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ORIGINAL PAPER

Influence of microclimate control on the growth of asparagus under greenhouse in tropical climates

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Abstract

High temperatures have become common in cities in Taiwan, and this phenomenon has spread to surrounding agricultural areas. Tainan, a city located in a tropical climate zone with agriculture as its primary development industry, is one of the cities considerably affected by the high temperature. High temperatures can reduce crop yields and even cause plant death, especially for vulnerable high-value crops, which are severely to microclimate conditions. Asparagus is a high-value crop that has long been cultivated in the Jiangjun District of Tainan. Recently, asparagus has been planted in greenhouses to protect against pests and natural disasters. However, the greenhouses can overheat. To identify the optimal growth environment for asparagus, this study applies vertical monitoring to record the temperature in the greenhouse and the soil moisture content of a control (canal irrigation) and an experimental (drip irrigation) group. When the surface layer of the soil exceeds 33°C, the tender stems of asparagus bloom readily, reducing its commercial value. Therefore, drip irrigation was conducted with cool water (26°C) to reduce soil temperature in summer and warm water (28°C) to increase soil temperature in winter. The study also recorded the growth of asparagus using daily yields measured by farmers during weighing and packing to understand the benefits of controlling the greenhouse microclimate. This study reports a correlation of 0.85 between asparagus yield and temperature and a correlation of 0.86 between asparagus yield and soil moisture content. The use of a drip irrigation system with a water temperature adjustment function not only saves up to 50% of water but also resulted in an average yield increase of 10% through maintaining stable soil moisture content and temperature. Therefore, the findings of this study can be applied to asparagus yields affected by high temperature and can solve the problems of poor quality in summer and low yield in winter.

Keywords Greenhouse · Asparagus · Microclimate control · Drip irrigation · Warming

Introduction

As global urbanization becomes increasingly prevalent, the urban heat island effect is increasingly prevalent worldwide. As the villages and towns around cities urbanize, their temperatures increase, which can increase the difficulty of growing local crops that have specific temperature requirements (Huang et al. 2020; Chen and Sheng 2022). Tainan, Taiwan, is one such city. It is located in the tropical climate zone and has a high potential for thermal stress (Chen et al. 2016, 2018, 2019).

Tainan has urbanized and expanded considerably in recent years. Thus, the temperature in Tainan has been increasing annually. High urban temperatures cause problems for agriculture (Alexander et al. 2017; Kabano et al. 2021) and for residents, such as thermal discomfort and poor health (Arifwidodo and Chandrasiri 2020; Aram et al. 2020).

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Much of the land in Jiangjun District, a rural township of Tainan, is used for agriculture; in particular, this district has a long history of growing asparagus. Asparagus (*Asparagus officinalis* L.) originated from the Mediterranean coast and has evolved to thrive in a cool environment (Zafiriou et al. 2012). Asparagus is planted outdoors in temperature climates. To extend the harvesting period in winter, soil heaters are used (Soode et al. 2015) or the soil is covered with a layer of pine bark (Knaflewski and Krzesiński 2002) to raise the soil temperature.

According to the Council of Agriculture of Taiwan, asparagus cultivation in Taiwan was promoted in 1965 after the mother-stalk cultural method was developed. This method involves leaving the first few stalks of the plants (mother stems) in the soil after they yellow and continuing to cultivate and harvest adjacent asparagus spears. Approximately 3,096,825 kg of asparagus is obtained per year from an area of approximately 586 ha in Taiwan (Council of Agriculture 2021). The Taiwanese government is promoting the use of sustainable, energy-saving, high-yield, and inexpensive methods of cultivation to improve the competitiveness of Taiwan's asparagus industry in the global market.

White and green asparagus are cultivated using different planting methods; Taiwan mainly produces green asparagus. Asparagus is conventionally planted outdoors. However, negative climate conditions, such as suboptimal temperatures, strong wind, and heavy rain, hinder its growth. In particular, temperatures exceeding 33°C cause the photosynthetic capacity and respiration of asparagus to decrease and increase, respectively, which directly reduce yields (Faville 1999; Bai Y and Kelly 1999). If asparagus is exposed to high temperatures for a long period, it is susceptible to growth problems, such as a decreased number of spears that are produced and an increased ratio of deformed spears. In the winter, asparagus growth slows at <15°C and stops at <5°C; asparagus plants enter dormancy after being exposed to low temperatures for 1 week. Soil moisture above 75% causes significant damage to asparagus by damaging its roots and can result in the loss of an entire harvest (Hsieh et al. 2019).

To protect it from the outdoor environment, farmers have planted asparagus in greenhouses. The most common type of greenhouse for growing asparagus is one covered with plastic film and can be manually rolled up to naturally ventilate the plants. However, greenhouses are hotter than the surrounding environment. This reduces the length of the harvest season and causes asparagus to split at the top of the spear, thus decreasing its quality and possibly rendering it unmarketable (Chen 2010; Chen and Lu 2013).

Studies have demonstrated that high temperature and low soil moisture are the two main reasons for split spears in asparagus and have observed that the asparagus spears are of higher quality when asparagus is grown at a temperature of 28–34°C with sufficient irrigation (Chen 2010; Hughes et al. 1990; Yamaguchi 2012). A study of asparagus cultivation in Tainan discovered that asparagus spears tend to split when the average temperature is higher than 30°C (Chen and Zheng 1974). Another survey on asparagus in Taiwan reported that asparagus grows between 5 and 37°C, respectively (Hsieh et al. 2017).

Studies on asparagus grown in temperate countries have primarily focused on irrigation. Brainard et al. (2018, 2019) examined three irrigation water levels—none, overhead, or subsurface drip—in the Midwestern United States and compared two asparagus breeds. Campi et al. (2019) studied the effect of irrigation amount on asparagus yield in southern Italy, which has a typical Mediterranean climate.

Several studies have focused on greenhouse environmental control. Lee et al. (2019) studied nine temperature sensors 0.9 m above the ground to monitor the effects of the microclimate in a greenhouse environment on Irwin mangoes in South Korea. Ali et al. (2019) studied balsam (*Impatiens balsamina*) in a greenhouse in France by installing temperature and humidity sensors at the top of the plants and the greenhouse canopy to detect the relationship between leaf transpiration and the regulated greenhouse environment. However, because the sensors were placed at the same height and the number of sensors was insufficient, the study could not completely monitor and record the growing conditions of the plants at different heights.

Various methods for greenhouse environment control have been proposed in the literature. For example, Ghoulem et al. (2019) discussed different means of cooling the climates of greenhouses, such as natural ventilation, mechanical ventilation, evaporation, solar drying, shading nets, water curtains, misting spray system, and cooling systems. Katsoulas et al. (2006) applied a fog system to reduce the temperature in a greenhouse to increase production. Chen and Sheng (2022) applied a near-infrared reflective diffusion coating on a simple plastic greenhouse to decrease its internal temperature.

The aforementioned studies have the following gaps.

First, studies have installed sensors at different locations at the same height or at a small height range to compare the temperature and soil moisture differences on the canopy and at the tops of the plants. However, such arrangements fail to provide measurements that elucidate the effect of varying environmental conditions at different heights as the plant growth.

Second, various environmental control techniques have been developed, and each has its own advantages and disadvantages. Many types of plants are grown in greenhouses, and they all require specific growing environments.

The current state of research regarding greenhouse microclimate control for asparagus is incomplete, and empirical data should be used to determine the optimal growth range of asparagus.

To investigate the optimal environmental control methods for growing asparagus in greenhouses, this study used a greenhouse in Jiangjun District, Tainan City, Taiwan, as a research site using the following methods. Temperature sensors were installed at different heights to monitor asparagus as it grew, and soil moisture sensors and image recording devices were also installed. The greenhouse environment data were analyzed to identify factors affecting asparagus yield. On the basis of the study's results, this study proposed environmental control strategies that increase asparagus value and yield in greenhouses in tropical climates.

Research method

Research site and procedure

The site of this study was a greenhouse with roll-up sides made of plastic film located in Jiangjun District, Tainan City, in southwestern Taiwan (23°12′39″N, 120°08′44″E). This region has a tropical monsoon climate, with an average annual temperature of 20–35°C. The average temperature during July is 33°C. The prevailing winds in summer and winter are southwest and northeast, respectively (Central Weather Bureau of Taiwan 2015).

The greenhouse was north-south oriented, 100 m long, 18 m wide, and 4.5 m high. The roof and all four sides were constructed of a metal frame covered by plastic film, and the greenhouse could be naturally ventilated by adjusting the height of the plastic film on the sides.

The research framework is illustrated in Fig. 1. Data on microclimate characteristics that affect the growth of asparagus in the greenhouse, including air temperature, soil temperature, and soil moisture content, were gathered.

Air temperature and humidity outside the greenhouse were also measured at multiple reference points. In addition, thermal imaging cameras were used to identify greenhouse hotspots, and timelapse cameras were arranged to observe the growth of the asparagus. Fisheye photographs of the asparagus were captured from where the sensors of various heights were installed to monitor the amount of solar radiation the asparagus received.

Correlation analysis was conducted from the actual measurement data and daily yield records to understand the effects of temperature and soil moisture content on the asparagus yield in the greenhouse. After a feasibility assessment of actual measurements, the study proposes a temperature-controlled drip irrigation system that connected the air-conditioning compressor to the irrigation water tank and a stable drip irrigation pipe to improve the greenhouse temperature and soil moisture level in the greenhouse; this solved the problem of high temperature splitting in the summer and low yields in the winter and improved asparagus yield and quality.

Microclimate condition measurements

In this study, data were gathered using cameras and other equipment. In the greenhouse used in this study (Fig. 2a), asparagus plants grew to 190 cm; the leaves and branches

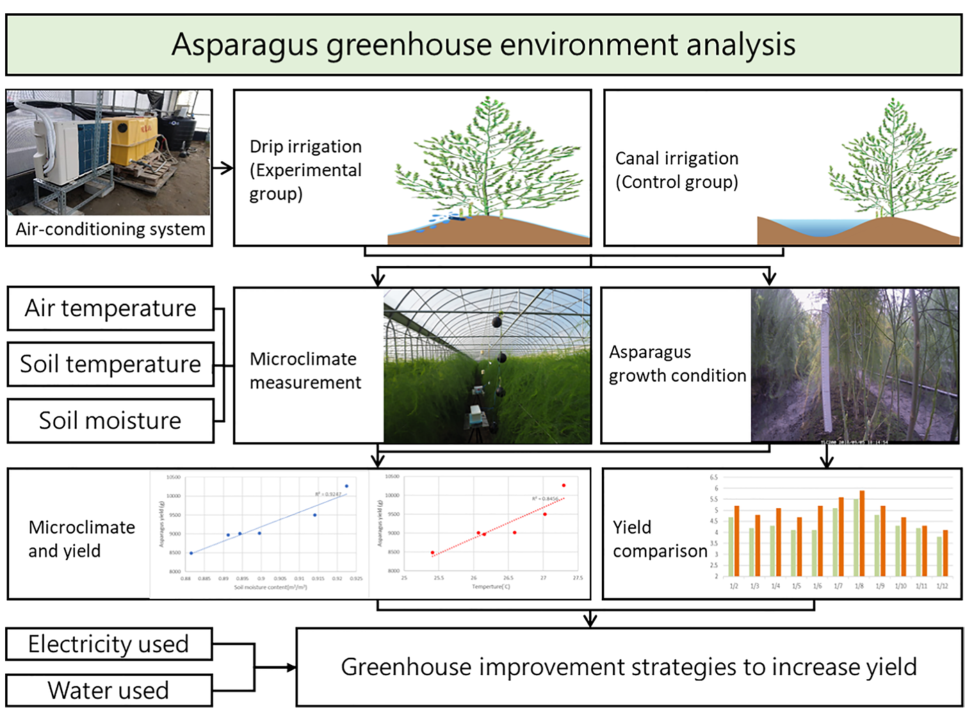
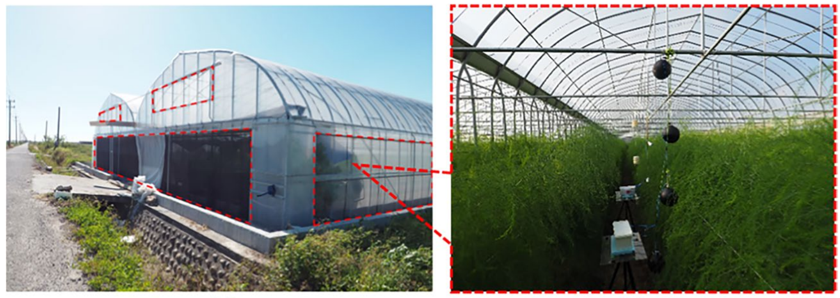


Fig. 1 Flow chart of research process



(a) (b)

Fig. 2 (**a**) External view of the asparagus greenhouse. Red lines indicate the adjustable roll-up plastic curtain. (**b**) Vertical monitoring system in the greenhouse

were the densest in the 110–150-cm regions of the plants. When the new asparagus spears grew 20–25 cm above the soil, they could be harvested. These three heights—maximum height, height of greatest density, and harvest height—are critical for asparagus growth.

First, a vertical monitoring system was installed (Fig. 2b) to record data, including asparagus growth data, at critical heights. Air temperature (Ta) was monitored using a LOGPRO TR-32 (TECPEL, Taiwan) to understand the changes in the greenhouse thermal environment at different times; the LOGPRO TR-32 has a IP67 ingress protection rating and can measure temperatures ranging from −30 to 70°C at an accuracy of ±0.5°C and a measurement resolution of 0.1°C. The real-time changes in Ta and soil temperature were monitored, and the real-time black globe temperature (Tg) was monitored and used to infer the mean radiation temperature (Tmrt) to investigate the effect of radiation on the asparagus. The soil moisture was recorded at a soil depth of 25 cm with a HOBO H21 Micro Station Data Logger (Onset Computer Corp, USA) to determine its effect on asparagus yield; the HOBO H21 has a measurement range of 0 to 0.57 m^3/m^3, accuracy of ±3.3%, and a measurement resolution of 0.08%. The system was set to record data every 10 min.

Second, this study used three TLC200 timelapse cameras (Brinno Incorporated, Taiwan) to observe the greenhouse environment and the growth of the asparagus spear. Because asparagus grows very fast, accurate image records are necessary for the optimal harvest time to be determined.

To determine whether the temperature measured by the vertical monitoring system was affected by sunshine at different heights, a fisheye camera was used to capture photographs at heights of 25, 50, 100, 150, and 200 cm, and the results were compared with those of the vertical temperature monitoring. In addition, a timelapse camera placed 30 cm above the soil was used to record asparagus spear growth at 10-min intervals.

Irrigation water temperature control method

To grow asparagus in Tainan during summer, the temperature inside the greenhouse must be cooler than it is outside the greenhouse and vice versa during winter. This study controlled soil temperature to provide better microclimate conditions for asparagus quality and yield.

In canal irrigation, the water in the low-lying area between two planting beds is channeled to avoid overwatering the roots and wasting water. In the past, the traditional method of watering asparagus was canal irrigation, but this system can substantially alter the growth environment of asparagus by destabilizing the temperature and soil moisture content.

Therefore, a drip irrigation system (the experimental group) was compared with a canal irrigation system (the control group) in this study. Drip irrigation uses a pipe with small hole to slowly and evenly penetrate the soil with water, saving water and avoiding root rot.

An air-conditioning system was also used to adjust the water temperature. The original water storage container for irrigation was connected to a compressor, which generates irrigation water at a temperature that different from the temperature of the rest of the water; it supplied cool water to the irrigation pipe in summer and warm water to the irrigation pipe in winter. A pump transferred water to the pipe of the drip irrigation system, which dripped water onto the soil through holes in the pipe.

In this study, asparagus watered with canal irrigation formed the control group. Every week, approximately 5.5 metric tons of water is used for a study area of 0.015 ha. Soil moisture content decreased from a maximum of 40 to 25% on a daily basis. The drip irrigation group used 0.4 metric tons of water once a day in a study area of 0.015 hectares, and the soil moisture level was maintained at stable level of 30 to 35% for a relatively long time.

In summer, the temperature in the greenhouse during the daytime often exceeds 35°C. This study irrigated the asparagus with cold water (26°C), which also reduced the soil and air temperatures, to reduce the incidence of asparagus spear splitting, thus increasing the quality of asparagus.

In winter, the greenhouse temperature was often lower than 15°C at night, resulting in a slow asparagus growth rate. Therefore, this study used warm water (28°C) for irrigation, which also increased the soil temperature and the temperature of the surrounding environment to a suitable range, thus enabling asparagus to be grown during winter.

Collection of yield data

To determine the optimal microclimate conditions for asparagus growth, statistical analysis was conducted on the basis of the daily asparagus yield, which was measured by the farmer when weighing and packing the asparagus and on the data measured in the greenhouse.

The correlation between daily production and microclimate conditions from April 13 to April 18, 2019, was analyzed. Each row in the greenhouse was 100 m long. To compare the effect of different microclimate conditions on asparagus growth, the greenhouse area was divided into two sections, one for the experimental group and the other for the control group.

A total of eight rows on the right side of the greenhouse, four rows for the experimental group and four rows for the control group, were used to measure microclimate and yield, and temperature and soil moisture content measurements were measured in the middle of the greenhouse at the 50-m point (Fig. 3a).

The yield data were obtained from the weight of marketable stems harvested each day. The rightmost two strips from the control group and the leftmost two strips from the experimental group of asparagus were selected for yield sampling (Fig. 3b). The two groups were separated by a 1.5-m gap with no irrigation to prevent interference.

Results

Temperature difference between height levels

This study analyzed the temperature change in the greenhouse throughout the day. Air temperature was highest at a height of 150 cm, where the leaves and branches were dense, thus hindering ventilation.

Figure 4 presents the temperature at different heights in a day. The change in soil temperature was smaller than that in air temperature because the branches and leaves of the asparagus provide adequate shelter, thus preventing solar radiation from directly impacting the soil.

Therefore, the soil temperature is lower during the day than the air temperature. However, the soil temperature absorbs radiant heat during the day and releases heat into the air at night when the temperature is low, but because of the relatively high humidity of the environment, the air is not conducive to evaporative cooling of the potential heat into the air. Also, because of the close spacing of asparagus leaves and dense branches, the effect of nighttime sensible heat emission from the soil was reduced due to the low ventilation. The results of the onsite measurement and camera monitoring are detailed as follows.

The spear of asparagus can tolerate temperatures of up to 33°C in Taiwan (Chen et al. 2007). Figure 4 presents the data measured on August 2, 2018. The air temperature in the greenhouse increased to 33°C by 10:00, and the soil temperature increased to 33°C by 12:00; this temperature remained constant until 17:00. This finding indicated the necessity of reducing the greenhouse temperature because it was above the optimal temperature for asparagus growth.

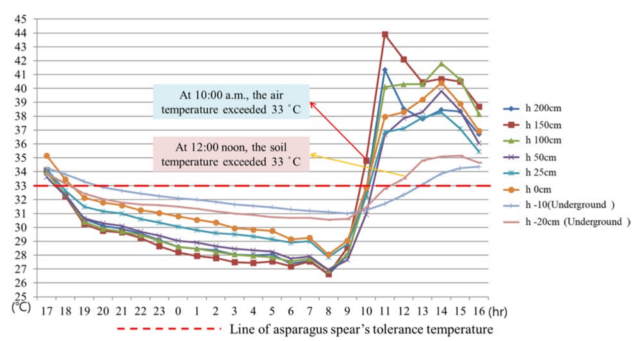
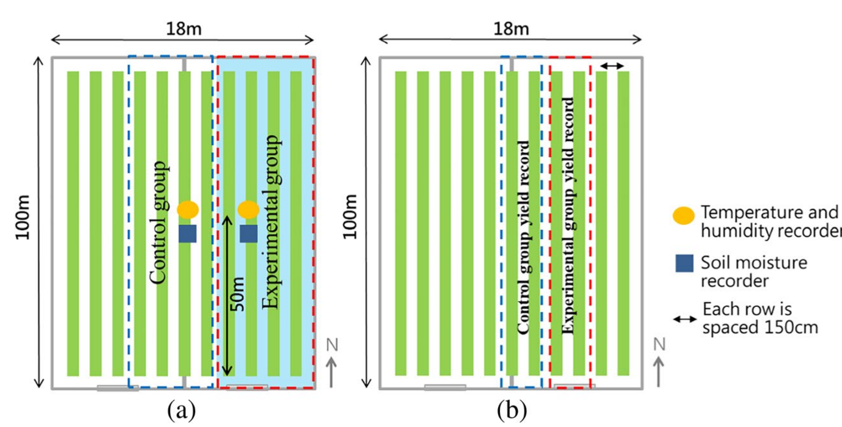


Fig. 4 Changes of air and soil temperature at different height above or underground during experiment. The data were collect from August 1 to August 2, 2018

Fig. 3 **a** Area whose asparagus yield was recorded. **b** Areas whose microclimate conditions were recorded in different drip irrigation system



Thermal characteristics at different periods

A thermal imaging camera was used to detect the heat source and verify the measured value of soil temperature to indicate that the environment in the greenhouse will be unfavorable for asparagus growth and must be improved through the microclimate system of the greenhouse. Figure 5 depicts the presence of two hot spots in the greenhouse at different times: one located in the roof and one located where the soil reaches up to 25 cm above the ground. The heat of the roof is caused by it being the highest point and being made of transparent plastic; it thus receives direct sunlight, which increases the temperature of the area.

The other hot spot is at the high point of the soil, because the distance between asparagus plants is only 20–25cm; leaves thus block the soil from radiating and convecting heat, which increases the temperature in this area. Previous studies have shown that soil temperature affects the quality and price of asparagus because the asparagus spear tends to split when the temperature around the soil exceeds 30°C.

Threats to asparagus growth

Figure 6a reveals that during summer, the daytime temperature in the greenhouse exceeded 30°C for 75% of the time. The maximum temperature 45°C was recorded at a height of 110 cm (h110) and 190 cm (h190), where branches and leaves were dense. The average daytime temperature was highest at h110 because the direct sunlight heated the area, and the leaves and branches reflected the long-wave radiation and hindered ventilation.

During the day, the ground surface was heated by solar radiation. Thermal energy trapped in the greenhouse was transferred into the soil, thereby mitigating the increase in temperature at the surface soil. During the nighttime, the surface cooled, and thermal energy in deeper soil was gradually released, thus mitigating the ground soil temperature reduction and reducing the range of soil temperature variance throughout the day.

In summer during the night, the soil temperature (h-10) averaged 30°C; however, the temperature remained higher than 30°C for 50% of the time, making it unsuitable for the

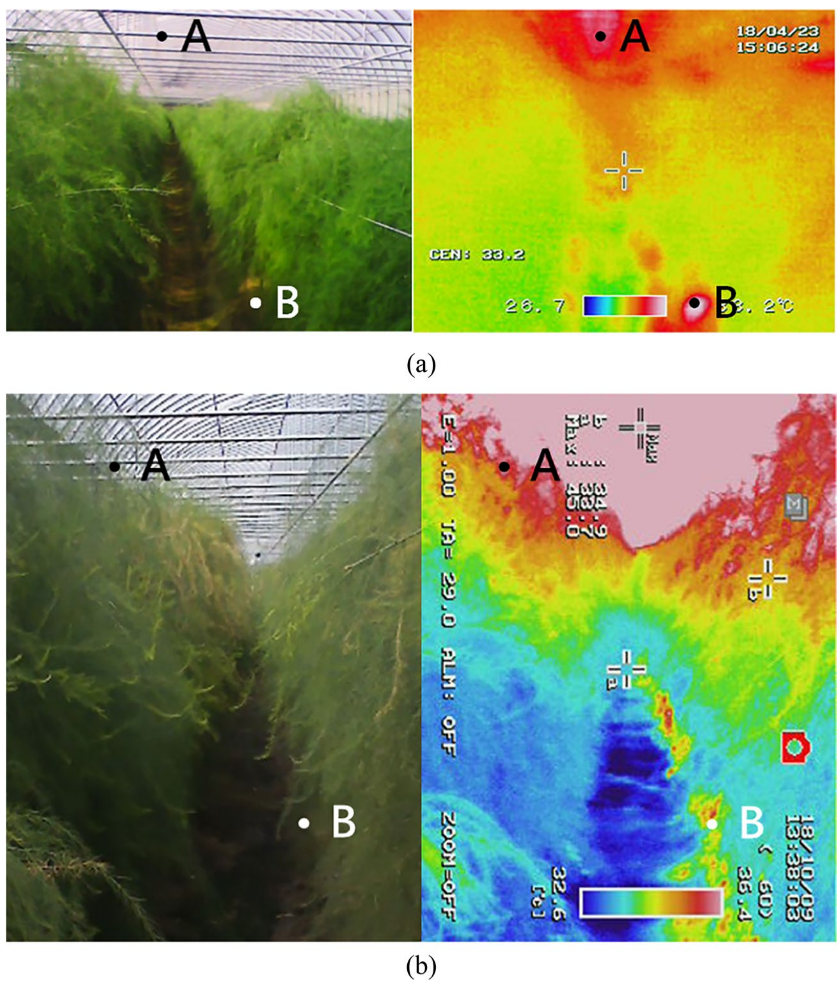


Fig. 5 Thermal image captured on **a** 2018/4/23 and **b** 2018/10/09 inside the greenhouse. Hotspots are at the greenhouse roof (point A) and the soil (point B) in different time

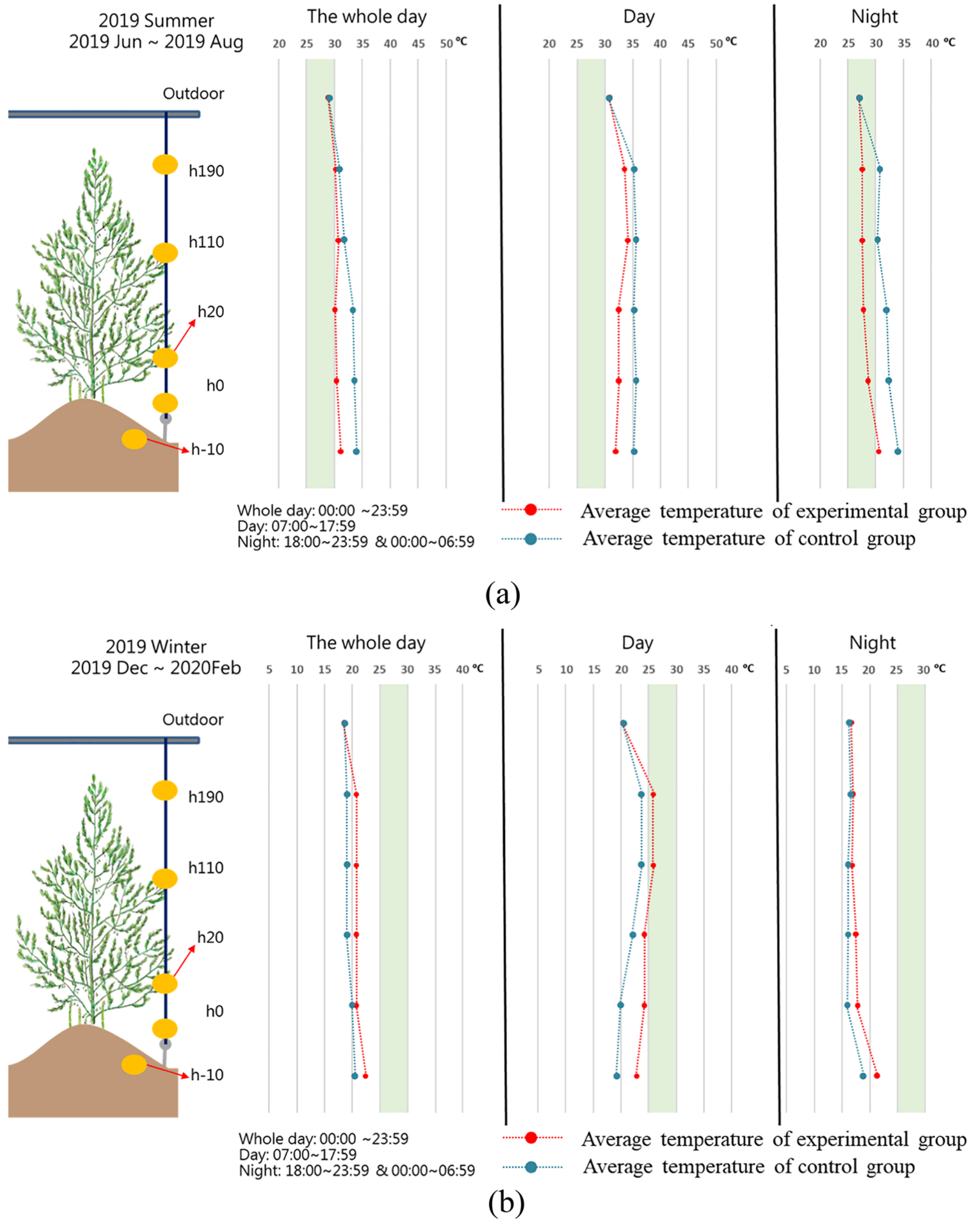


Fig. 6 Temperature distribution plots: **a** 2019 summer, **b** 2019 winter. Leftmost column shows a schematic of the measurement of asparagus

growth of asparagus spears. Taiwan's high summer temperature harm asparagus quality.

When the greenhouse temperature was approximately 35°C, the surface temperature of soil was reduced to approximately 30°C by using drip irrigation with an air-conditioning system, and the temperature was 4°C lower than that of the canal irrigation method.

As indicated in Fig. 6b, the whole day temperature was 25°C or lower for 75% of the time during winter. During the day, the soil temperature was also 25°C or lower for more than 75% of the time. This low-temperature environment slows asparagus growth, resulting in reduced yield. The increase in soil temperature can improve the yield of winter asparagus.

In Fig. 6, the green ranges represent 25°C–30°C, which is suitable for asparagus growth. The red and blue dots represent the average temperature measured at different heights in the experimental and control groups.

Effect of shading on growth

This study compared the result of fisheye images and vertical monitoring temperatures. The sky view factor (SVF) is used to quantify the percentage of shading; a higher SVF indicates less shading. Figure 7 indicates that the measurement points at lower heights were more covered by shade than higher points were. The temperature was lower at a height of 50 cm or lower, where more cover was present. By contrast, at heights

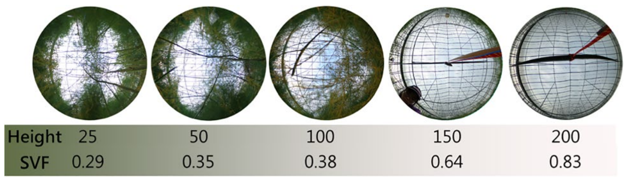


Fig. 7 Fisheye images of asparagus growth at heights of 25 cm (h25) to 200 cm (h200) and the corresponding SVF

of 100 cm or higher, the temperature was also higher because more solar radiation was stronger here. The measured black globe temperature was incorporated into the ISO7726 equation to estimate the average Tmrt (ISO 7726, 2002).

The black globe temperature was highest at the height of 100 cm. The temperature at 100 cm was higher than at 200 cm, where the most direct sunlight was received, because the black globe absorbed both the heat retained by the leaves and branches and the long-wave radiation reflected from the asparagus leaves and branches after the receiving of sunlight. The temperatures indicated in the black globe and fisheye images were consistent with each other. The 100-cm image was more covered by dense leaves and branches than the 200 cm fisheye image was.

Comparison of yield

After the temperature-controlled drip irrigation equipment was installed to improve the greenhouse environment, this study compared the yields of the experimental group which the drip irrigation system was used and the control group where conventional canal irrigation was used (Fig. 8).

Figure 8 also depicts the comparison between the soil moisture levels of the experimental and control groups on different days. The soil moisture level of the experimental group was more stable than that of the control group. Conversely, the control group exhibited high moisture content on the first irrigation day; this moisture content gradually decreased each day, resulting in a significant variation in moisture content from the first day on. The standard deviations of moisture content in the experimental and control groups differed significantly (0.01 and 0.05, respectively), and the standard errors also have a noticeable difference (0.003 and 0.01, respectively).

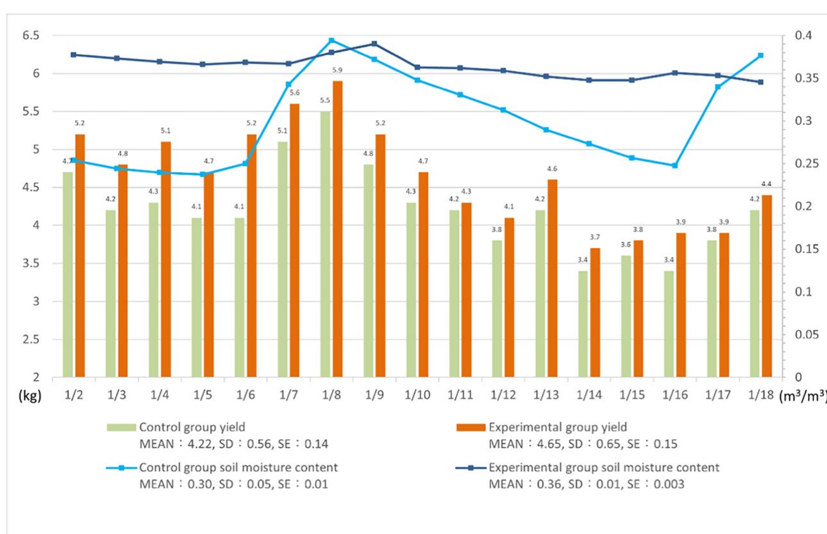
Therefore, the soil moisture content of the experimental group could be maintained at a more stable level for a longer period of time than that of the control group, which exhibited significant variation in soil moisture content. Therefore, the experimental group (average asparagus yield of 4.65 kg in 0.03 ha) had an average yield that was 10% higher than that of the control group (average asparagus yield 4.22 kg in 0.03 ha).

Microclimate factors affecting yield

This study also measured the microclimate environment in the asparagus greenhouse from April 13 to April 18, 2019, and the yield on the next day and was used to analyze the correlation between microclimate and yield. The asparagus yield was highest with 10,265g; the mean temperature and mean soil moisture were 27.3°C and 0.348 m^3/m^3, respectively.

The average soil moisture content and temperature also significantly influenced the yield with drip irrigation system; Fig. 9a shows the soil moisture content provides asparagus with the required water between 0.34 and 0.38 (m^3/m^3), and the lower the soil moisture content, the higher the asparagus yield trend. Figure 9b shows the asparagus yield increases when the soil temperature is closer to 28°C. These observations suggest that soil moisture content and temperature are strongly correlated with asparagus yield, with correlation coefficients of 0.86 and 0.85, respectively.

Fig. 8 Yield and soil moisture in the experimental (drip irrigation) and control (canal irrigation) groups



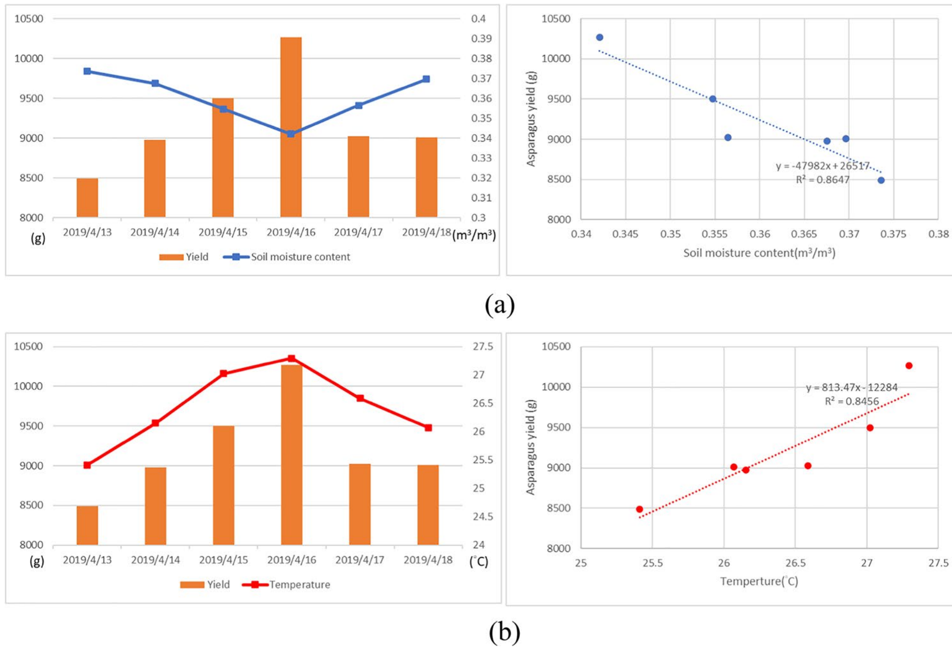


Fig. 9 **a** Mean soil moisture content(m^3/m^3) and yield, **b** mean temperature (°C) and yield

Discussion and suggestions

Benefits and limitations of drip irrigation

The energy costs of operating crop systems can be reduced with microclimate control and energy-efficient strategies (Rabbi et al. 2019). The drip irrigation method has higher yields and lower energy and labor costs than other methods that aim to improve the crop growing environment in greenhouses, such as the use of different watering methods (Yuan et al. 2004; Hooshmand et al. 2019), different floating row covers (Kalisz et al. 2018; López-Martínez et al. 2021), and different soil types (Demir 2019; Rayburn and Basden 2022). Drip irrigation is even more viable and beneficial in regions where water is scarce (Suresh 2016). This study demonstrates that drip irrigation has many benefits in asparagus greenhouse cultivation and can replace traditional canal irrigation. Drip irrigation has the following advantages:

1. The temperature and amount of water used can be controlled, allowing for easier adjustment of greenhouse environment to match the optimal microclimate growing conditions for asparagus.
2. It produces less mud than does canal irrigation, thus facilitating field operations and improving the efficiency of harvesting green asparagus.
3. Asparagus cultivation with a drip irrigation system uses less than 50% of the water canal irrigation uses.

The cost of water temperature control is also low; running the system for 8 h per day only consumes 16 kWh, which only costs approximately NT$25.6 per day at the basic agricultural electricity rate of NT$1.63 per kWh..

Although the materials to set up the system are easy and affordable and the cost of water is low, the drip irrigation system still has several limitations. For example, pipe must be manually installed, and farmers may need to check for problems such as leaks, clogged pipes, or broken pipes to maintain the system.

Microclimate condition improvement plan

Conventional methods for reducing the temperature in a greenhouse are using a water curtain combined with a negative-pressure fan and air-conditioning equipment. However, in asparagus greenhouses, these methods are expensive, and the results are less favorable than those that direct reduce the soil temperature.

The greenhouse air temperature in this study increased to 33°C by 10:00, which hindered the growth of asparagus. Subsequently, the soil temperature rose to 33°C and remained at that temperature until 17:00. By keeping the soil temperature low, as opposed to cooling it down after the temperature increases, the greenhouse environment can be effectively controlled. A drip irrigation system is proposed as an optimal method for farmers to improve the conditions of their greenhouse microclimate.

In addition, an air-conditioning system was used to cool or warm water before the water was irrigated to the soil through a drip irrigation system. In summer, relatively cold water (26°C) was suggested for drip irrigation, whereas in winter, relatively warm water (28°C) was recommended.

Through the use of a drip irrigation system, soil temperature and the temperature in the lower part of the greenhouse were maintained at 25–30°C, which is suitable for asparagus cultivation. This environmental control method consumed little electricity and substantially increased the quality and yield of asparagus by solving the problems of split spears in summer and low yields in winter.

This study investigates the effects of different irrigation methods and the implementation of a water temperature control system on asparagus production at relatively small time scales. In future studies, long-term monitoring data should be gathered to determine the optimal microclimate conditions for asparagus growth.

Conclusions

This study recorded data from August 2018 to January 2020. Equipment-based monitoring and camera-based monitoring were used to improve the conditions of a greenhouse microclimate to improve asparagus yield. The following key findings were obtained.

First, a vertical monitoring system was used to observe the environmental change in greenhouses. The temperature was highest at 100 cm above the ground. The branches and leaves were denser at this position, resulting in increased temperature from poor ventilation and heat retention. The soil temperature was high because of direct sunlight. The asparagus spears grew from under the soil to 25 cm above the ground; thus, the temperature and environment near the soil were crucial.

Second, 25–30°C is a suitable temperature range for asparagus growth. In summer, the daytime temperature in greenhouse exceeded 30°C for 75% of the time and the nighttime temperature exceeded 30°C for approximately 50% of the time, underscoring the need for summer cooling. In winter, temperatures were below 25°C for 75% of the time, even during the daytime with solar radiation.

Therefore, a temperature-controlled drip irrigation system was adopted to improve the conditions of the greenhouse microclimate. In summer, cool water (26°C) was used for drip irrigation to reduce the soil temperature. In winter, warm water (28°C) was used for drip irrigation to increase the soil temperature.

Consequently, the soil temperature and the temperature at the lower part of the greenhouse were maintained at 25–30°C, which is suitable for asparagus growth. And from the measurement data, drip irrigation could maintain a stable soil moisture content level for extended periods with a standard deviation of 0.01 for the daily average soil moisture content during the measurement period. At the same time, the canal irrigation method with a standard deviation of 0.05 would cause the soil moisture level to decrease significantly every day after irrigation. This study demonstrated that drip irrigation can provide better thermal conditions and soil moisture content condition than canal irrigation can, resulting in an asparagus yield 10% higher than that of canal irrigation. Additionally, drip irrigation requires 50% less water than conventional canal irrigation.

After comprehensive measurement and camera monitoring were obtained, temperature-controlled drip irrigation was adopted to improve greenhouse soil and air temperatures. In summer, drip irrigation was performed using cold water to reduce the soil and indoor temperature, whereas, in winter, drip irrigation was performed using warm water to increase the temperature. The greenhouse environment was controlled to produce suitable condition for asparagus growth, thus increasing the yield, quality, and profitability of asparagus.

This method featured low installation cost, electricity reduction, and water reduction, thus improving returns for farmers. And can be applied to other crops, such as tomatoes, cantaloupes, strawberries, and lettuce. The environmental control method in this study can be to adjust the environment of the greenhouse to the optimal conditions for the growth of the target crop.

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Data Availability Data are available on request to the authors.

Declarations

Conflicts of interest The authors declare no competing interests.

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