Agricultural Science; Vol. 5, No. 1; 2023
ISSN 2690-5396 E-ISSN 2690-4799
https://doi.org/10.30560/as.v5n1p8

Investigation on Combination of Airflow Disturbance and Sprinkler Irrigation for Horticultural Crop Frost Protection

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Received: March 15, 2023 Accepted: April 20, 2023 Online Published: June 13, 2023

The research is financed by the China and Jiangsu Postdoctoral Science Foundation (2022M711396 and 2021K614C), the Natural Science Foundation of the Jiangsu Higher Education Institutions of China (21KJB210019), and the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD-2018-87), and Synergistic Extension Program of Major Agricultural Technologies in Jiangsu (2021-ZYXT-06).

Abstract

Frost tends to be detrimental to the growth and development of horticultural crops, leading to yield or quality reduction with sizable economic losses. Therefore, it is very important to develop frost protection technology for horticultural crops. In this study, the development of frost protection technology is reviewed, and the research of mechanized frost protection technology in recent years is analyzed. In view of the poor frost protection effect of some single mechanized frost protection technology, the combination frost protection technology is put forward. The combination frost protection technology with airflow disturbance and sprinkler irrigation is discussed and analyzed.

Keywords: frost protection, airflow disturbance, sprinkler irrigation, horticultural crop, combination frost protection

1. Introduction

Frost is a common agrometeorological disaster that can cause significant damage to crops by reducing yields, lowering quality, and even resulting in crop failure. There are two types of frost: stratospheric frost and radiation frost. Radiation frost is the most common type worldwide and occurs when heat is lost near the ground in the form of radiation, causing the energy lost to be greater than the energy received and resulting in frost. This type of frost typically occurs on clear, windless, cold nights in mid-winter and spring. Since spring is a crucial growth period for most horticultural crops, frosts that occur during this time can have a particularly severe impact on these crops. In recent years, inversions have occurred more frequently because of global warming, causing varying degrees of frost damage to horticultural crops during the budding period and resulting in economic losses worldwide. Therefore, protecting horticultural crops against frost damage is a necessary task in agricultural production. Principle diagram of radiation frost formation as shown in Figure 1.

The traditional agricultural frost protection measures include irrigation, smoking and mulching, but these measures have poor effect and cause serious environmental pollution (Yongguang Hu 2011). In order to reduce the pollution caused by frost protection, mechanized frost protection technology such as heating furnace, airflow disturbance, sprinkler irrigation and helicopter frost protection have been gradually developed in recent years. However, the single mechanized frost protection technology still has poor frost protection effect. in order to solve this problem, combination frost protection technology has been mentioned, including the combination of heating furnace and airflow disturbance, the combination of sprinkler irrigation and airflow disturbance, and the combination of heating furnace and sprinkler irrigation.

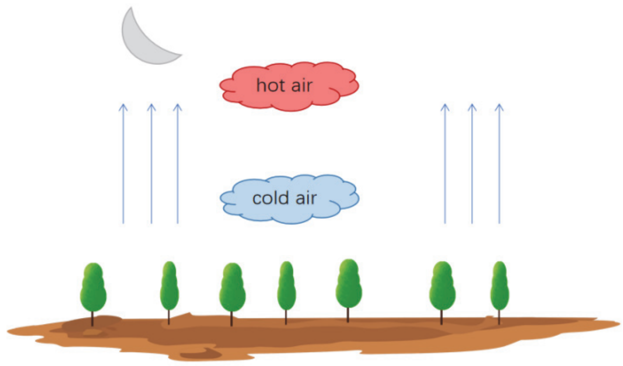

Figure 1. Principle diagram of radiation frost formation

2. Mechanization Technology for Frost Protection

In recent years, with the rise of large agricultural enterprises, the cultivation of horticultural crops has also begun to be large-scale and centralized. In order to reduce the consumption of human resources, it is urgent to develop mechanized frost protection technology. The most commonly used technologies for frost protection are the airflow disturbance, sprinkler irrigation, and combination of airflow disturbance and sprinkler irrigation. Mechanization technology provide efficient and effective solutions to combat the negative effects of frost on crops.

2.1 Airflow Disturbance Technology

The main devices used in the airflow disturbance include overhead wind machine, suction-exhaust wind machine and helicopter. The principle of this technology is to disturb the air near the ground using the frost protection device, which causes the high-temperature air above the plant canopy to the canopy height. As a result, the air temperature at the canopy height gradually increases, and it becomes higher than the critical frost temperature of the plant, effectively protecting frost damage. One advantage of the airflow disturbance technology is its ability to use the unique inverse temperature phenomenon of radiation frost nights, which reduces material consumption, minimizes environmental pollution, and facilitates the mechanization and automation of frost control equipment. However, the technology has some limitations, such as its effectiveness being restricted to strong frost night inversion temperatures. In cases where the inversion temperature is weak, the technology may not provide adequate frost protection due to the weak intensity of the near-ground inversion temperature. As shown in Figure 2.

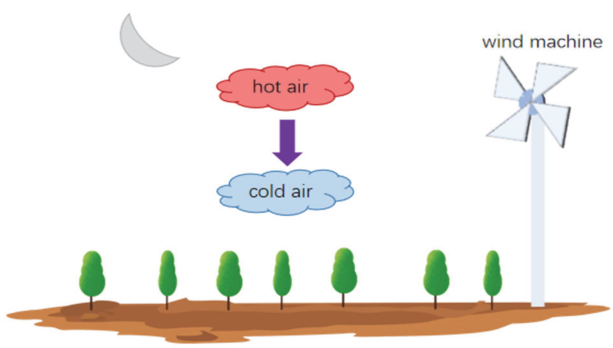

Figure 2. Schematic diagram of the airflow disturbance

The airflow disturbance technology is currently the most widely studied mechanical frost protection technology globally. Reese first applied the elevated fan in orchards for frost protection experiments and found that the temperature increase effect of the elevated fan is positively correlated with the strength of the inversion on the frost night(Reese, R.L. & Gerber, J.F. 1969) . Doesken et al. used the minimum air temperature at the surface of fruit trees and the strength of the inversion on the night as the timing for the fan to start, and successfully conducted frost protection experiments in orchards using the airflow disturbance technology (Doseken, N.J. *et al.* 1989). Ribeiro et al. found that the air temperature increase at the canopy of fruit trees after the fan starts depends on the strength of the inversion(Ribeiro, et. al. 2006). Battany conducted comparative experiments on the frost protection effect of suction and exhaust fans and traditional tower fans during 12 spring frost nights in 2010 and 2011, and the experimental results surface that the frost protection effect of traditional tower fans is significantly better than that of suction and exhaust fans, and the experiments also tracked the airflow of suction and exhaust fans through smoke, and found that suction and exhaust fans will suck the cold air to 25m in the frost protection process Then the cold air will slowly sink to the ground, and the cold air sucked out in the frost protection process will again sink to the plant canopy height, causing secondary frost damage to crops. This can cause secondary frost damage to crops(Battany, et al. 2012).

With the continuous research on airflow disturbance technology, Kimura et al. conducted an experimental study on the thermal effects on frost protection fans in tea fields through the spatial and temporal analysis of leaf heat balance. The time and space distribution of the thermal effect of the fan was visualized by numerical calculation, and the experimental results showed that the thermal effect of the frost protection area showed a dynamically changing distribution in space and time under the variation of the blade boundary conductance and the blade-air temperature difference, but the periodic oscillation of the wind machine led to different intervals and durations of airflow, which made the thermal effect uneven throughout the tea field and increased the risk of frost damage(Kimura, *et al.* 2017).

In recent years, with the rapid improvement of domestic mechanization level, the air disturbance technology has been experimented several times in China, and mature products have been developed. Hu analyzed the spatial and temporal distribution of near-ground air temperature, and developed the first domestically produced elevated wind machine, which has been successfully tested in tea fields with significant effect(Hu *et al.* 2018). Hong Zhang designed and developed a new type of suction and discharge device, which has also been successfully used in tea fields, but with weaker effect than the elevated wind machine(Zhang 2012). Based on the overall design of the frost protection machine, Yang conducted simulation of the biconvex impeller, analyzed its surface pressure distribution characteristics, and designed and developed a biconvex wing type tea field frost protection machine, which successfully protected frost in the tea field, and the frost protection area was significantly increased compared with the traditional frost protection fan, and the frost protection cost per unit area was significantly reduced (Yang 2014). Zhu studied the operation timing of the frost protection machine and its frost protection effect under different time scales and frost damage levels, and then established a prediction model for the occurrence of early spring late frost damage based on historical meteorological data, on the basis of which a decision system for the operation of the tea field frost protection machine was initially developed(Zhu 2014).

Liu studied the helicopter flight process using computational fluid dynamics, and found that when the flight speed was constant, the wind speed in the crown decreased with increasing flight height(Liu 2015).Wu analyzed the distribution characteristics of the airflow disturbance of the wind machine in the canopy height of the frost protection object under the typical installation conditions of the wind machine with circular arc plate and wing-shaped blades, and found that the airflow disturbance characteristics are closely related to the blade shape(Wu 2015). Huang built a 3D physical model of wind machine and selected the SST k-ω turbulence model to study the airflow characteristics and temperature changes at the canopy of tea trees, and found that the airflow speed at the canopy of tea trees was proportional to the rotational speed, while the temperature in some areas increased and then decreased with the increase of rotational speed, but the average temperature of the whole canopy increased with the increase of rotational speed (Huang *et al.* 2016). Sun established the airflow disturbance model of the wind machine, and found that moderately reducing the installation height and installation pitch angle can increase the frost protection area, but as the installation pitch angle decreases, however, as the installation pitch angle decreases, the blind area increases; as the installation height becomes smaller, the value of the right endpoint of the frost protection range does not change much. The value of the right endpoint of the frost protection range does not change much with smaller installation height(Sun 2020).

Figure 3. Overhead wind machine

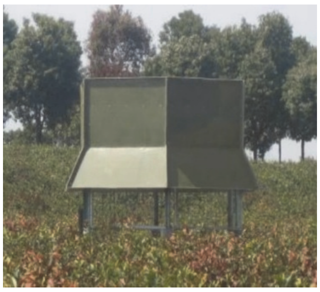

Figure 4. Suction-exhaust wind machine

Figure 5. Helicopter

2.2 Sprinkler Irrigation Technology

The main equipment of the sprinkler irrigation is the sprinkler head, pump and pipe, which has been successfully applied in the United States, Japan and other countries, used for tea plantations, strawberry orchards and orange groves(Zhao 2015). The working principle of the sprinkler irrigation is: under the low temperature of frost night, by sprinkling the surface of crops, water is continuously sprayed on the surface of crops, and the water releases latent heat by solidifying into ice, thus raising the temperature at the surface of crops above the critical frost temperature of the crops. The sprinkler irrigation can achieve good frost protection with sufficient water and low wind speed. The main disadvantages of the sprinkler irrigation are: when the spraying water is insufficient, it will aggravate the frost damage of crops, and when the spraying water is too much, it will cause the waste of water and flooding. As shown in Figure 6.

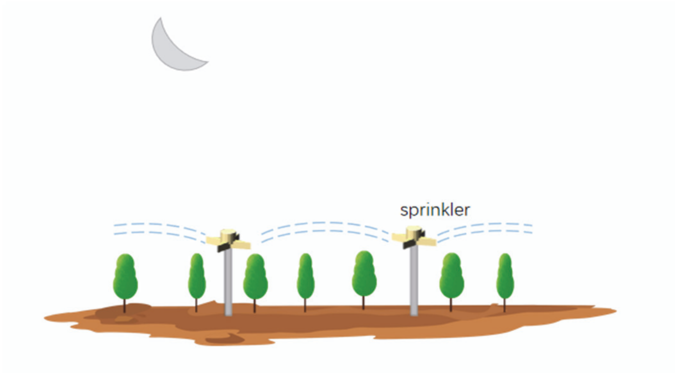

Figure 6. Diagram of sprinkler irrigation for frost protection

Sprinkler irrigation has been applied to Orchards in Europe and the USA since its inception. Various studies have been conducted to optimize the system's performance. Rieger conducted frost protection experiments in apple orchards in the southeast of England and found that a sprinkler intensity of 2.5 mm/h can protect buds from frost damage at -4 °C air temperature during spring radiation frost(Rieger, *et al.* 1986). Stefano studied the influence of different sprinkler head combinations and different water spray amounts on the air temperature of the fruit tree canopy in Italian orchards, optimized the sprinkler head combination in the sprinkler irrigation system, and reduced the water spray amount (Stefano, *et. al.* 2002). In 2009, Ghaemi designed and developed an automatic tree sprinkler irrigation system in peach and orange orchards in southern Iran, and the peach trees reached a temperature rise of 4.5°C during the frost night, while the orange trees also reached a temperature rise of 2.5°C, and both were above the critical low temperature(Ghaemi, *et. al.* 2009). Issa studied the freezing of water droplets sprayed on a single orange tree during the sprinkler irrigation process through numerical simulation, providing a basis for the sprinkler water volume of orange tree frost protection systems (Issa, *et. al.* 2012).

In China, sprinkler irrigation for frost protection has been applied to forestry nurseries and grape vineyards with good results (Chen Hua & Ge Peizhen 2011; Lu *et al.* 2018). Chen Zhao considered the effect of water source water temperature on sprinkler intensity and modified the Barfield frost protection sprinkler intensity calculation model to arrive at a model of sprinkler intensity required for tea tree sprinkler irrigation frost protection, according to which the sprinkler system provides suitable sprinkler intensity under different meteorological conditions to avoid over or under sprinkler intensity and successfully maintains the tea field canopy temperature above -1°C during a frost night to achieve a good frost protection effect while avoiding causing water wastage (Barfield, *et al.* 1981).

2.3 Combination Frost Protection Technology

With the global warming, frost disasters are becoming more and more frequent and serious. Under the influence of heavy frost, single mechanized frost protection technology cannot provide effective protection for horticultural crops. Some scholars have proposed combination technology to deal with the poor effect of single mechanized technology, including the combination of heaters and wind machines, the combination of sprinklers and wind machines, and the combination of sprinklers and heaters.

2.3.1 Combination of Heaters and Airflow Disturbance

The combination of heaters and airflow disturbance can improve the frost protection effect. Since heaters and wind machines tend to inhale cold air near the ground at the outer edge of the reserve, placing more heaters on the outer edge will warm the inflow of cold air. It is recommended to have a heater for every two trees on the outer edge and inside of the first row of crops. In practical application， the wind machine should be started first, and if the temperature continues to drop, ignite the heater.

2.3.2 Combination of Airflow Disturbance and Sprinkler Irrigation

The combination of airflow disturbance and sprinkler irrigation has been widely used in some parts of the United States, especially in citrus orchards. When frost comes, farmers usually turn on the sprinkler irrigation first, and then turn on the wind machine when the sprinkler irrigation does not provide enough protection.

2.3.3 Combination of Sprinklers and Heaters

Combination of sprinklers and heaters is rarely mentioned. Generally, a metal baffle is installed on top of the heating furnace to protect the sprinkler irrigation from extinguishing the heating furnace. The heating furnace is generally turned on first, and then the sprinkler irrigation is turned on when the protection provided by the heating furnace is not enough.

3. Investigation on Control Combination of Airflow Disturbance and Sprinkler Irrigation

In the combination frost protection technology, most of the heaters are combustion furnaces, which are easy to cause air pollution, but now they are seldom used, wind machine and water spraying systems may also lead to the extinguishment of heating furnaces. Therefore, combination of airflow disturbance and sprinkler irrigation will become an important research direction to deal with crop frost. In this study, the combination of airflow disturbance and sprinkler irrigation is discussed and analyzed.

3.1 Composition of Combination of Airflow Disturbance and Sprinkler Irrigation

The combination frost protection system is mainly composed of wind machine and sprinkler irrigation system. The principle of combination of airflow disturbance and sprinkler irrigation is to force the high-temperature air above the plant to height through the airflow disturbance device, increase the air temperature at the plant canopy, and spray water on the plant canopy through the irrigation system. The water undergoes sensible heat exchange in the surface of crops, and the latent heat is released after the water solidifies and freezes, increasing the temperature of the surface of crops to above the critical freezing temperature and combining the heat generated by the airflow disturbance with the heat generated by the sprinkler irrigation to achieve a frost protection effect greater than the sum of the individual technology. The main disadvantage is that the frost protection strategy is not clear and can lead to water waste.

As early as 2000, Evens proposed that combination of airflow disturbance and sprinkler irrigation could achieve twice the frost protection effect, but no experimental research or analysis was conducted. It was not until 2020 that the first theoretical analysis and experimental verification of combination of airflow disturbance and sprinkler irrigation was carried out in China by Lu from Jiangsu University(Lu 2020). They constructed a tea field open path eddy covariance system and estimated the latent and sensible heat based on the atmospheric-tea tree-soil system energy transfer model using eddy covariance theory. Frost protection experiments conducted in tea fields showed that the composite frost protection technology had a significant temperature rise effect. See Figure 7 for details.

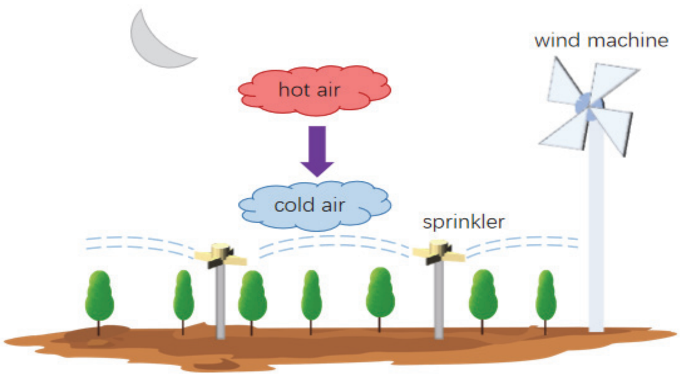

Figure 7. Schematic diagram of combination of airflow disturbance and sprinkler irrigation

A composite frost control system generally consists of wind machine and a sprinkler irrigation system. The sprinkler irrigation system is composed of nozzles, pipes, pumps, and water valves. To reduce costs, UPVC plastic pipes are usually selected for the sprinkler irrigation system. The overall design of the compound frost prevention system is shown in Figure 8.

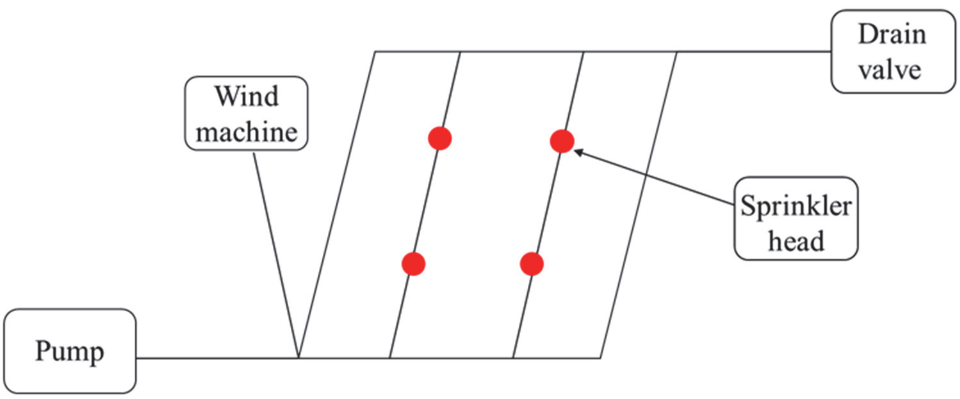

Figure 8. Overall schematic diagram of compound frost prevention system

3.2 Control Strategy for Combination Technology

When the water spray frost prevention system and the frost prevention fan are started simultaneously and the sprayed water has not frozen, the airflow disturbance will increase the evaporation of the sprayed water, thereby causing an initial temperature drop in the composite frost prevention system. Considering the shortage of water resources, the composite frost control system should prioritize reducing water resource losses. The control strategy is to first open the frost prevention fan. When the frost prevention fan cannot provide sufficient protection, the water spray system is then activated.

When the sprayed water freezes, the latent heat released by the system and the sensible heat caused by the airflow disturbance will increase the temperature of crops crown layer. When the temperature rises to 1°C, the sprayed water will no longer freeze(Lu et al. 2017, 2019). At this time, if the composite frost control system is not turned off, the airflow disturbance will increase the evaporation of the newly sprayed water, and the new sprayed water will no longer freeze and release latent heat, causing the temperature to drop again.

The start time of the composite frost control system is set to when the air temperature at the crown layer is less than or equal to 0°C. When the composite frost control system is started, the frost prevention fan is first activated. When the temperature of crops crown layer is still less than or equal to 0°C after ten minutes of starting the frost prevention fan, the water spray frost prevention system is activated. When the temperature of crops crown layer is greater than 1°C, the water spray frost prevention system and the frost prevention fan are turned off. After the airflow disturbance stops, the ice on crops crown layer can slow down the rapid temperature rise caused by the sunrise, avoiding damage to the tea caused by rapid temperature rise.

3.3 Issues of Combination Technology

In the process of combination frost protection, convective air can not only bring sensible heat, increase the air temperature of crop canopy, but also increase the evaporation of spraying water, resulting in heat loss. if the effect of water-air coupling in the process of combination frost protection can be clearly analyzed, it is possible to minimize the heat loss and maximize the frost protection effect of the combination frost protection.

4. Summary

It is obvious that mechanized frost prevention technology can protect horticultural crops from frost, but under heavy frost, single mechanized frost prevention technology cannot provide enough protection for horticultural crops. Therefore, it is necessary to study the combined frost prevention technology. Considering the protection of the environment and the loss of resources, we should consider is the combination of airflow disturbance and sprinkler irrigation first. In this study, through the comparison test of the defrosting effect of air disturbance, sprinkler irrigation and combination of airflow disturbance and sprinkler irrigation, it was found that combination frost protection can provide more protection for horticultural crops in frost night. However, in the process of combination frost protection, the interaction between irrigation and airflow disturbance is still unclear, which is the difficulty of future research. Meanwhile, the control strategy of combination frost protection is also worth paying attention to.

Acknowledgments

This research was funded by the China and Jiangsu Postdoctoral Science Foundation (2022M711396 and 2021K614C), the Natural Science Foundation of the Jiangsu Higher Education Institutions of China (21KJB210019), and the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD-2018-87), and Synergistic Extension Program of Major Agricultural Technologies in Jiangsu (2021-ZYXT-06).

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