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Plant Density and Vertical Trellis Configuration Affect Cucumber Pollination Efficiency and Marketable Yield

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Abstract In current cucumber cultivation, how to arrange the appropriate planting density and trellis configuration is of great significance for improving pollination effect and yield. This study collated the latest research on the relationship between cucumber planting space and flowering and fruiting, analyzed the impact of vertical trellis configuration at different densities on flower visibility, pollinating insect activity and fruiting conditions, and discussed how to balance leaf growth and fruit output through planting management to improve cucumber quality. This study hopes to provide practical suggestions for cucumber cultivation, helping farmers grow more and better cucumbers, and also protecting the ecological environment.
Keywords Cucumber cultivation; Plant density; Vertical trellis configuration; Pollination efficiency; Marketable yield

1 Introduction

Cucumber (*Cucumis sativus* L.) is a common vegetable worldwide with a large planting area. Whether eaten fresh or processed, the market demand is very high (Sharma et al., 2020; Kaur and Sharma, 2021). It has brought considerable income to farmers and agricultural enterprises. The output and quality of cucumbers directly affect the income of farmers and the supply capacity of the market. Therefore, improving the planting methods of cucumbers is very important for enhancing agricultural benefits (Shah et al., 2015; Tscharntke et al., 2015).

Cucumbers are monoecious and need to be pollinated by insects and other means to produce good fruits. Research has found that the quality of pollination directly affects the yield and fruit quality of cucumbers. When the pollination efficiency is high, there are more and heavier fruits, more ideal fruit growth and seed number, and better appearance and nutrition (Shah et al., 2015; Chauhan and Singh, 2022; Kika et al., 2022; Kariuki et al., 2023; Patel and Pastagia, 2023). If pollination is insufficient, even if fertilizers and pesticides are used, it is difficult to make up for the loss of yield (Tscharntke et al., 2015). Therefore, improving pollination efficiency is the key to achieving high yields, good quality and good sales of cucumbers.

This study mainly investigated the effects of different planting densities and trellving methods (vertical trellis) on cucumber pollination and yield, and analyzed how planting densities and trellving methods affect the activities of pollinating insects, the accessibility of flowers, and the final fruit quantity. This study aims to provide a basis for more scientific cultivation methods of cucumbers, help farmers improve pollination efficiency, and also increase the yield and quality of cucumbers.

2 Cucumber Floral Biology and Pollination Requirements

2.1 Flower morphology and reproductive structures

Cucumber (*Cucumis sativus*) is mostly an annual vine plant. Its flowers are unisexual, that is to say, there will be both male and female flowers on one plant. Some varieties may have all female flowers or bisexual flowers (Kaur et al., 2021). Male flowers are used to produce pollen, and female flowers have ovaries that can develop into fruits. Flowers usually bloom between 6 a.m. and 8 a.m. At this time, the pollen vitality of male flowers is the strongest, and the stigma fertilization ability of female flowers is also the best (Kaur et al., 2021). The proportion of female flowers varies among different varieties, and the nutrient conditions in the soil can affect the number of female flowers (Li et al., 2021).

2.2 Pollination mechanisms in cucumbers

The pollination of cucumbers is mainly accomplished by bees and wild bees (Lowenstein et al., 2015). They carry pollen from the male flowers to the stigma of the female flowers. Then the pollen begins to germinate, the pollen tube grows downward, and finally fertilization is completed. The quantity and vitality of pollen, as well as the fertilization ability of the stigma, are the keys to successful pollination (Kaur et al., 2021). At the molecular level, some enzymes, such as CsCWIN3, can regulate sugar supply and have an impact on pollen development, pollen tube growth and seed formation (Figure 1) (Fan et al., 2024). Moreover, soil nutrients can affect the quantity and composition of pollen and nectar, thereby influencing the number of visits by pollinators and the pollination effect (Li et al., 2021; Patch et al., 2022).

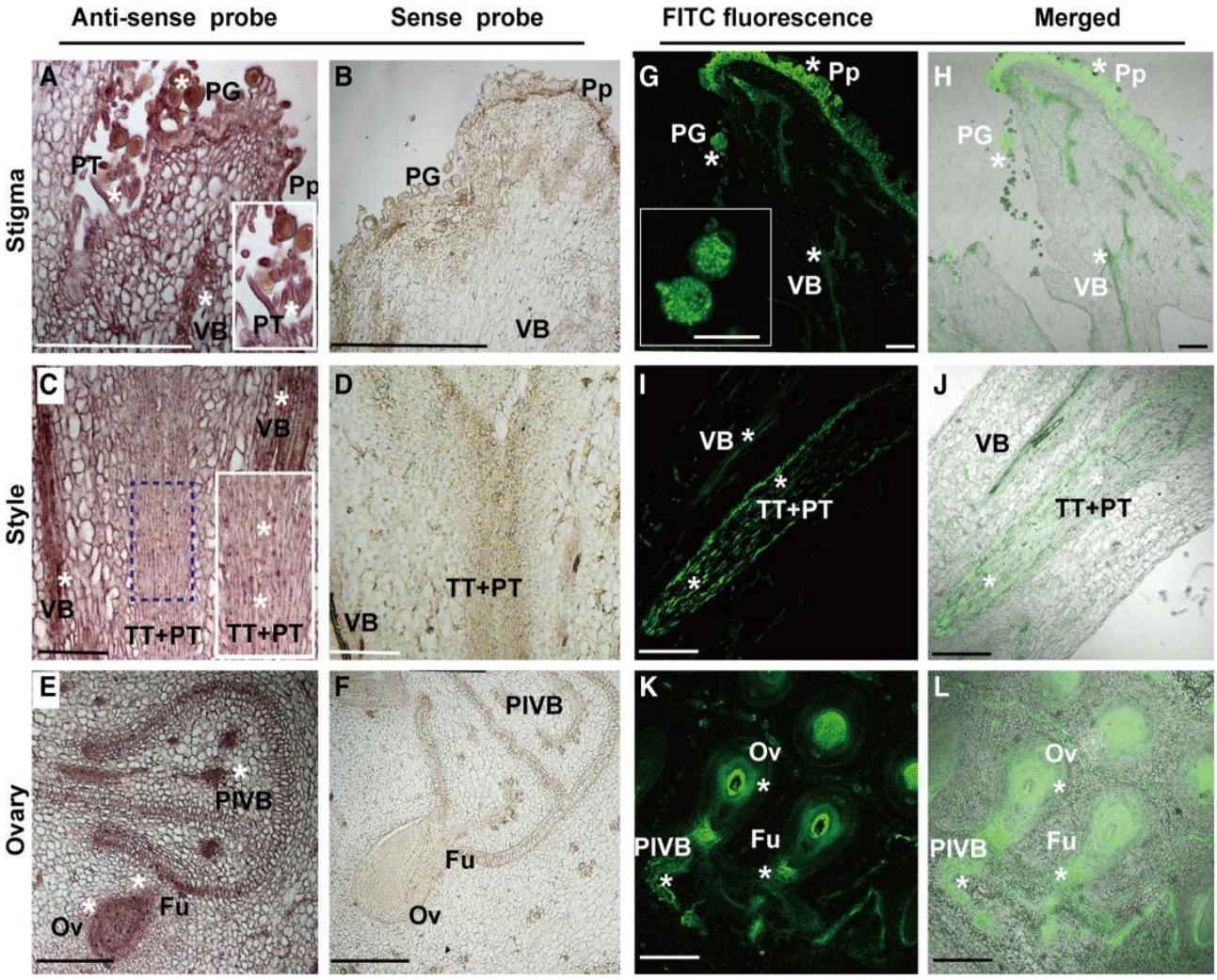

Figure 1 Expression of *CsCWIN3* and localization of its protein in pollinated stigma and fertilized ovules in WT cucumber (Adopted from Fan et al., 2024)

Image caption: A to F) In situ hybridization of *CsCWIN3* in pollinated stigma and fertilized ovule. *CsCWIN3* was expressed in PG, PT, Pp, VB, TT, PlVB, Fu, and Ov A, C, E). Asterisks indicate positive signal. B, D, F) Negative control for in situ hybridization using *CsCWIN3* sense probe in the pollinated stigma B), style D), and the fertilized ovary/ovule F). G to L) Fluorescence immunolocalization of CsCWIN3 protein in pollinated stigma and fertilized ovule. CsCWIN3 was located in PG, PT, Pp, VB, TT, PlVB, Fu, and Ov. Asterisks highlight the protein signals. The secondary antibody was fluorescein isothiocyanate (FITC)-labeled anti-rabbit IgG. The green color indicates fluorescence from FITC. G, I, K) Green fluorescence-field image in the pollinated stigma G), style I), and the fertilized ovary/ovule K), respectively. H, J, L) Merged images of green fluorescence- and bright-field in the pollinated stigma H), style J), and the fertilized ovary/ovule L), respectively. The boxed insets in A), C), and G) were the close-up images, showing the signals in the germinated PG A, G) and the pollinated TT tissue C). Scale bars: 200 μm. Fu, funiculus; Ov, ovule; PG, pollen grain; PlVB, placenta vascular bundle; Pp, papillae cell; PT, pollen tube; TT, transmitting tract; VB, vascular bundle (Adopted from Fan et al., 2024)

2.3 Role of pollinators and environmental influences

Bees (such as *Apis mellifera*) and some wild sweat bees (*Lasioglossum* spp.) are the main pollinators of cucumbers. The more types and quantities of pollinators there are, the higher the yields of fruits and seeds will be (Lowenstein et al., 2015; Hall et al., 2022). Whether these pollinators frequently visit the flowers is influenced by "rewards" such as nectar and pollen as well as environmental conditions. If the ratio of nitrogen to phosphorus in the soil is inappropriate, fewer flowers will bloom, the rewards will be less, the attractiveness of pollinators will decline, and the yield will also decrease accordingly (Patch et al., 2022). In addition, pests such as cucumber beetles can interfere with pollination, reduce the stay time of bees, and thereby affect pollination efficiency and fruit quantity (Kaplan and Leach, 2024). Even in urban or greenhouse cultivation environments, wild bees and honeybees remain the main pollinators, while some thornless bees offer relatively limited assistance for cucumber pollination (Hall et al., 2022).

3 Plant Density Strategies in Cucumber Cultivation

3.1 Definitions and categories of planting density

Planting density refers to the number of cucumber plants per square meter, which is an important factor affecting whether cucumbers grow well, have a high yield and good quality. Generally speaking, density can be classified into low density (such as 2.25 plants /m²), medium density (3.0 plants /m²) and high density (3.75 plants /m²) (Ayala-Tafoya et al., 2019; Ding et al., 2022; Babatunde et al., 2023) Under different planting methods, such as greenhouse, open-air, hydroponics or hydroponics, the selection of density should also be adjusted according to the characteristics of the variety (Ayala-Tafoya et al., 2019; Ding et al., 2022; Babatunde et al., 2023)

3.2 Effects on canopy architecture and microclimate

Whether cucumbers are planted densely or not will directly affect the leaf structure and microclimate conditions of cucumbers. When the density is high, the competition among plants is fierce. The leaves grow densely and overlap a lot. Light cannot enter, and the lower leaves are not easy to carry out photosynthesis (Ayala-Tafoya et al., 2019). When the density is a little lower, sunlight can reach more evenly, leaves can absorb light better, and dry matter accumulates more (Ding et al., 2022). Planting too densely will also affect the temperature, humidity and carbon dioxide distribution in the greenhouse, thereby influencing the growth and yield of cucumbers (Shen and Tao, 2024; Guo et al., 2025). If the density is appropriate, not only will the ventilation be better, but also the occurrence of diseases can be reduced.

3.3 Impact on flower distribution and access to pollinators

Planting density also affects the position of flowers and the activities of pollinators, such as bees. When the density is too high, the flowers are mostly concentrated in the upper layer and block each other, making it difficult for pollinating insects to find the flowers and the access efficiency will also decrease (Tscharntke et al., 2015). If the density is appropriately reduced, the flower distribution will be more uniform, the activity space of bees will be larger, the number of visits to flowers will increase, and the pollination efficiency and fruit setting rate can be improved. Studies have also found that the quantity and distribution of flowers directly affect the number and activity level of pollinating insects, ultimately influencing the yield and fruit commercialization rate of cucumbers (Tscharntke et al., 2015; Stein et al., 2020).

4 Vertical Trellis Systems: Structures and Agronomic Roles

4.1 Common trellis configurations in protected and open fields

In cucumber cultivation, common vertical trellis methods include high rope type, umbrella type, modified umbrella type, inclined plane type, T type and inverted Y type, etc. These structures can be used in greenhouse and open-field cultivation (Berghage et al., 2024; Jamil et al., 2023). Among them, the high-rope system is the most common in greenhouse hydroponics. It not only facilitates the management of cucumber plants but also makes fruit picking convenient (Berghage et al., 2024). These trellis can not only support cucumbers to grow upwards, but also cooperate with the irrigation and fertilization systems to improve the overall planting efficiency (Jamil et al., 2023).

4.2 Influence on light penetration, air circulation, and flower exposure

Vertical trellis can enable plants to be better distributed in space, greatly improving the light and air circulation inside the canopy, facilitating photosynthesis in leaves and allowing more flowers to be seen. Systems like the high-rope system can make the light distribution more uniform, reduce leaf overlap, enable the bottom leaves to absorb sunlight well, and improve photosynthetic efficiency (Berghage et al., 2024). Good air circulation can also reduce diseases. Meanwhile, flowers are more exposed and easier to be found by pollinating insects, improving the pollination rate and fruiting rate (Tscharntke et al., 2015).

4.3 Benefits in mechanization, disease management, and labor efficiency

The use of vertical trellis can also facilitate mechanized operations more conveniently. For example, harvesting and plant management are also more convenient (Jamil et al., 2023). Because the plants do not have direct contact with the ground, the fruits are less likely to rot and there are fewer soil-borne diseases. Moreover, using trellis can also make it more convenient to spray pesticides and inspect pests and diseases, improving the control effect. Overall, allowing cucumbers to grow vertically not only makes tasks such as picking and pruning easier, but also reduces labor input and improves labor efficiency (Berghage et al., 2024).

5 Interactions Between Plant Density and Vertical Trellis Configuration

5.1 Synergistic or antagonistic effects on pollination conditions

The combination of plant density and vertical trellis will jointly affect the pollination of cucumbers, which may produce a synergistic effect or may cancel each other out. If the density is a little lower, not only can the flowering amount of each cucumber plant be increased, but also the quality of the fruit can be improved, and the overall yield will not decrease too much (Ding et al., 2022). Vertical trellis such as elevated or umbrelle-shaped ones can improve the ventilation and lighting of plants, reduce the occurrence of diseases, and also create a better environment for pollinating insects. When the density is moderate and the trelli design is reasonable, it can make the flowers easier to be seen and provide a larger space for insects to move, thereby improving the pollination efficiency and fruit uniformity (Ding et al., 2022).

5.2 Optimization of floral visibility and pollinator pathways

Vertical trellis can also make flowers more conspicuous and make it easier for pollinating insects to find and pollinate them. Low-density planting reduces the overlap between leaves, allowing the exposed area of flowers to be larger and facilitating the free flight of insects (Ding et al., 2022). The elevated planting method not only makes harvesting more convenient, but also optimizes the plant structure, increases the movement efficiency of pollinators among plants, and improves the pollination success rate. Therefore, a reasonable combination of density and frame type is conducive to optimizing the pollination route and the accessibility of flowers.

5.3 Influence on yield components and quality parameters

The combination of density and trellis also affects the yield structure and fruit quality of cucumbers. When the density is low, each plant bears more fruits and has better quality, such as higher contents of sugar, vitamin C and flavonoids (Ding et al., 2022). While too high density can increase the yield per square meter, it may lead to smaller fruits and decreased quality (Ayala-Tafoya et al., 2019). Vertical trellis can also make the fruit color more uniform, the grade higher, reduce diseases and fruit damage, and increase the proportion of commercial fruits. Meanwhile, the appropriate combination of density and trellis type can also increase the market rate of fruits and the overall economic benefits (Babatunde et al., 2023)

6 Effects on Pollination Efficiency

6.1 Floral accessibility and spatial arrangement

How densely the plants are planted and how the trellis are set up directly affect whether pollinating insects can reach the flowers smoothly. When planted not too densely, the air circulation and light conditions among the plants are better, and the flowers are easier to be seen and approached. This is very friendly to pollinating insects such as bees and can improve the pollination efficiency (Ding et al., 2022). Planting with vertical trellis, such as raising the plants and distributing the flowers more widely, not only reduces mutual occlusion but also makes it easier for insects to fly onto the flowers, thereby increasing the success rate of pollination. In addition, if the

flowers can be distributed more reasonably in space, the number of flowers per unit area can also be increased, attracting more pollinators to visit and further enhancing the overall pollination opportunity (Tscharntke et al., 2015).

6.2 Pollinator behavior in high vs. low density settings

When planted too densely, the plants will crowd together and the leaves are prone to blocking the flowers, which makes it more difficult for pollinating insects such as bees to find the flowers and affects their visit frequency and pollination efficiency (Ayala-Tafoya et al., 2019; Ding et al., 2022). On the contrary, if they are planted more sparsely, not only will the yield and fruit quality of each plant increase, but bees will also be more likely to approach each plant and have a higher visit frequency (Ding et al., 2022). Some studies have also found that when there are more flowers blooming, the number of visiting bees will also increase. In this way, the pollination effect is better and the yield will also increase (Tscharntke et al., 2015). Therefore, appropriately reducing the planting density is conducive to the activity of pollinating insects and can also improve the pollination efficiency.

6.3 Pollination success rates under different trellis designs

The design of the trellis frame will also affect the pollination effect. Compared with ground planting, the use of vertical trellis can double the yield, and the fruit quality is also better and the grade is higher. Although high-wire trellis can ensure stable yields, modified umbrella trellis have more advantages in increasing the number and weight of fruits per plant. This is because different brackets will change the light distribution and the position of the flowers. Some designs can make the flowers easier to be seen and approached. Overall, vertical trellis can make the plant structure more reasonable and the flowers more exposed, thereby improving the pollination effect and the yield of commercial fruits (Berghage et al., 2024).

7 Effects on Marketable Yield and Fruit Quality

7.1 Impact on fruit set, size, and uniformity

The planting density and the way of trellis will affect the fruit setting of cucumbers, the size of the fruits and whether the fruits are uniform. Planting them sparsely, for example, 2.25 plants per square meter, can enable each cucumber plant to bear more fruits. Meanwhile, the nutrients such as sugar and vitamin C in the fruits will also be higher, and the overall yield will not decrease (Haque and Sakimin, 2022; Ding et al., 2022). Although planting denser can increase the total output of each plot, the weight and size of each cucumber may decrease, and the uniformity of the fruit may also decline (Knerr et al., 1992; Haque and Sakimin, 2022). In terms of the trellis, the number of fruits and fruit weight per plant under the modified umbrella trellis were higher than those under the high-line trellis. However, the yield of the high-line trellis was relatively stable (Berghage et al., 2024). In addition, if combined with pruning and appropriate density arrangement, it can also make the yield and fruit grading more reasonable (Ayala-Tafoya et al., 2019).

7.2 Effects on fruit shape, skin quality, and shelf life

A thinner density can not only enhance the nutrition of the fruit, but also make the fruit shape better, the skin flatter, and reduce nitrite (Ding et al., 2022). Growing cucumbers on trellis can also make the fruits more uniform in size and color, less likely to have deformed fruits, and can also reduce pests and diseases, making the fruits easier to sell. Cucumbers with good peels and few diseases are more durable and can be sold for several more days. However, if they are planted too densely, the fruits will be small, irregular in shape and not in good condition (Knerr et al., 1992; Haque and Sakimin, 2022).

7.3 Economic evaluation of density and trellis combinations

The economic benefits of cucumbers are also affected by planting density, type of trellis and planting input. Although the yield is higher when the density is high, due to the increased input of seeds, fertilizers, etc., the profit may not be as much instead. Some studies suggest that planting moderately, such as 220 000 to 245 000 plants per hectare, yields the highest returns (Knerr et al., 1992; Ngouajio et al., 2006). Trellis planting can increase the proportion of commercial fruits and harvest efficiency of cucumbers, reduce disease losses, and thus achieve higher economic benefits. Coupled with auxiliary technologies such as carbon dioxide fertilization, both yield and efficiency can be increased simultaneously (Guo et al., 2025).

8 Case Study: Optimizing Plant Density and Trellis Configuration in Greenhouse Cucumber Production

8.1 Experimental setup: treatments and design

This case is centered around growing cucumbers in greenhouses. The study sets different planting densities, such as 2.25, 3.0 and 3.75 cucumber plants per square meter, as well as different trellis methods, including high rope trellis, high umbrella type and modified umbrella type, etc. (Figure 2) (Ding et al., 2022; Berghage et al., 2024). Some experiments also added different pruning methods, such as leaving only one main vine and two main vines, to see how much impact they had on the growth of the plants, the number of flowers, fruit growth and yield (Ayala-Tafoya et al., 2019). In addition, some experiments planted companion plants that could attract bees to observe whether the pollination activity and yield increased (Stein et al., 2020).

Figure 2 The cultivation arrangement of three density treatments in greenhouses (Adopted from Ding et al., 2022)

Image caption: (A), the semi-closed, Venlo-type glass greenhouse used in the experiment. (B), picture of the plants, with about 15 leaves unfolding in different density treatments (Adopted from Ding et al., 2022)

8.2 Data on pollinator activity, fruit set, and yield

Studies have found that associated plants can attract more bees to visit cucumber flowers, especially in autumn when the effect is most obvious, which is of great help in improving pollination efficiency and yield (Tscharntke

et al., 2015; Stein et al., 2020). Pollination is more important than fertilization and weeding. Without it, even if other management is done well, the yield will not increase (Tscharntke et al., 2015). When planted sparsely (2.25 plants per square meter), each plant yields more fruits with better quality, such as high contents of sugar, vitamin C and protein, and the total output does not decrease (Ding et al., 2022). Although planting densely can increase the yield of each plot of land, the fruits become smaller, the weight decreases, and the profit is not necessarily higher (Ngouajio et al., 2006). In terms of the trellis, the modified umbrella type had higher yield and fruit count per plant, while the high rope trellis was more stable in terms of total output (Berghage et al., 2024). In terms of pruning, plants with two main vines left have more flowers and higher yields. However, if they are planted too densely, the growth of the plants will become weaker (Ayala-Tafoya et al., 2019).

8.3 Key takeaways for practical cultivation

Overall, appropriately reducing the planting density, such as 2.25 plants per square meter, is conducive to improving the fruit quality and yield per plant, and the total output can also be maintained (Ngouajio et al., 2006; Ding et al., 2022). The high rope frame has good stability, and the modified umbrella shape is more suitable for improving the performance of individual plants (Berghage et al., 2024). Planting some companion plants that attract bees or leaving more flowers can also improve pollination efficiency and yield (Tscharntke et al., 2015; Stein et al., 2020). Although high density has a high yield, the input costs such as seeds are also higher, so the returns are not necessarily the best (Ngouajio et al., 2006). If the appropriate density is combined, leaving double main vines can further increase the yield (Ayala-Tafoya et al., 2019).

9 Innovations and Sustainable Practices

9.1 Smart farming technologies for trellis and plant spacing

Nowadays, more and more intelligent agricultural technologies are being applied in the cultivation of cucumbers, especially in the construction of trellis and the arrangement of plant spacing. These technologies can help improve pollination efficiency and yield. By installing sensors, farmers can know the light, temperature, humidity and carbon dioxide concentration in real time, and then use the automatic control system to adjust the planting density and the way of trellis. For example, using different amounts of carbon dioxide generating kits (CGBs) can increase the CO_2 concentration in greenhouses, which can help cucumbers grow faster, have a higher yield, and the cost is not high (Guo et al., 2025). Meanwhile, intelligent data analysis can also tell farmers which density and trellis are more suitable, which is conducive to improving both yield and quality (Ding et al., 2022; Omerkhil et al., 2023; Berghage et al., 2024).

9.2 Low-input systems with high efficiency

Studies have pointed out that slightly reducing the planting density (for example, 2.25 plants per square meter) will not decrease the total output. Instead, it enables each plant to produce more fruits, with higher contents of nutrients such as sugar, vitamin C and flavonoids in the fruits, and lower nitrite content (Ding et al., 2022). In terms of fertilization, the combined use of NPK fertilizer with an appropriate density (for example, applying more fertilizer at a plant and row spacing of 75×55 cm) can also significantly improve the growth and yield of cucumbers (Omerkhil et al., 2023). Some studies have also found that using organic liquid fertilizer in combination with simple trellis (such as binding ropes or wooden sticks) can also make cucumbers grow well and have a decent yield (Odewale et al., 2020). These methods have low investment but good efficiency, saving resources and making money (Guo et al., 2025).

9.3 Recommendations for climate-resilient cultivation models

To cope with the possible impacts of climate change, the planting patterns should also be more diversified. For example, growing cucumbers together with other crops (intercropping) can make better use of the land. However, attention should also be paid to the seasonal and density arrangements to avoid crops competing with each other for resources and affecting the yield (Dutra et al., 2019). In greenhouses, slightly reducing the density can improve the quality of fruits and ensure stable yields under different climatic conditions (López-Elías et al., 2015; Ding et al., 2022). In addition, the selection of the appropriate trellis can also be flexibly adjusted according to the

production target (Berghage et al., 2024). Overall, it is recommended to adopt methods such as intelligent regulation and control equipment, low-density cultivation, high-quality management, and the combination of multiple trellis to better cope with climate change and market demands (Omerkhil et al., 2023; Guo et al., 2025).

10 Concluding Remarks

Appropriately reducing the planting density of cucumbers, for instance, by 2.25 plants per square meter, not only will the total output not decrease, but each cucumber plant will also bear more fruits, and the quality of the fruits will be better. For example, the content of sugar, vitamin C and flavonoids will be higher, and the nitrite content will be lower instead. Although a higher density may lead to a greater total output and an increase in the number of commercial fruits, individual fruits may become smaller and their quality may decline. Using high-line trellises (high-rack planting) can make the weekly yield of cucumbers more stable. Although the improved umbrella trellis can enable each plant to produce more and heavier fruits, the yield may not be very stable. Compared with ground planting, vertical trellis performs better. It can double the number of commercial fruits, with more uniform fruit sizes and more beautiful colors. Moreover, it has fewer diseases and is easier to harvest.

If the goal is to grow high-quality fruits, it is recommended to reduce the planting density to 2.25 plants per square meter. However, if more emphasis is placed on the total output, the density can be appropriately increased. High-line trellises are more suitable for those who want a stable yield, while umbrella-shaped trellises are more appropriate for growers who pursue high yields. No matter which type it is, three-dimensional trellis can increase yield and quality, and at the same time, they are more convenient for pest control and picking. They are recommended for priority consideration.

At present, there is still a lack of research on the behavior of pollinating insects and pollination efficiency caused by different frame types. In the future, you can focus on studying it. For example, see which kind of shelf is more attractive to insects like bees and whether it is related to the number of flowers. In addition, the long-term impact of different densities combined with different trellis on aspects such as the proportion of commercial fruits, fruit uniformity, and harvesting efficiency also needs to be further evaluated. In the future, it is also possible to try to study the combination of planting density, trellis style and associated plants together to see which combination is most conducive to improving pollination and yield. Establishing a more universal planting model based on different climates and planting methods will be very helpful for precise planting.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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