change in a typical karst agricultural region: A case study of Xiaojiang watershed, Yunnan. *J. Geogr. Sci.* **2006**, *4*, 23–32. [CrossRef]
7. Dahlberg, J.A. *The Influence of Drip Irrigation on Cotton Petiole Nitrates and Yield*; The University of Arizona: Tucson, AZ, USA, 1987.
8. Alam, M. Crop production using subsurface drip irrigation (SDI) and in-field evaluation. *Trans. Vis. Soc. Jpn.* **1990**, *10*, 97–98.
9. Aydinsakir, K.; Buyuktas, D.; Din, N.; Erdurmus, C.; Yegin, A.B. Yield and bioethanol productivity of sorghum under surface and subsurface drip irrigation. *Agric. Water Manag.* **2021**, *243*, 106452. [CrossRef]
10. Cao, X.; Feng, Y.; Li, H.; Zheng, H.; Wang, J.; Tong, C. Effects of subsurface drip irrigation on water consumption and yields of alfalfa under different water and fertilizer conditions. *J. Sensors* **2021**, *2021*, 6617437. [CrossRef]
11. Wang, Z.; Liu, Z.; Zhang, Z.; Liu, X. Subsurface drip irrigation scheduling for cucumber (*Cucumis sativus* L.) grown in solar greenhouse based on 20 cm standard pan evaporation in Northeast China. *Sci. Hortic.* **2009**, *123*, 51–57. [CrossRef]
12. Incrocci, L.; Malorgio, F.; Bartola, A.D.; Pardossi, A. The influence of drip irrigation or subirrigation on tomato grown in closed-loop substrate culture with saline water. *Sci. Hortic.* **2006**, *107*, 365–372. [CrossRef]
13. Al-Omran, A.R.; Wahab-Allah, M.A.; Nadeem, M.; El-Eter, A. Impact of saline water rates under surface and subsurface drip irrigation system on tomato production. *Turk. J. Agric. For.* **2010**, *33*, 1–15.
14. Franco, L.; Motisi, A.; Provenzano, G. Evaluation of subsurface drip irrigation emitters on a split-root container-grown citrus rootstock (citrange 'Ccarrizo'). *Acta Hortic.* **2022**, *1335*, 533–540. [CrossRef]
15. Geerts, S.; Raes, D. Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. *Agric. Water Manag.* **2009**, *96*, 1275–1284. [CrossRef]
16. Spreer, W.; Müller, J.; Hegele, M.; Ongprasert, S. Effect of deficit irrigation on fruit growth and yield of mango (*Mangifera indica* L.) in northern Thailand. *Acta Hortic.* **2009**, *820*, 357–364. [CrossRef]
17. Romero, P.; Botia, P.; Garcia, F. Effects of regulated deficit irrigation under subsurface drip irrigation conditions on water relations of mature almond trees. *Plant Soil* **2004**, *260*, 155–168. [CrossRef]
18. Ahmed, R.; Yusoff Abd Samad, M.; Uddin, M.K.; Quddus, M.A.; Hossain, M.A.M. Recent Trends in the Foliar Spraying of Zinc Nutrient and Zinc Oxide Nanoparticles in Tomato Production. *Agronomy* **2021**, *11*, 2074. [CrossRef]
19. Li, F.; Chen, X.; Zhou, S.; Xie, Q.; Chen, G. Overexpression of slmbp22 in tomato affects plant growth and enhances tolerance to drought stress. *Plant Sci.* **2020**, *301*, 110672. [CrossRef]
20. Zheng, C.; Wan, L.; Wang, R.; Wang, G.; Dong, L.; Yang, T.; Yang, Q.; Zhou, J. Effects of rock lithology and soil nutrients on nitrogen and phosphorus mobility in trees in non-karst and karst forests of southwest China. *For. Ecol. Manag.* **2023**, *548*, 121392. [CrossRef]
21. An, S.; Zhou, J.; Liu, B.; Cheng, M.; Yang, H.; Sun, X. Effects of trace irrigation pipe depth on development, yield and water use efficiency of tomato in solar greenhouse. *Crops* **2013**, *3*, 86–89. (In Chinese)
22. Zhang, R.; Liu, J.; Zhu, J.; Jin, J.; Wei, Q.; Shi, Y. Trace quantity irrigation technology with crop water-requirement triggering and self-adaptive function. *Water Sav. Irrigation.* **2013**, *1*, 48–51. (In Chinese)
23. Zhu, H. Micro-irrigation Primary Bar Scree Device Research. *J. Irrig. Drain.* **2017**, *36*, 29–33. (In Chinese)
24. Trovato, M.; Mattioli, R.; Costantino, P. Multiple roles of proline in plant stress tolerance and development. *Rend. Lincei* **2008**, *19*, 325–346. [CrossRef]
25. Singandhupe, R.B.; Rao, G.G.S.N.; Patil, N.G.; Brahmanand, P.S. Fertigation studies and irrigation scheduling in drip irrigation system in tomato crop (*Lycopersicon esculentum* L.). *Eur. J. Agron.* **2003**, *19*, 327–340. [CrossRef]
26. Zhuge, Y.; Zhang, X.; Zhang, Y.; Li, J.; Yang, L.; Huang, Y.; Liu, M. Tomato root response to subsurface drip irrigation. *Pedosphere* **2004**, *14*, 205–212.

27. Shabbir, A.; Mao, H.; Ullah, I.; Buttar, N.A.; Lakhiar, I.A. Effects of drip irrigation emitter density with various irrigation levels on physiological parameters, root, yield, and quality of cherry tomato. *Agronomy* **2020**, *10*, 1685. [CrossRef]
28. Locascio, S.J.; Smajstsrla, A.G.; Hensel, D.H.; Weigartner, D.P. Potato growth uniformity as affected by subsurface drip and seepage irrigation. *HortScience Publ. Am. Soc. Hortic. Sci.* **1997**, *32*, 529C–529. [CrossRef]
29. Singh, D.K.; Singh, R.M.; Rao, K.V.R. Subsurface drip irrigation system for enhanced productivity of vegetables. *Environ. Ecol.* **2010**, *28*, 1639–1642.
30. Wang, H.; Wang, N.; Quan, H.; Zhang, F.; Fan, J.; Feng, H.; Cheng, M.; Liao, Z.; Wang, X.; Xiang, Y. Yield and water productivity of crops, vegetables and fruits under subsurface drip irrigation: A global meta-analysis. *Agric. Water Manag.* **2022**, *269*, 107645. [CrossRef]
31. Seidel, S.J.; Schütze, N.; Fahle, M.; Ruelle, P. Optimal Irrigation Scheduling, Irrigation Control and Drip Line Layout to Increase Water Productivity and Profit in Subsurface Drip-Irrigated Agriculture. *Irrig. Drain.* **2014**, *64*, 501–518. [CrossRef]
32. Douh, B.; Boujelben, A. Water saving and eggplant response to subsurface drip irrigation. *J. Agric. Segm.* **2010**, *1*, 1525.
33. Lamm, F.R.; Trooien, T.P. Subsurface drip irrigation for corn production: A review of 10 years of research in Kansas. *Irrig. Sci.* **2003**, *22*, 195–200. [CrossRef]