

Article

Influences of Sprinkler Frost Protection on Air and Soil Temperature and Chlorophyll Fluorescence of Tea Plants in Tea Gardens

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Abstract: Sprinkler irrigation is an effective method for protecting economic crops from frost damage; however, current research on its impacts is insufficient and lacks comprehensive evaluation. This research investigated the effects of sprinkler irrigation for frost protection on the air, soil, and tea plants in the tea garden. Sprinkler frost protection experiments were conducted in the tea garden, where temperature sensors measured the air and soil temperatures, and Monitoring-PAM was used to measure the chlorophyll fluorescence parameters (Fv/Fm) of the tea plants. The results indicated that lower initial ambient temperatures or smaller droplet sizes accelerate the rate of air temperature increase and slow the cooling rate. Under conditions of heavy frost, ice formation from irrigation water acts as an insulating layer, protecting the inter-row soil. Additionally, the Fv/Fm values of tea leaves protected by sprinkler irrigation ranged from 0.6 to 0.7, and were significantly higher than those of leaves exposed to frost damage. The results also showed that air and soil temperature and tea Fv/Fm can be used to perform a comprehensive assessment of sprinkler frost protection effectiveness.

Keywords: sprinkler irrigation; frost protection; tea tree; air temperature; soil temperature; chlorophyll fluorescence; Fv/Fm



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1. Introduction

Tea plantations and products play a vital role in the economic development of hilly regions in China [1,2]. Frost poses a significant meteorological challenge that jeopardizes the healthy growth of tea trees and the quality of the resulting products [3]. It can cause the buds of tea plants to turn brown or black, leading to substantial financial losses for growers. To protect crops from frost damage, frost prevention techniques are continuously evolving. In the past, growers often relied on labor-intensive methods such as mulching, heating, and smoking [4,5], which can also have detrimental effects on the environment. Frost protection fans represent an automated solution that has been extensively studied and widely adopted in various regions around the world [6–8]. However, the frost prevention fan only works during radiation frost and has a high cost.

Sprinkler irrigation systems are easy to install and maintain, and the associated technologies are widely used in agricultural production [9,10]. Researchers have demonstrated that sprinkler irrigation is an effective method of frost protection, not only in tea gardens [11] but also in various orchards, where they can be used to protect blueberries [12], strawberries [13], apples [14], cranberries [15], and citrus [16]. The principle of this method is to spray liquid water onto the surface of crops in frost conditions. As the liquid water freezes, it releases latent heat, thereby elevating the ambient temperature [17]. The primary advantages of employing sprinkler irrigation for frost protection include low initial equipment investment and operational costs, minimal environmental impact, and multifunctional benefits, such as drought resistance and fertilization [18].

However, this method may also present challenges, including potential damage to fruit tree branches and excessive water consumption [19]. This highlights that inappropriate sprinkler volumes can lead not only to water wastage but also to physical harm to the plants. Consequently, research has focused on determining the optimal amount of water for sprinkler irrigation and reducing water usage. Two main solutions have emerged: the use of water-saving microsprinklers [20] and the enhancement of sprinkler irrigation methods and control strategies [21]. The improved method, commonly referred to as automatic, intermittent, or cycle sprinkler irrigation, incorporates additional sensors and controllers to monitor temperature in real time and manage the operation of the sprinkler system. In conclusion, research on sprinkler irrigation for frost protection has primarily concentrated on the selection of suitable sprinkler heads, optimization of irrigation systems, refinement of irrigation techniques, and development of effective control strategies. The effects of sprinkler irrigation water on air, soil, and plants under frost conditions have not been thoroughly explored.

The process of sprinkler irrigation for frost protection in tea garden involves liquid water being sprayed out of a sprinkler head, part of which falls directly into the soil and part of which is trapped, frozen and wrapped around the tea tree leaves [22]. Temperature variations are frequently cited in the literature as critical indicators for evaluating the effectiveness of this process. With continuous sprinkler irrigation, the air temperature rises from the initial level to approximately 0 °C and remains stable throughout subsequent irrigation cycles [12]. Under intermittent sprinkler irrigation, temperatures fluctuate as the system cycles on and off [15]. These studies primarily focus on whether sprinkler irrigation raises the temperature to the target value and do not analyze the rates of temperature rise and fall. This has led to a lack of further understanding of the processes and details of temperature changes during sprinkler irrigation. In addition to air temperature, soil and tea plants represent two critical components of a tea garden. Soil temperature plays a pivotal role in influencing the germination, growth, and yield characteristics of crops [23]. It not only affects the growth rate of root systems but also influences nutrient absorption and the overall development of tea plants. While soil temperatures at various depths and over different time scales have been extensively studied [24], the specific impact of sprinkler water on soil temperature in tea gardens, particularly under frosty conditions, has not been explored. Chlorophyll fluorescence (CF) measurement has emerged as a non-invasive technique to assess the photosynthetic performance of plants. CF has been utilized to detect damage to photosystem II (PSII) in several crops, including potatoes [25], wheat [26], and rice [27], under environmental stress conditions. However, this indicator is typically employed to determine stress levels [28] or evaluate crop resistance [29]. The variation in chlorophyll fluorescence parameters in tea leaves during sprinkler irrigation for frost protection has not been adequately investigated. Examination of chlorophyll fluorescence parameters in tea leaves can be utilized to assess the protective effectiveness of sprinkler irrigation frost protection, thereby aiding farmers in deciding whether to adopt additional protective measures.

This study aims to investigate the effects of sprinkler irrigation for frost protection on the rates of air temperature, soil temperature variation, and chlorophyll fluorescence parameters in tea tree leaves. The research findings inspire researchers to comprehensively evaluate more aspects of sprinkler irrigation frost protection and provide a foundation for the promotion and optimization of this technology.

2. Materials and Methods

2.1. Air Temperature in Sprinkler Irrigation Frost Protection

All experiments were conducted at Yinchun Biya Tea Farm (32°20′35″ N, 120°80′20″ E) in Danyang City, China. The sprinkler irrigation system was designed as illustrated in Figure 1a. The sprinkler irrigation system consists of a water source (municipal water), a water pump (1.1 kw), main and branch pipelines, valves, and sprinklers. The main pipe diameter is 32.0 mm and the branch pipe diameter is 25.0 mm. Branch pipes were installed

along the edges of the tea rows, 8.0 m apart, and the water pressure in each branch pipe was 1.3 MPa. The water valve used was a manual ball valve, and the switch of the valve was manually operated during the experiment. A microsprinkler and an impact sprinkler were used, as shown in Figure 1b,c. Branch pipes numbered 1–3 were installed with microsprinklers, and branch pipes numbered 4–6 were installed with impact sprinklers. When frost occurred, the water source and valve were activated, enabling this system to transport water through pipes to the tea field and sprinkle it onto the tea trees through nozzles. After the experiment was completed, the water source and pump were turned off, and the drain valve at the end of the pipeline was opened to drain the water from the pipes to prevent freezing. The tea variety was *C. sinensis* cv. *Zhongcha 108*, featuring a row spacing of 1.1 m and a gap width of 0.4 m between the rows. The tea tree height was about 1.2 m, with a crown width of about 0.7 m, and it was growing in good conditions, with no pests or diseases.

Temperature sensors (model: ZDR-3WIS, accuracy: ± 0.1 °C; Hangzhou Zeda Instrument Co., Ltd., Hangzhou City, China) recorded data at a frequency of one reading per minute. The temperature sensor used has two temperature probes. Two sensors were placed in the canopy 1.0 m away from each sprinkler, and the canopy temperature was obtained by averaging the temperature values of the four probes. The ambient temperature was measured by two temperature sensors 8.0 m away from the sprinkler. The test duration was 60.0 min, in which the spraying duration was 30.0 min and the stopping duration was 30.0 min. Each experiment was repeated three times. Data analysis was performed using SPSS 24.0 software, and graphs were created using Origin 2018 software.

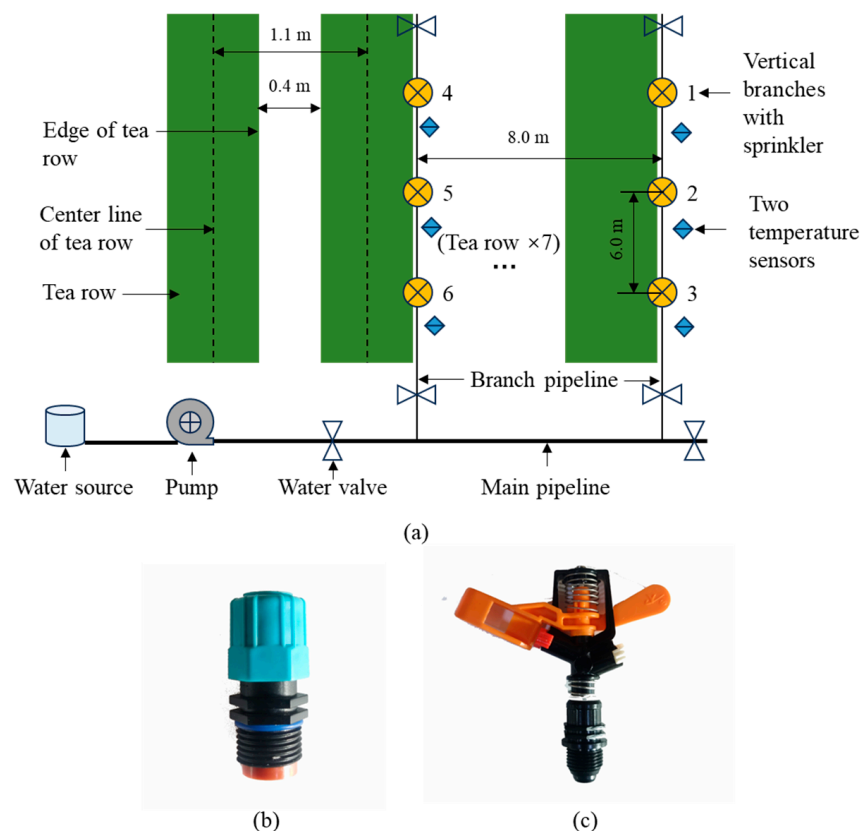


Figure 1. (a) Schematic diagram of sprinkler irrigation system. (b) Microsprinkler. (c) Impact sprinkler.

2.2. Soil Temperature in Sprinkler Irrigation Frost Protection

The test area, temperature sensors, and sprinkler system were consistent with those described in Section 2.1. The arrangement of the temperature sensors is shown in Figure 2, while the sprinkler system has been simplified and is not depicted. The tea garden soils were classified into two categories: inter-row soil and sub-canopy soil. The detection of soil

moisture was conducted using the digital display soil moisture meter (LY-201). The initial soil moisture content was $80\% \pm 5\%$. In the sprinkler-irrigated area, the temperature of the inter-row soil was measured using three temperature probes. Each probe, measuring 3.0 cm in length, was inserted vertically into the soil, with the insertion point located at the center of the inter-row. The probes were spaced 0.5 m apart and labeled as p1, p2, and p3, with probe p1 positioned 1.0 m horizontally from the sprinkler.

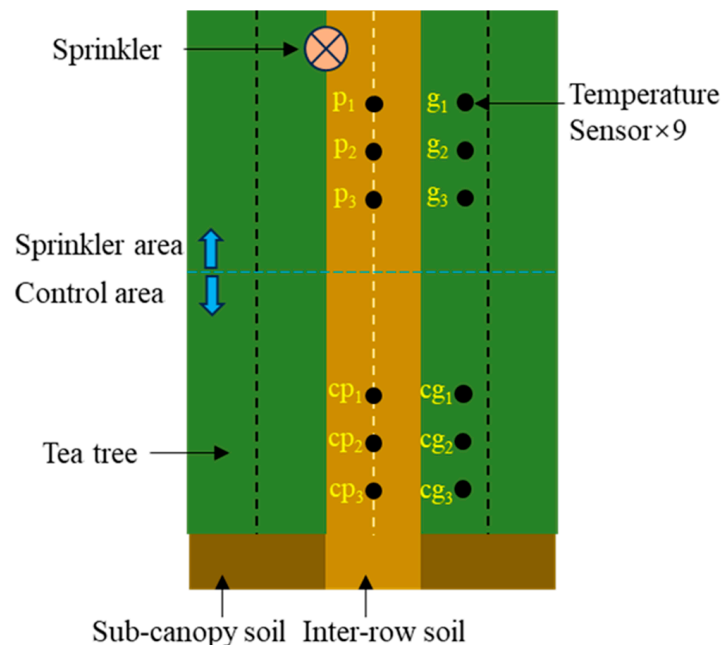


Figure 2. Schematic diagram of temperature sensor arrangement in soil temperature test.

The temperature probes for measuring sub-canopy soil were arranged parallel to those in the inter-row soil, located at a horizontal distance of 0.5 m and labeled g1, g2, and g3, respectively. The temperature values measured by the p1–p3 and g1–g3 probes were averaged as the inter-row soil temperature and the sub-canopy soil temperature in the sprinkler area, respectively. The non-sprinklered area, situated 8.0 m from the sprinkler head, served as the control area. The arrangement and spacing of the temperature probes in the control area mirrored those in the sprinkler area. The temperatures from the three probes in each area were averaged to represent the overall temperature for that area. The temperature values measured by cp1–cp3 and cg1–cg3 probes were averaged as the inter-row soil temperature and the sub-canopy soil temperature in the control area, respectively.

2.3. Tea Leaves F_v/F_m in Sprinkler Irrigation Frost Protection

To ensure consistent fluorescence characteristics of tea leaves between the experimental and sprinkler-irrigated areas, the same row of tea trees with similar growth were selected. The maximum photochemical efficiency of Photosystem II (PS II) was measured and expressed as F_v/F_m , calculated as $(F_m - F_o)/F_m$, using a Monitoring-PAM (WALZ, Germany) at 7:00 p.m. for four consecutive days prior to the commencement of sprinkler irrigation. F_v/F_m is an important index to assess whether plants are subjected to environmental stress. When the tea tree is exposed to frost, the function of its Photosystem II reaction center may be impaired, resulting in a decrease in F_v/F_m values. Therefore, it can be used to compare and explain the protective effect of sprinkler irrigation frost protection. The fifth leaf from the terminal bud was selected for measurement, with ten leaves assessed in each area. The clamping piece at the end of the probe holds the leaf, and the probe emits a saturating light pulse of 1 s actinic light ($1500 \mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$) to obtain the chlorophyll a fluorescence transient. F_v/F_m was processed by the software WinControl 3.0. Tukey's test

was performed to analyze the differences in the measured data using Origin. There was a significant difference between the two sets of data if the p -value was less than 0.05.

Sprinkler irrigation was initiated at 2:00 a.m. on 1 January 2024, utilizing the same sprinkler system as described in Section 2.1 for a continuous duration of four hours. Leaf measurements were conducted after turning off the sprinkler irrigation, during which ice and frost were removed from the leaf surfaces and excess water was wiped away. Due to the limitation of the irrigation timing, five leaves were measured from both the irrigated area and the control area.

3. Results

3.1. Air Temperature Rise and Fall Rate

3.1.1. Influence of Different Ambient Temperatures

Figure 3 illustrates the temperature fluctuations during 30.0 min of sprinkler irrigation followed by 30 min of cessation at different ambient temperatures. Sprinkler irrigation commenced on 3 January 2024, at 8:00 p.m. (-2.9°C , $\text{SD} = 0.16$) and on 4 January 2024, at 6:00 p.m. (-1.2°C , $\text{SD} = 0.10$). The critical lethal temperature for tea tree shoots ranges from -6.0 to -4.0°C [30]. In this study, the tea trees were dormant adult trees, which could withstand the low temperatures experienced during the experiment.

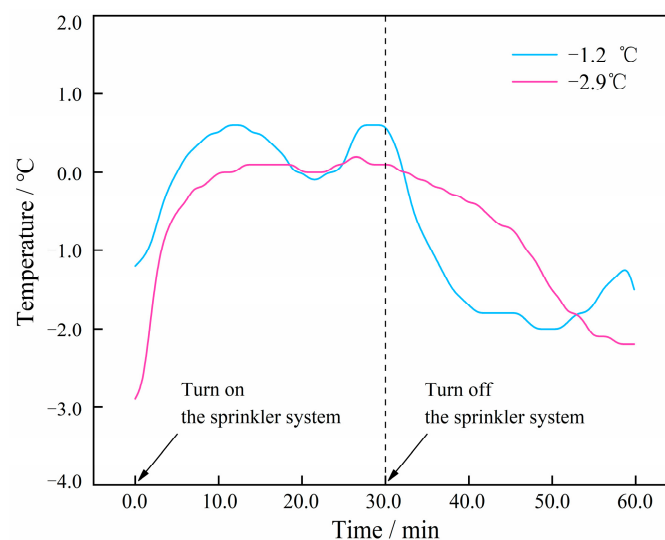


Figure 3. The temperature variations in sprinkler frost protection under different initial environmental temperatures.

After the sprinkler irrigation began, the rate of air temperature increase was slower at -1.2°C , measured at $0.3^{\circ}\text{C}/\text{min}$ ($\text{SD} = 0.02$). In contrast, at -2.9°C , the warming rate was $0.54^{\circ}\text{C}/\text{min}$. The magnitude of warming then increased as the ambient temperature decreased. The warming magnitude was 1.7°C ($\text{SD} = 0.25$) and 2.9°C ($\text{SD} = 0.35$) for the two environments, respectively. After the sprinkler irrigation was stopped, the air temperature cooled faster at the initial ambient temperature of -1.2°C , with a cooling rate of $0.3^{\circ}\text{C}/\text{min}$ ($\text{SD} = 0.07$). The cooling rate was counterintuitively slower at the lower temperature of -2.9°C , $0.1^{\circ}\text{C}/\text{min}$ ($\text{SD} = 0.02$). The warming rate and cooling rate at -2.9°C were, respectively, 1.8 times and 0.3 times those at -1.2°C . This shows that at -2.9°C , sprinkler irrigation made the air warm up faster and cool down slower than at -1.2°C .

3.1.2. Influence of Droplet Size

Figure 4 shows the temperature changes after simultaneous sprinkler irrigation with two different droplet sizes. Larger particle size droplets were produced by the impact sprinkler, while smaller particle size droplets were generated by the microsprinkler. Due

to the test being conducted in the field, there was a $0.5\text{ }^{\circ}\text{C}$ ($\text{SD} = 0.05$) difference in the initial temperature at the locations of the two sprinklers. Upon activation of the sprinkler irrigation, the air temperature immediately increased. The warming rate was notably higher with smaller droplets, being 2.1 times greater than that observed with larger droplets. The final temperature after irrigation with small droplets was $-0.25\text{ }^{\circ}\text{C}$ ($\text{SD} = 0.05$), whereas the final temperature with large droplets was $-0.75\text{ }^{\circ}\text{C}$ ($\text{SD} = 0.09$). After the sprinkler irrigation was turned off, the air warming rate under sprinkling with smaller diameter droplets was $0.04\text{ }^{\circ}\text{C}/\text{min}$, while under sprinkling with larger diameter droplets, it was $0.11\text{ }^{\circ}\text{C}/\text{min}$, which was 2.75 times that of the former.

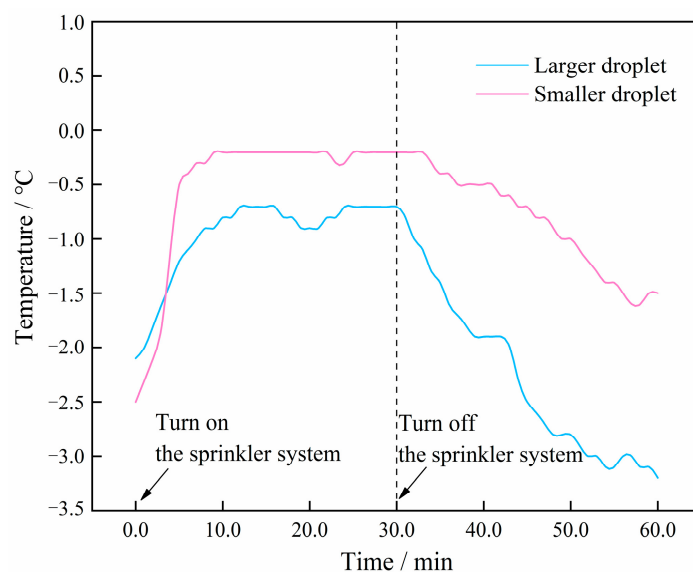


Figure 4. Influence of two droplet sizes on temperature.

3.2. Influence of Sprinkler Irrigation Water on Soil Temperature

Figure 5 illustrates the changes in air and soil temperatures in the control area over a 24 h period, from 6:00 p.m. on 6 January to 6:00 p.m. on 7 January 2024. The weather was clear and cloudless, with no fog or wind during the night, leading to radial frost formation. During the nighttime cooling process, air and soil exhibited similar cooling rates, although soil temperatures remained higher than air temperatures. At 1:50 a.m., the air temperature dropped to freezing point, while the average soil temperature was recorded at $3.9\text{ }^{\circ}\text{C}$ ($\text{SD} = 0.25$). On 7 January at 7:03 a.m., the air temperature reached a minimum of $-3.6\text{ }^{\circ}\text{C}$ ($\text{SD} = 0.34$), while the average soil temperature was $2.5\text{ }^{\circ}\text{C}$ ($\text{SD} = 0.51$). Following sunrise, air temperatures rose rapidly, exceeding soil temperatures, which increased at a slower rate. After 2:00 p.m., both air and soil temperatures began to decrease due to lower light intensity. The maximum air temperature recorded was $11.7\text{ }^{\circ}\text{C}$ ($\text{SD} = 1.23$), while the maximum temperatures for inter-row and sub-canopy soil were $8.1\text{ }^{\circ}\text{C}$ ($\text{SD} = 0.83$) and $5.8\text{ }^{\circ}\text{C}$ ($\text{SD} = 0.54$), respectively.

During the warming period from 9:00 a.m. to 12:00 p.m., the sub-canopy soil temperature was consistently higher than that of the inter-row soil. However, due to the intense solar radiation at midday, the inter-row soil temperature rose rapidly, reaching a maximum of $8.1\text{ }^{\circ}\text{C}$ ($\text{SD} = 0.83$) by 2:00 p.m. The sub-canopy soil temperature also increased, resulting in a temperature difference of $2.3\text{ }^{\circ}\text{C}$ between the two soil types.

Figure 6 illustrates the variation in soil temperatures between the sprinkler-irrigated and control areas. Sprinkler irrigation commenced at 4:30 a.m. on 7 January 2024, and continued for 3 h until 7:30 a.m. Prior to irrigation, the inter-row and sub-canopy soil temperatures in the control area decreased at similar rates. In the sprinkler-irrigated area, the soil temperatures at both locations exhibited the same cooling rate as those in the control area before the sprinklers were activated. The two areas were located 8.0 m apart, and there

were slight differences in soil temperatures between the two locations. At 4:30 a.m., the air temperature was -2.6°C (SD = 0.33), while all soil temperatures remained above 3.0°C .

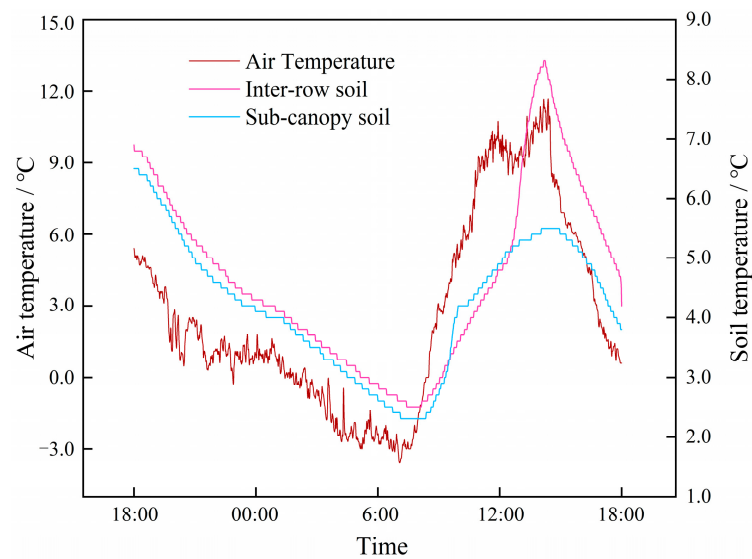


Figure 5. Changes in air and soil temperatures over 24 h (6:00 p.m. on 6 January–6:00 p.m. on 7 January 2024) in winter tea plantations.

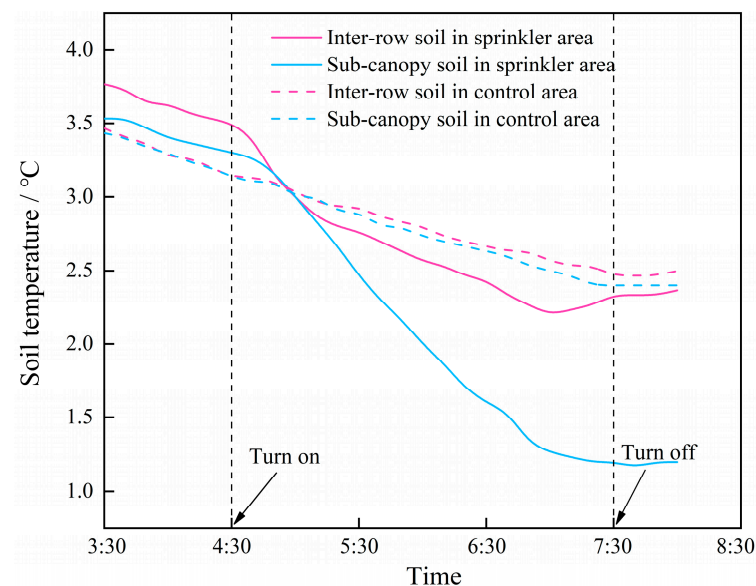


Figure 6. Influence of sprinkler irrigation on two soil temperatures.

Soil temperature changes in the sprinkler-irrigated and control areas under heavy frost conditions (with a minimum air temperature of -6.5°C , (SD = 0.51)) are shown in Figure 7. One hour before the sprinkler irrigation began, the inter-row soil temperatures in both the sprinkler and control areas were identical. After the sprinkler system was activated, the inter-row soil temperature in the sprinkler area stabilized at 0.7°C (SD = 0.05), while in the control area, it continued to decrease to a minimum of 0.5°C (SD = 0.09). The sub-canopy soil temperature exhibited a similar cooling trend to that of the inter-row soil in the control area, with a decrease of 0.2°C . In contrast, the sub-canopy soil temperature in the sprinkler-irrigated area gradually decreased during irrigation, showing a cooling of 0.4°C , which was greater than the cooling observed in the control area.

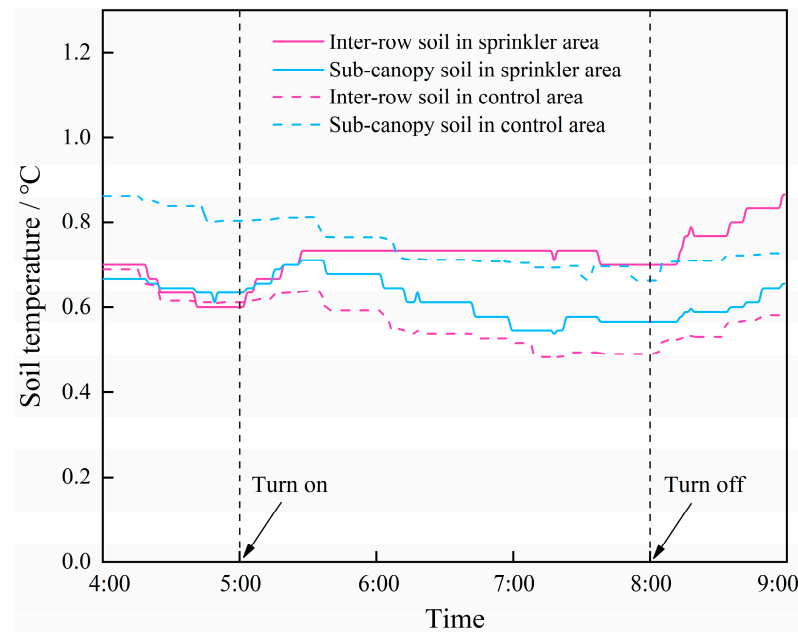


Figure 7. Variations in soil temperature under heavy frost conditions (air minimum temperature -6.5°C).

3.3. Influence of Sprinkler Irrigation on F_v/F_m of Tea Leaves

Figure 8 displays the F_v/F_m values of leaves in both areas from 19:00 to 19:30 over four consecutive days prior to the sprinkler irrigation test. Throughout this period, the F_v/F_m average values for leaves in both areas consistently remained between 0.65 and 0.70.

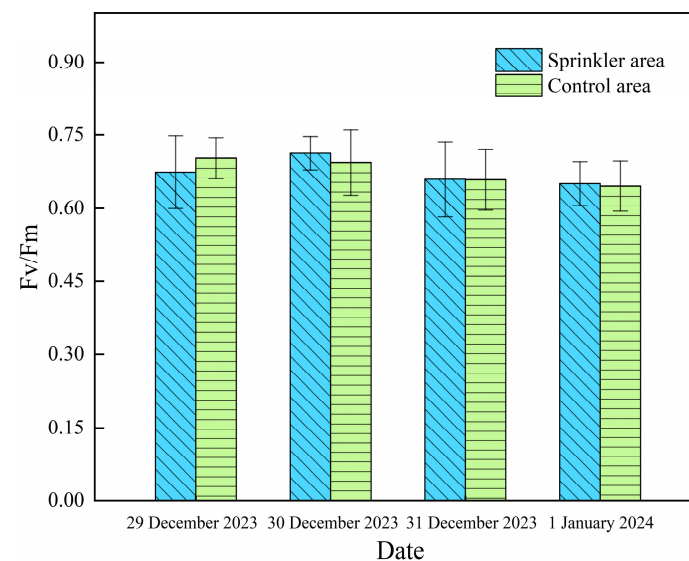


Figure 8. F_v/F_m for 4 consecutive days prior to the sprinkler irrigation test. There was no significant difference in F_v/F_m between sprinkler area and control area ($p > 0.05$) after t -test.

Figure 9a illustrates the temperature variations in the sprinkler and control areas during the irrigation process. At 2:00 a.m. on 2 January 2024, the temperature in the control area showed a decreasing trend, reaching a minimum of -5.1°C ($\text{SD} = 0.29$) throughout the experiment. In contrast, the temperature in the sprinkler area rapidly rose to approximately 0°C once irrigation began. Throughout the experiment, temperatures in the sprinkler-irrigated area were maintained between -2.0 and 0°C , while the temperature in the sprinkler zone remained about 3.0°C higher than that in the control area.

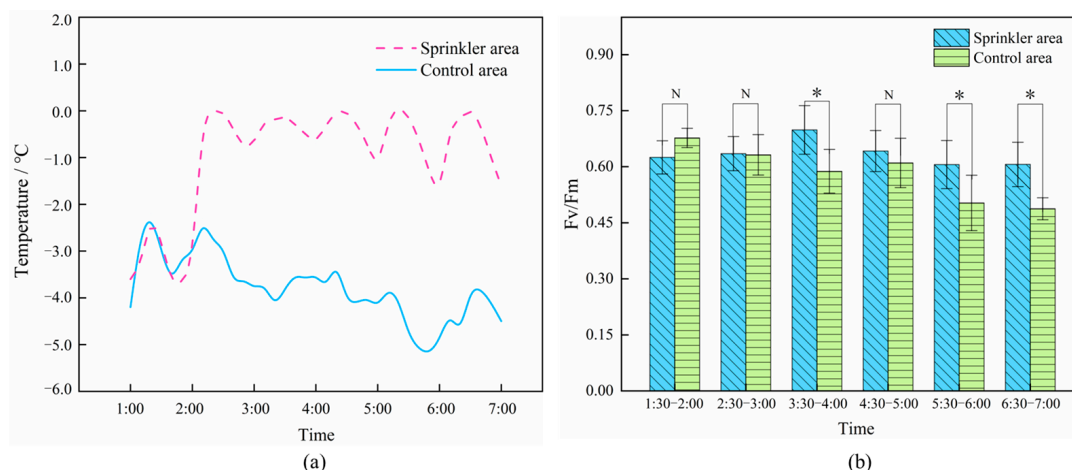


Figure 9. (a) Air temperature variation during sprinkler irrigation. (b) Tea leaf Fv/Fm during sprinkler irrigation. Asterisk indicates significant differences (*, $p < 0.05$) and N indicates no significant difference, as determined by t -test.

Figure 9b illustrates the changes in leaf Fv/Fm during the sprinkler irrigation experiment on 2 January 2024. After 0.5 h of irrigation, the leaf Fv/Fm average values in sprinkler and control area were 0.64 (SD = 0.04) and 0.70 (SD = 0.05), respectively, showing minimal differences. The temperature in the sprinkler area stayed between -1.0 and 0 °C since the irrigation began, allowing the leaf Fv/Fm in this area to remain 0.70 (SD = 0.06) from 3:30 to 4:00 p.m. In contrast, as the temperature in the control zone continued to drop, the leaf Fv/Fm in the control area was 0.59 (SD = 0.05). Subsequent measurements revealed that leaves in the sprinkler-irrigated area consistently exhibited higher Fv/Fm values than those in the control area. Notably, after 5:30 a.m., leaf Fv/Fm in the control area decreased to 0.50 (SD = 0.07) due to prolonged exposure to cold temperatures, while the Fv/Fm of leaves in the sprinkler-irrigated area was maintained at 0.61 (SD = 0.06).

4. Discussion

4.1. Air Temperature Rise and Fall Rate

4.1.1. Influence of Different Ambient Temperatures

As shown in Figure 3, initiating sprinkler irrigation at different initial ambient temperatures increased the temperature to about 0 °C [12,15]. But the lower ambient temperatures led to faster air warming. This phenomenon can be attributed to the limited amount of sprinkler water that became trapped and frozen on the canopy at -1.2 °C (SD = 0.10). In this condition, the primary source of heat for frost protection is the latent heat released during the freezing of the sprinkler water. Considering the sprinkler water as a heat-generating mechanism, the heat generation at -1.2 °C (SD = 0.10) is less effective than at -2.9 °C (SD = 0.16), leading to a slower rate of warming at the higher temperature.

In a -1.2 °C environment, after the maximum temperature was reached via sprinkler irrigation, there was a brief, slight drop in temperature. This decline occurred because the heat released from water freezing was insufficient to counterbalance the heat lost through evaporation. This phenomenon suggests that sprinkler control systems could be optimized to halt irrigation upon detecting a temperature peak followed by a subsequent decline.

The lower the initial ambient temperature, the slower the cooling rate observed after the cessation of sprinkler irrigation. During irrigation at -2.9 °C (SD = 0.16), more ice formation occurred, releasing a greater amount of latent heat [22]. The evaporative effect of the unfrozen water on the canopy was the primary reason for the quicker cooling at -1.2 °C (SD = 0.10), particularly when temperatures were above 0 °C at the time the sprinklers were turned off.

4.1.2. Influence of Droplet Size

Impact sprinklers are widely employed in sprinkler irrigation for frost protection [8]. To promote water conservation, microsprinklers have also been extensively studied for frost protection in irrigation [17]. This decline occurs because sprinklers provide a continuous and steady supply of water to the canopy, despite producing smaller droplets. In contrast, the larger droplets generated by impact sprinklers result in less water reaching the canopy, which is the primary reason for the lower final temperature observed after irrigation. Additionally, the larger droplets from impact sprinklers form less ice on the canopy, leading to reduced heat generation and a more rapid decrease in air temperature after irrigation ceases.

In summary, during sprinkler irrigation for frost protection, even if irrigation continues after the canopy temperature reaches its maximum, a temperature drop may still occur. Therefore, pauses in the sprinkler operation are permitted during the irrigation process. Lower ambient temperatures and the use of smaller diameter droplets can increase the rate of air warming and slow down the cooling rate. These findings provide a theoretical foundation for improving the responsiveness and control capabilities of sprinkler irrigation systems in tea garden environments.

4.2. Influence of Sprinkler Irrigation Water on Soil Temperature

The influences of factors such as season, soil depth, vegetation, and geographical region on soil temperature have been extensively studied [23,31]. In a well-managed tea garden, the soil can be divided into two distinct areas: inter-row soil, which is directly exposed to the air, and sub-canopy soil, which is shaded by the tea tree canopy. As shown in Figure 5, air and soil temperatures exhibited similar trends, demonstrating a significant correlation [32]. Both soil areas reached their maximum temperatures at 2:00 p.m., which was consistent with findings in the literature [33]. Changes in soil and air temperatures are primarily influenced by solar heat input, leading to similar patterns. However, when the same amount of heat is gained or lost, the change in soil temperature is less pronounced than that of air temperature due to the soil's higher specific heat capacity.

Inter-row and sub-canopy soil temperatures fluctuated with the sun's movement. Due to the north–south orientation of the tea rows in the test area, the sub-canopy soil received more heat when the sunlight was angled, while the inter-row soil was shaded by the tea plants. After 12:00 p.m., the sun began to shine more directly on the tea garden, resulting in direct irradiation of the inter-row soil while the sub-canopy soil remained shaded.

When the air temperature was $-2.6\text{ }^{\circ}\text{C}$, soil temperatures in the inter-row and sub-canopy areas significantly decreased after sprinkler irrigation was initiated. The water temperature in the sprinkler pipe was $2.8\text{ }^{\circ}\text{C}$ (SD = 0.19). As the sprinkler water was sprayed in droplets and moved through the cold air, the temperature of these droplets was likely lower than $2.8\text{ }^{\circ}\text{C}$ by the time they reached the soil. Thus, the temperature of the sprinkler water was lower than that of the soil. Following the irrigation, the temperature difference between the inter-row and sub-canopy soils in the irrigated area compared to before irrigation was $1.9\text{ }^{\circ}\text{C}$ and $2.3\text{ }^{\circ}\text{C}$, respectively. This indicates that sprinkler irrigation plays a significant role in lowering soil temperatures, with a more pronounced effect on sub-canopy soil temperatures.

When the air temperature was $-6.5\text{ }^{\circ}\text{C}$, the soil in the sprinkler-irrigated area did not warm up as much as the air temperature, despite the sprinkler water being warmer than the soil. During this time, the air temperature dropped to $-6.0\text{ }^{\circ}\text{C}$, causing water on the soil surface to freeze and impeding the infiltration of liquid water. As the amount of water increased, the ice layer gradually thickened, providing insulation. This insulating effect kept the soil temperature in the irrigated area relatively constant, while the temperature in the control area decreased gradually due to radiative heat loss. As a result, inter-row soil temperatures in the sprinkler-irrigated area were $0.2\text{ }^{\circ}\text{C}$ higher than those in the control area.

The significance of studying the impact of sprinkler irrigation on soil temperature is twofold: First, simulation methods are being utilized to model the energy transfer in tea gardens under frost protection through sprinkler irrigation, with the patterns of soil temperature variation providing experimental validation for the simulation results. Second, Zhang et al. [32] utilized the significant correlation between air and soil temperatures to predict the depth of frozen soil based on air temperature. This inspires us to explore the use of soil temperature in the future for controlling or assisting in the control of sprinkler frost protection systems. Furthermore, sprinkler irrigation prevents drastic changes in air and soil temperatures the next day, thereby reducing the stress response of tea plants to such temperature fluctuations. The results show that it is possible to use soil temperature as an auxiliary parameter to control sprinkler irrigation.

4.3. Influence of Sprinkler Irrigation on Fv/Fm of Tea Leaves

The Fv/Fm of tea leaves peaks in summer, ranging from 0.80 to 0.83, and declines in fall and winter [34]. The Fv/Fm of tea leaves under cold stress was reported to drop to 0.2–0.4 in the results from Fu et al. [35]. This is significantly lower than the Fv/Fm levels observed in the control area of our study. The main reason for this discrepancy is believed to be the use of mature tea trees in the experiment, which have stronger cold resistance compared to the seedlings used in the literature. In contrast, sprinkler irrigation effectively maintained the Fv/Fm of tea tree leaves between 0.6 and 0.7 under frost conditions, as shown in Figure 9b. This represents a significant difference from the control area. These findings indicate that sprinkler irrigation has beneficial effects on the physiology of tea trees and suggest that Fv/Fm could serve as a valuable evaluation index for establishing a comprehensive assessment of frost protection technologies for tea trees in the future. Based on the development of sensors for monitoring plant leaves, it may be more accurate and water-saving to use changes in crop physiological indicators to control the water supply of sprinkler irrigation systems.

The frost protection experiments were all conducted in southern Jiangsu (Danyang City), China, and the frost type was radiation frost. The frosts occurred on clear, cloudless days with no wind. The air, plants, and soil release heat by radiation, and the temperature gradually decreases to form frost. Therefore, the results and conclusions of the study are considered universal in tea gardens located in the Anhui, Jiangsu, and Zhejiang regions of China, because the most common type of frost in these areas is radiation frost. However, the effectiveness of sprinkler irrigation in protecting against advection frost—caused by the movement of cold air masses—requires further investigation, particularly in tea and fruit gardens in northern China. Additionally, developing predictive models for the variations in these parameters, utilizing the available data to enhance the applicability of the research outcomes, represents a future research direction.

5. Conclusions

This study views tea gardens as an integrated system composed of air, soil, and tea trees, investigating the effects of sprinkler irrigation on the air temperature change rates, soil temperature variations, and chlorophyll fluorescence parameters of tea leaves. The main conclusions are as follows:

- (1) The air temperature following sprinkler irrigation is influenced by both the initial environmental temperature and the size of the droplets. Specifically, lower initial environmental temperatures and smaller droplet sizes result in faster temperature increases and slower decreases. The warming rate and cooling rate at -2.9°C were, respectively, 1.8 times and 0.3 times those at -1.2°C . When the ambient temperature is -2.5°C , the warming and cooling rate of air after smaller particle droplets is 2.1 times and 0.38 times that of larger particle size droplets, respectively.
- (2) Sprinkler irrigation for frost protection had an influence on the soil temperature of tea plantations and varied with frost levels. Under light frost conditions, sprinkler water cools the soil in both inter-row spaces and beneath the canopy, as its temperature is

lower than that of the soil. Under heavy frost conditions, the freezing of the sprinkler water provides insulation to the inter-row soil.

- (3) The freezing of sprinkler irrigation water that envelops the tea leaves has a positive effect on their chlorophyll fluorescence parameters. Sprinkler water can maintain the F_v/F_m value of tea leaves between 0.6 and 0.7, while leaves that have experienced frost show an F_v/F_m value below 0.6.
- (4) Sprinkler irrigation for frost protection has a significant effect on the air temperature, soil temperature, and chlorophyll fluorescence parameters of tea plants. These three parameters can be used to establish a comprehensive assessment of frost protection effectiveness.

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