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Recent Advances in Cucumber Cultivation for Maximizing Yield

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Abstract As a widely consumed vegetable, whether cucumbers can achieve stable and high yields has always been a key concern in production. To address this issue, this paper reviews the recent research progress on cucumber high-yield cultivation from multiple perspectives, covering both basic understandings of growth, development, and yield formation, as well as practical measures such as environmental conditions, variety selection, seed treatment, water and fertilizer management, and facility and cover cultivation. Additionally, it combines the application of green pest and disease control and intelligent technologies, and illustrates through typical production models in specific regions. Based on comprehensive analysis, the current technical effects are evaluated, shortcomings are pointed out, and future development trends are predicted. Overall, the coordinated application of various technologies helps to simultaneously enhance cucumber yields and quality.

Keywords High-yield cucumber; Cultivation technology; Green control; Smart agriculture; Facility cultivation

1 Introduction

In daily vegetable production, cucumbers are often regarded as "common crops", but their significance is hard to be overlooked, whether in protected cultivation or open field conditions. Taking 2020 as an example, the planting area of cucumbers in China has reached 1.27 million hectares, accounting for more than half of the global total, with a production of approximately 73.36 million tons, which even exceeds 80% of the world's total (Wang et al., 2024; Li et al., 2024). Such a scale is no accident and also reflects the weight of cucumbers in China's vegetable system from the side. Coupled with their refreshing taste, stable nutrition, high market acceptance, and the ability to be cultivated throughout the year, they have played a substantial role in stabilizing vegetable supply and increasing farmers' income.

Over the past few years, the approaches taken by different regions to increase and stabilize cucumber yields have not been exactly the same. However, research and practice have not ceased. Many domestic production areas have started by improving water, fertilizer, and environmental conditions first, and as yields gradually increased, they also began to pay attention to the application of new varieties with disease resistance and high yield. Grafting and hydroponic cultivation have been used more and more, aiming to enhance stability (Samba et al., 2025; Gianco et al., 2019). In the foreign context, countries with mature facility conditions have already achieved a high level in greenhouse cucumber production, with large investment and meticulous management being their common characteristics. In comparison, our overall level still has room for improvement. However, with the gradual popularization of drip irrigation and intelligent greenhouses, this gap is being narrowed. Overall, the combination of various technologies has led to significant achievements in high-yield cucumber production.

This article focuses on how cucumbers can achieve stable and high yields. It systematically reviews the relevant research conducted in recent years and thereby clarifies the research and overall plan. Starting from the issues commonly concerned in cultivation practices, the article first introduces the biological and ecological basis on which high yield of cucumbers relies, and then combines variety selection and seed treatment to outline key cultivation measures and green control technologies for pests and diseases. At the same time, it also pays attention to the application of intelligent and information-based means in production， and through case studies of high-yield models in typical regions, demonstrates the actual effects of the collaborative application of multiple technologies (Maeda et al., 2022; Kang et al., 2024). Based on this, it evaluates the existing technologies, analyzes their shortcomings, and makes an outlook on future development directions, with the aim of providing a reference for increasing cucumber yields.

2. Biological and Ecological Basis for High-Yield Cultivation of Cucumbers

2.1 Growth and development characteristics of cucumbers and mechanism of yield formation

In actual production, people often first notice the issue of the flower shape of cucumbers. Cucumbers are hermaphroditic plants, but only the female flowers can actually produce fruits. This is not complicated but very crucial. Sometimes, even with good management conditions, there are still few female flowers, and the yield still cannot increase; conversely, if there are too many female flowers, there will be a foundation for fruiting. Therefore, when discussing high yield, promoting the formation of female flowers and increasing the fruit setting rate are often unavoidable topics (Figure 1) (Pan et al., 2018; Yamasaki et al., 2003).

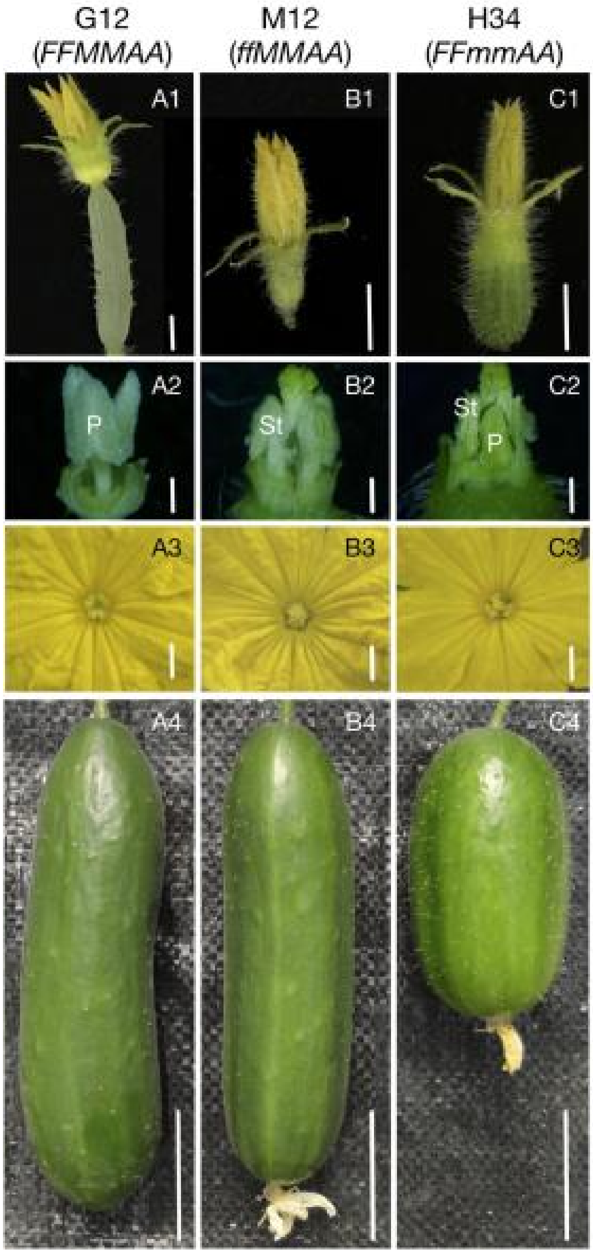

Figure 1 Sex expression, flower, and fruit morphology of NILs. Flower organs showed different morphology between G12 (FFMMAA), M12 (ffMMAA), and H34 (FFmmAA). (A1–C1) Flowers before antheses. Bars = 0.5 cm, (A2–C2) Floral organ without petal and sepal. Bars = 0.2 cm, (A3–C3) Floral organ with petal. Bars = 0.2 cm, (A4–C4) Mature fruit. Bars = 4 cm. P, pistil; St, stamen (Adopted from Pan et al., 2018)

It should be noted that the growth of cucumbers does not stop quickly. It will continuously produce vines, flowers, and fruits. The final yield depends on how many cucumbers a plant can produce and how well the cucumbers grow. More leaves and better growth mean that the nutrient supply can keep up, and a strong root system means stable water and fertilizer absorption. Considering that cucumber roots are shallow, growth is fast, and the harvest period is long, if not adjusted through pruning and controlling the number of remaining cucumbers, it is very easy to cause imbalance in growth, affecting the continuous fruiting and stable yield in the later stage.

2.2 Effects of environmental factors (temperature, light, water) on yield

Many growers will find that before they can even discuss management, the environmental conditions have already created a significant difference in yields. Cucumbers prefer a warmer environment, with optimal growth occurring when the temperature is between 25–30°C during the day and close to 16°C at night. Once the temperature drops below 12°C, growth slows down, and in severe cases, they may even be damaged by frost. However, too high a temperature is also not suitable; exceeding 35°C can lead to abnormal flowering and fruit drop (Zhang et al., 2022; Wang et al., 2025). Light is often overlooked. Insufficient sunlight duration and insufficient photosynthesis can affect flowering and fruit setting. Generally, 8–10 hours of sunlight per day is more appropriate. In terms of water, there are also specific requirements. Cucumbers have a high water requirement but are afraid of waterlogging. If the soil is too dry, young cucumbers cannot grow well. Waterlogging can easily damage the roots and cause diseases. Therefore, it is necessary to keep the soil moist but not waterlogged, and pay attention to ventilation to prevent excessive humidity from affecting yield.

2.3 Relationship between soil physical and chemical properties and root development

Most of the time, the growth of cucumbers depends on the "conditions" beneath the ground. If the soil layer is deep and loose, with sufficient nutrients and smooth drainage, the plants tend to have more vitality. Especially in neutral or slightly alkaline soil, the roots grow deeper and there are more lateral roots, making it easier for them to absorb water and nutrients. If the soil is compacted and has poor fertility, the root system cannot expand, and the above-ground part cannot grow vigorously. The yield will also be difficult to improve. In facility cultivation, there is another common problem - continuous cropping over the years. Over time, it is prone to accumulate salts, become acidic, and have more pathogens. In mild cases, the growth will weaken; in severe cases, even seedlings may die. Therefore, to achieve stable and high yields, one cannot only focus on the above-ground management; efforts must also be made to improve the soil by increasing organic fertilizer application, rotating crops, or necessary soil treatment, to first cultivate a good root environment (Zhou et al., 2018; Li et al., 2020).

3 Breeding of High-yield and Drought-resistant Cucumber Varieties and Seed Treatment Techniques

3.1 Progress in selecting new high-yield and drought-resistant cucumber varieties

In actual production, many people start by focusing on management, but eventually they will realize that the choice of variety is crucial. In recent years, breeding units across various regions have continuously introduced new varieties. Some focus more on high yield, while others have obvious advantages in disease resistance and stress tolerance. For instance, the "Jingyan" series developed by the Vegetable Research Institute of Beijing Academy of Agricultural Sciences has dozens of varieties, maintaining stable yields while having reliable disease resistance; in regions with high pressure from southern blight disease, such as the "Yueshou 3" variety selected by the Agricultural Science Institute of Guangdong, it can still ensure harvest under adverse conditions. After introducing methods such as molecular markers during the breeding process, the selection efficiency has significantly improved. Coupled with the promotion of all-female and parthenocarpy types, more nutrients are used for fruiting, resulting in an increase in the number of fruits (Pan et al., 2017; Li et al., 2019). Overall, the continuous update of varieties has laid a foundation for achieving high yields of cucumbers.

3.2 Application of hybrid advantage in high-yield cucumber breeding

In actual production, many people start by focusing on management, but eventually they will realize that the choice of variety is crucial. In recent years, breeding units across various regions have continuously introduced new varieties. Some focus more on high yield, while others have obvious advantages in disease resistance and stress tolerance. For instance, the "Jingyan" series developed by the Vegetable Research Institute of Beijing Academy of Agricultural Sciences has dozens of varieties, maintaining stable yields while having reliable disease resistance; in regions with high pressure from southern blight disease, such as the "Yueshou 3" variety selected by the Agricultural Science Institute of Guangdong, it can still ensure harvest under adverse conditions. After introducing methods such as molecular markers during the breeding process, the selection efficiency has significantly improved. Coupled with the promotion of all-female and parthenocarpy types, more nutrients are used for fruiting, resulting in an increase in the number of fruits (Pan et al., 2017; Li et al., 2019). Overall, the continuous update of varieties has laid a foundation for achieving high yields of cucumbers.

3.3 Seed treatment techniques

Many people only start to pay attention to yield during the seedling stage. In fact, the gap has gradually widened even before sowing. If the seeds are properly treated, the seedlings tend to emerge more uniformly and the seedlings themselves are healthier. The subsequent management will naturally be more convenient. Among the common methods, soaking the seeds in warm water is used most frequently. Place the seeds in 55–60℃ warm water and stir while soaking for about ten minutes, which can reduce the risk of various diseases; some people also soak the seeds in a 0.1% carbendazim solution for one hour, wash them clean before sowing, and the effect is also good. However, not all seeds need to be treated in this way. Nowadays, many commercial seeds have been coated, containing bacteriostatic components and trace elements, and can be directly sown. In recent years, some people have also tried to add chitosan and other biological stimulants to make the germination faster and the root system stronger, laying a foundation for stable yield in the later stage (Paparella et al., 2015; Hidangmayum et al., 2019).

4 Key Technical Measures for High-Yield Cultivation of Cucumbers

4.1 Appropriate plant spacing and pruning techniques

In actual cultivation, many people tend to be confused about whether to plant the plants densely or sparsely at the beginning. In fact, this is closely related to how to manage the branches later. If the plants are planted too densely in the greenhouse, they will crowd together, resulting in poor ventilation and light penetration, and flower drop and diseases will follow. However, if the spacing is too wide, it will waste light and space, and the yield per area will not increase. Therefore, the density cannot be generalized; it needs to be adjusted according to the variety and season. The common practice in greenhouses is to plant in rows of different sizes. The large row spacing is approximately 80 centimeters, and the small row spacing is 60 centimeters. The plant spacing is around 30 centimeters. About 4,000 plants per mu is relatively appropriate. After the density is determined, pruning and topping of branches are also very important. In early-maturing greenhouse cucumbers, there are many lateral branches, which consume nutrients. Generally, the lateral branches are pinched when they grow to 2–3 leaves, and then the lower 8–10 leaves of the main vine are gradually removed, and the old leaves, excessive male flowers and tendrils are also cleared. This way, the greenhouse becomes more transparent, and the nutrients are more concentrated on the fruiting (Qian et al., 2016; Marcelis et al., 2018).

4.2 Integrated water and fertilizer management and precision fertilization technology

For many farmers, they believe that as long as water and fertilizer are continuously provided, the crop will grow well. However, what really makes a difference is whether the water and fertilizer are applied accurately. Now, some production areas have started to adopt integrated water and fertilizer management, using drip irrigation to directly deliver water and nutrients to the roots. This significantly reduces water usage. Compared to the previous method of flooding irrigation, this approach not only saves water but also has the potential to increase yield. The fertilizer application strategy is also changing. Instead of blindly pursuing large quantities, it now takes into account the soil conditions and the actual needs of the cucumbers. In some places, by conducting soil tests or using fertilizer plans, the amount of chemical fertilizers is appropriately reduced, yet the yield does not decrease and the cost even goes down. Research has also found that in greenhouse cucumber production, when the usage of nitrogen, phosphorus, and potassium is reduced, the yield remains stable while the profits are higher (Zhang et al., 2020; Wang et al., 2021). Considering all these factors, proper water and fertilizer combination is more conducive to stable production and increased efficiency than simply increasing the amount of fertilizer.

4.3 Film mulching, substrate cultivation and facility cultivation techniques

In many cases, the inability to increase production is not due to poor management, but rather to the inappropriate choice of cultivation methods. In open-field conditions, mulching with plastic film is widely used. When the ridge surface is covered, the temperature and moisture are relatively stable, and there are fewer weeds, allowing the seedlings to grow faster. The effect is particularly noticeable when spring cultivation is carried out earlier. When it comes to facilities, the situation is different. In many places, substrate soilless cultivation is being used, such as rock wool and coconut coir combined with nutrient solutions. This not only avoids diseases caused by continuous cropping but also makes it convenient to precisely control water and fertilizer, allowing the plants to grow more evenly. In addition, greenhouses and sheds can regulate temperature and light, enabling cucumbers to be produced out of season and some even harvested throughout the year. The combination of multiple methods often breaks the limitations of natural conditions and increases the yield per unit area (Lamont et al., 2005; Savvas et al., 2018).

5 Green Pest and Disease Control and High-yield Stable-yield Technology

5.1 Occurrence patterns of main pests and diseases in cucumber

Throughout the entire growth process of cucumbers, pests and diseases are almost inevitable issues, and they occur rapidly and in various forms. If the seedlings are exposed to low temperatures and high humidity during the seedling stage, sudden blight and damping-off diseases are likely to occur in concentrated form, and in severe cases, the seedlings will collapse in large numbers. As the plants grow, new problems arise. Downy mildew is most likely to break out when the humidity is high, the temperature is low, or there is continuous rainy weather. The leaf function is quickly affected; powdery mildew is more common in the middle and later stages, especially in situations with poor ventilation and dense growth. With prolonged consecutive cropping, soil-borne diseases such as wilt disease will gradually worsen. Once the roots are infected, the plants will quickly wilt. In terms of pests, in greenhouses and warm seasons, aphids and mealybugs reproduce rapidly and can also carry viruses. In dry and hot conditions, the number of thrips and red spiders increases significantly. The striped tent caterpillar often feeds at night. Only by understanding the favorable environments and periods for the occurrence of these pests and diseases, and taking preventive measures in advance, can the losses be reduced and the yield be guaranteed (Lebeda et al., 2011; Savory et al., 2011).

5.2 Biological control and physical control technologies

In actual production, if one wants to keep pests and diseases under control without using too much pesticide, a single method alone is often not sufficient. In many cases, choosing the right variety or using grafted healthy seedlings from the very beginning has already significantly reduced risks. In greenhouse management, some people start from the details, installing insect-proof nets at ventilation openings and entrances, which significantly reduces the chances of pests entering the greenhouse. The yellow and blue boards commonly hung in the fields, although simple to look at, can continuously reduce the numbers of aphids, mealybugs, and thrips, and when combined with insect traps at night, they also help control nocturnal moth pests. In addition, biological control is also increasingly used. By releasing ladybugs, lacewings, or parasitic wasps, it can maintain long-term control of the pest population density. Combined with biological organic fertilizers and biological pesticides, it is also effective against soil-borne diseases. The use of multiple measures in combination can reduce pesticide usage while ensuring stable cucumber yields (Bale et al., 2008; van Lenteren et al., 2018).

5.3 Chemical control reduction and safe drug use strategies

In cucumber cultivation, many growers are well aware that pesticides are not the preferred method; rather, they are more like a last resort. If pesticides are used too frequently, not only will there be residue, but pests will also develop resistance, and the ecological balance in the field will be affected. Therefore, in high-yield cultivation, it is often emphasized that pesticides should be used sparingly if possible. Only when the disease and pest problems become severe and the previous measures are ineffective, will chemical control be considered. At this time, low-toxicity and short-lasting pesticides should be selected and used according to the recommended concentration and safe interval period. When applying pesticides, the focus areas are targeted, and the entire field is not sprayed. At the same time, different pesticides should be rotated. For example, when controlling bacterial spot disease, streptomycin and copper-containing preparations can be alternated. By controlling the dosage and timing well, chemical control can serve as a safeguard, stabilizing the yield while also taking into account environmental and food safety (Gisi et al., 2018; Sparks et al., 2020).

6 Application of Intelligence and Informationization in High-Yield Cucumber Cultivation

6.1 Smart greenhouses and automatic environmental control technology

Over the past few years, with the continuous improvement of facilities, the methods of cucumber production have been quietly changing. Entering the smart greenhouse, you will find sensors everywhere in the greenhouse. Temperature, humidity, light, carbon dioxide and other data are collected at any time and then transmitted to the control system. When the temperature rises, the fans and wet curtains start working. At night when it gets cold, it automatically keeps warm. The shading, heating, water and fertilizer supply all operate according to the set program. Managers can operate these systems using computers or mobile phones. As a result, the crops are kept in a relatively stable environment for a long time, and the effects of high or low temperatures are significantly reduced. In practical applications, such systems not only save labor but also improve the efficiency of water, fertilizer and energy utilization, making cucumber yields more stable and providing support for continuous high production (Figure 2) (Shamshiri et al., 2018; Kang et al., 2024).

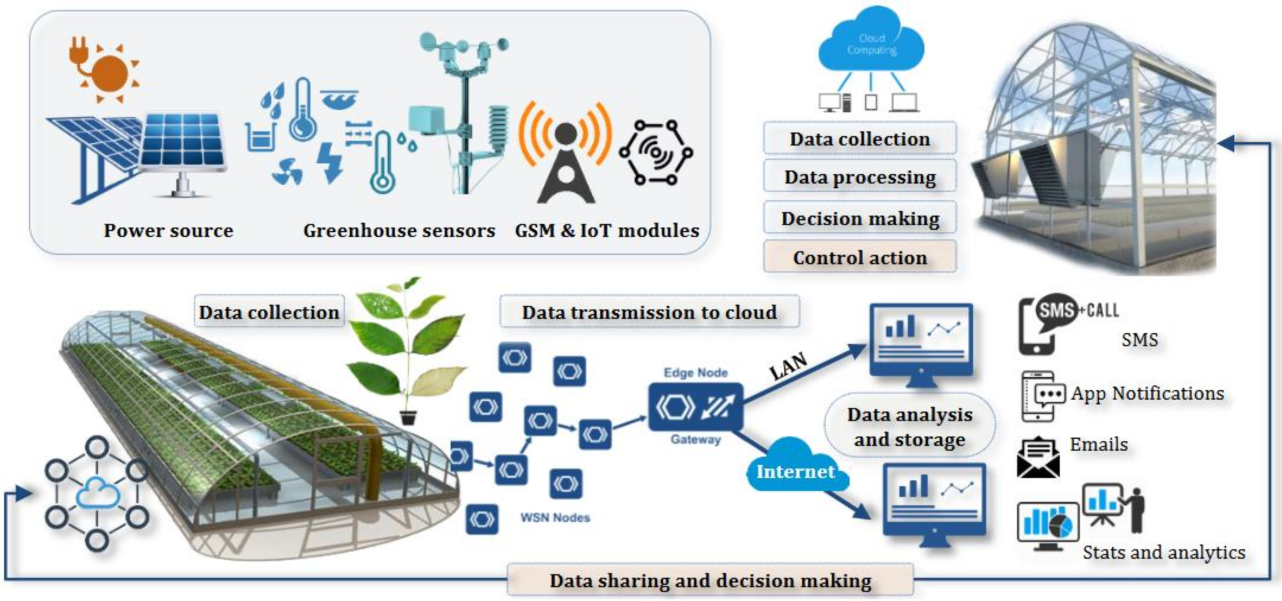

Figure 2 General components of a greenhouse environmental monitoring based in wireless sensor network and IoT concept (Adopted from Shamshiri et al., 2018)

6.2 Application of sensors and big data in cultivation management

In the past, when growing cucumbers, judgment was mostly based on experience and intuition. But now, the situation has gradually changed. Sensors installed in greenhouses or fields can continuously monitor changes in soil moisture and nutrients, and record temperature, humidity, and light conditions. In some places, cameras are also used to observe the growth of plants. After these data are centralized on a platform, they are used to arrange watering, fertilization, and environmental regulation. Over time, the historical data accumulates more and more. Which conditions are more conducive to high yield gradually become clearer, and the management plan can also be adjusted accordingly. Continuous monitoring has another advantage. Once an anomaly occurs, it can often be detected in advance, reducing losses. With the continuous improvement of data analysis capabilities, cucumber management is shifting from "based on intuition" to "based on data", with more controllable investment and more stable yields (Wolfert et al., 2017; Liakos et al., 2018).

6.3 Trends of artificial intelligence and precision agriculture

Looking ahead, the topic of high-yield cucumber cultivation cannot help but involve artificial intelligence and precision agriculture. With an increasing amount of production data, AI models are starting to identify patterns from this data to assist in regulating greenhouse environments, scheduling fertilization, and even participating in pest control. Some experiments have found that when environmental parameters are automatically adjusted by algorithms, there is still potential for an increase in yield. On the other hand, image recognition is also gradually being used. It can detect pests, diseases, or nutrient abnormalities in greenhouses or fields in advance, reducing the need for manual inspections. Harvesting robots, automatic pruning equipment, and drone pest control are still in the experimental stage, but they already show potential to alleviate the pressure on labor. Combined with precise seeding and variable fertilization, different plots can be managed more "appropriately". The use of multiple technologies in combination is pushing cucumber cultivation towards a more labor-saving and stable development direction (Liakos et al., 2018; Shamshiri et al., 2021).

7 Case Study: Analysis of High-Yield Cultivation Model for Cucumbers in Typical Areas

7.1 Overview of natural conditions and cultivation model in the case area

When it comes to high yield of cucumbers, many people immediately think of Shouguang in Shandong Province. This is no coincidence. The local terrain is flat, the water supply conditions are good, and the soil is suitable for high-density planting. However, the winters are cold, and open-field production is not advantageous. For this reason, Shouguang has long focused on solar greenhouses and gradually developed a strategy of off-season production in winter. Currently, the city's annual vegetable planting area remains above 600,000 acres, with greenhouses and sheds basically supporting the year-round supply. In cucumber production, most adopt a rotation method of winter and spring greenhouses and summer and autumn open fields. In winter, they are mainly sold in bulk, and in summer, they adjust the crop schedule or rest the greenhouses for land rest. Coupled with the experienced farmers and the fast promotion of new technologies, Shouguang has gradually become a typical area for high-yield and efficient cultivation of cucumbers (Zhang et al., 2019; Li et al., 2021).

7.2 Key high-yield technology integration and application effects

The reason why Shouguang cucumbers can consistently achieve high yields is not usually due to a single strategy. In production, many aspects work together. For example, in variety selection, in greenhouses, mostly all-female hybrid varieties are used, combined with grafting seedling cultivation, which gives the root system more vitality and stronger disease resistance. The greenhouses themselves have been continuously improved over the years, with heat collection plates, insulation covers, and automatic ventilation equipment gradually being adopted. Winter insulation and environmental regulation have become more stable. In terms of water and fertilizer management, integrated drip irrigation and fertilization is very common, providing more uniform water and fertilizer supply, and reducing human errors. In terms of pests and diseases, prevention-oriented measures are favored, with more physical and biological methods used, and the use of chemical pesticides has significantly decreased. It is the combination of these technologies that enables Shouguang cucumbers to maintain advantages in both yield and quality, forming a mature and stable high-yield model (Savvas et al., 2013; Zhang et al., 2019).

7.3 Economic benefits and promotion value assessment

If we only consider the economic benefits, the advantages of the Shouguang high-yield model are quite obvious. Seasonal production combined with high yields naturally leads to higher income per unit area compared to traditional farming. Although the initial investment is considerable, many farmers can recover their costs within a few years. This approach is not only applicable to Shouguang but also shows effectiveness when local experience is promoted externally. For instance, after introducing relevant technologies in Kaizhou, Chongqing, the per-plot output and net income of facility vegetables have significantly increased. In Shouguang, the vegetable industry has formed a relatively complete chain. Not only have the incomes of vegetable farmers increased, but it has also driven the development of related industries. As technology and management experience are continuously exported, the application scope of the "Shouguang model" is expanding. It shows good promotion potential both domestically and internationally (Li et al., 2020; Zhang et al., 2022).

8 Conclusion and Outlook

Looking back at this method for achieving high yields of cucumbers, it is no longer supported solely by a single technology. Instead, it has gradually formed a complete set of combinations. In production, from variety renewal, adjustment of cultivation methods, to disease and pest control and improvement of facility conditions, many aspects are working simultaneously, resulting in a unit area yield that is much higher than the traditional method. Superior varieties and grafting raise the potential of the crops first, while dense planting, water and fertilizer management, and environmental management further release the production capacity. Green control measures combined with intelligent equipment make the production more stable and management more effortless. While increasing yields, the utilization rate of resources and product quality have also improved. Of course, these technologies cannot be used randomly. They require higher operational skills and management capabilities from growers, and training and services need to keep up as well. Overall, this technical system is changing the production methods of cucumbers, and has practical significance for stable supply and increased income.

Although cucumber high-yield technologies are being used more and more, problems have not completely disappeared during the promotion process. When continuous cropping occurs in facilities for a long time, the soil is prone to accumulate salt and become acidic, beneficial microorganisms decrease, and the problem of continuous cropping remains a long-standing challenge. Pest and disease control is also not easy. With the reduction in pesticide usage, there is still room for improvement in the effectiveness of biological control. Viral diseases and resistance issues often cause pressure. Looking at the investment aspect, the costs of intelligent equipment and automation technologies are not low. Many small and medium-sized growers find it difficult to accept them at first, and the promotion is thus limited. In production, the pruning and harvesting stages still highly rely on manual labor. When there is a shortage of labor, it will get stuck. In addition, with the increase in extreme weather and insufficient understanding of the high-yield mechanism, these have brought new challenges to continuous yield increase. These still require continuous exploration and improvement through practice and research.

Looking ahead, the path for high-yield cucumber cultivation is gradually becoming clearer and is increasingly in line with actual production. In terms of breeding, genetic research is deepening, and some new methods are being used to directly improve plant shape, female flower characteristics, and stress resistance. While increasing yields, quality is also taken into consideration. In production, high-intensity chemical inputs will gradually be replaced, and organic fertilizers, biological control, and recycling will become more common. Smart agriculture is no longer just a demonstration. The Internet of Things and artificial intelligence are entering ordinary greenhouses, and automatic harvesting and pest control equipment will become increasingly mature. Coupled with the development of urban agriculture, vertical planting, and low-carbon greenhouses, high-yield cucumbers are expected to find a more suitable balance between increased production, environmental protection, and economic benefits.

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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.

References

Bale J.S., van Lenteren J.C., and Bigler F., 2008, Biological control and sustainable food production, Philosophical Transactions of the Royal Society B: Biological Sciences, 363(1492): 761-776.
https://doi.org/10.1098/rstb.2007.2182

Gianco F., Abdalla M.Y., and El-Gazzar A., 2019, Grafting improves fruit yield of cucumber plants grown under saline conditions, Agriculture, 7(3): 61.
https://www.mdpi.com/2311-7524/7/3/61

Gisi U., Sierotzki H., Cook A., and McCaffery A., 2018, Mechanisms influencing the evolution of resistance to Qo inhibitor fungicides, Pest Management Science, 74(3): 573-582.
https://doi.org/10.1002/ps.4816

Hidangmayum A., Dwivedi P., Katiyar D., and Hemantaranjan A., 2019, Application of chitosan on plant responses with special reference to abiotic stress, Physiology and Molecular Biology of Plants, 25(2): 313-326.
https://doi.org/10.1007/s12298-019-00668-1

Kang M., Lee J.E., Sohn S., Kim J., Park J., and Lee I.B., 2024, Estimation of cucumber net primary production using environmental and control information in a smart greenhouse, Computers and Electronics in Agriculture, 208: 108819.
https://doi.org/10.1016/j.compag.2024.108819

Lamont W.J., Orzolek M.D., Holcomb E.J., and Jarrett A.R., 2005, Plastics: modifying the microclimate for the production of vegetable crops, Annual Review of Plant Biology, 56: 531-556.
https://doi.org/10.1146/annurev.arplant.56.032604.144211

Lebeda A., Widrlechner M.P., Staub J.E., Ezura H., Zalapa J., and Křístková E., 2011, Cucurbits as a model for studying disease resistance and host-pathogen interactions, Critical Reviews in Plant Sciences, 30(5): 375-402.
https://doi.org/10.1080/07352689.2011.605749

Li J., Wang Y., Chen Q., and Zhao X., 2020, Economic performance and technology diffusion of facility vegetable production systems in China, Journal of Integrative Agriculture, 19(11): 2776-2787.
https://doi.org/10.1016/S2095-3119(20)63224-0

Li J., Wang Y., Zhao X., and Chen Q., 2021, Regionalized intensive vegetable production and technological innovation in China: A case study of Shouguang, Journal of Integrative Agriculture, 20(9): 2365-2376.
https://doi.org/10.1016/S2095-3119(20)63405-8

Li Y., Liu Q., Li X., Yang H., and Wang Y., 2020, Effects of organic fertilizer amendment on soil properties and cucumber growth under continuous cropping conditions, Scientia Horticulturae, 261: 108973.
https://doi.org/10.1016/j.scienta.2019.108973

Li Z., Zhang Z., Yan P., Huang S., Fei Z., and Lin K., 2019, RNA-seq improves efficiency of molecular marker-assisted selection in cucumber breeding, BMC Genomics, 20: 475.
https://doi.org/10.1186/s12864-019-5855-6

Liakos K.G., Busato P., Moshou D., Pearson S., and Bochtis D., 2018, Machine learning in agriculture: A review, Sensors, 18(8): 2674.
https://doi.org/10.3390/s18082674

Maeda K., and Ahn D., 2022, Analysis of growth and yield of three types cucumbers based on yield components, Horticulturae, 8(1): 33.
https://doi.org/10.3390/horticulturae8010033

Marcelis L.F.M., Elings A., Bakker M.J., Brajeul E., and Dueck T.A., 2018, Modelling growth and yield of greenhouse cucumber: effects of plant density and canopy management, Annals of Botany, 121(7): 1299-1311.
https://doi.org/10.1093/aob/mcy026

Pan J., Wang G., Wen H., Du H., Lian H., He J., Pan R., and Cai R., 2017, Molecular mechanism of sex determination in cucumber, Theoretical and Applied Genetics, 130(5): 843-856.
https://doi.org/10.1007/s00122-017-2860-0

Pan J., Wang G., Wen H., Du H., Lian H., He J., Pan R., and Cai R., 2018, Differential gene expression caused by the F and M loci provides insight into ethylene-mediated female flower differentiation in cucumber, Frontiers in Plant Science, 9: 1091.
https://doi.org/10.3389/fpls.2018.01091

Paparella S., Araújo S.S., Rossi G., Wijayasinghe M., Carbonera D., and Balestrazzi A., 2015, Seed priming: state of the art and new perspectives, Plant Cell Reports, 34(8): 1281-1293.
https://doi.org/10.1007/s00299-015-1784-y

Qian C., Zhang Y., Yang Q., Wang S., and Li T., 2016, Effects of plant density and pruning on growth and yield of greenhouse cucumber, Scientia Horticulturae, 201: 99-107.
https://doi.org/10.1016/j.scienta.2016.01.033

Samba N., Johkan M., Nakano A., and Tsukagoshi S., 2025, Response of grafted and non-grafted cucumber (*Cucumis sativus* L.) plants to different nutrient management methods in a hydroponic system, Horticulture, Environment, and Biotechnology, 66: 1043-1055.
https://link.springer.com/article/10.1007/s13580-025-00705-y

Savory E.A., Granke L.L., Quesada-Ocampo L.M., Varbanova M., Hausbeck M.K., and Day B., 2011, The cucurbit downy mildew pathogen Pseudoperonospora cubensis, Molecular Plant Pathology, 12(3): 217-226.
https://doi.org/10.1111/j.1364-3703.2010.00670.x

Savvas D., and Gruda N., 2018, Application of soilless culture technologies in the modern greenhouse industry — A review, European Journal of Horticultural Science, 83(5): 280-293.
https://doi.org/10.17660/eJHS.2018/83.5.2

Savvas D., Papastavrou D., Ntatsi G., Ropokis A., Olympios C., Hartmann H., and Schwarz D., 2013, Interactive effects of grafting and fertilization on yield and nutrient uptake of cucumber grown in soil, Scientia Horticulturae, 149: 8-16.
https://doi.org/10.1016/j.scienta.2012.02.019

Shamshiri R.R., Jones J.W., Thorp K.R., Ahmad D., Man H.C., and Taheri S., 2021, Review of optimum temperature, humidity, and vapor pressure deficit for microclimate evaluation and control in greenhouse cultivation of plants, International Journal of Agricultural and Biological Engineering, 14(1): 1-19.
https://doi.org/10.25165/j.ijabe.20211401.6202

Shamshiri R.R., Kalantari F., Ting K.C., Thorp K.R., Hameed I.A., Weltzien C., Ahmad D., and Shad Z.M., 2018, Advances in greenhouse automation and controlled environment agriculture: A transition to plant factories and urban agriculture, International Journal of Agricultural and Biological Engineering, 11(1): 1-22.
https://doi.org/10.25165/j.ijabe.20181101.3210

Sparks T.C., Crossthwaite A.J., Nauen R., Banba S., Cordova D., Earley F., Ebbinghaus-Kintscher U., Fujioka S., Hirao A., Karmon D., Kennedy R., Long J.K., Lowder P., Rauh J.J., Ruzo L.O., and Wehrman T., 2020, Insecticides, biologics and nematicides: updates to IRAC's mode of action classification, Pest Management Science, 76(1): 8-21.
https://doi.org/10.1002/ps.5669

van Lenteren J.C., Bolckmans K., Köhl J., Ravensberg W.J., and Urbaneja A., 2018, Biological control using invertebrates and microorganisms: plenty of new opportunities, BioControl, 63(1): 39-59.
https://doi.org/10.1007/s10526-017-9801-4

Wang J., Qu F., Zhang J., Zhao R., Wang H., and Hu X., 2025, Optimizing cultivation substrate moisture and calcium application for the comprehensive growth of cucumber under different air temperatures, Irrigation Science, 43: 491-503.
https://doi.org/10.1007/s00271-024-00980-0

Wang Y., Li J., Li Y., Zhang M., and Wang R., 2021, Reducing nitrogen, phosphorus and potassium inputs without yield loss in greenhouse cucumber production, Scientia Horticulturae, 276: 109747.
https://doi.org/10.1016/j.scienta.2020.109747

Wolfert S., Ge L., Verdouw C., and Bogaardt M.J., 2017, Big data in smart farming - A review, Agricultural Systems, 153: 69-80.
https://doi.org/10.1016/j.agsy.2017.01.023

Yamasaki S., Fujii N., and Takahashi H., 2003, Characterization of ethylene effects on sex determination in cucumber plants, Plant Reproduction, 16(2): 103-111.
https://doi.org/10.1007/s00497-003-0183-7

Ye X., Deng Q., Xu S., Huang Y., Wei D., Wang Z., Zhang Y., and Tang Q., 2024, CsSPL13A directly binds and positively regulates CsFT and CsBAM to accelerate flowering in cucumber, Plant Physiology and Biochemistry, 207: 108395.

Zhang F., Luo J., Yuan C., Li C., and Yang Z., 2022, A model for the effect of low temperature and poor light on the growth of cucumbers in a greenhouse, Agronomy, 12(12): 2992.
https://doi.org/10.3390/agronomy12122992

Zhang H., Chi D., Wang Q., Fang J., and Fang X., 2020, Yield, quality and water use efficiency of greenhouse cucumber as influenced by drip irrigation and fertilization management, Agricultural Water Management, 230: 105956.
https://doi.org/10.1016/j.agwat.2019.105956

Zhang X., Wang H., Liu Y., and Sun J., 2019, Development and characteristics of solar greenhouse vegetable production systems in Northern China, Horticultural Plant Journal, 5(6): 239-246.
https://doi.org/10.1016/j.hpj.2019.06.003

Zhang Y., Liu S., Sun J., and Wang H., 2022, Industrial upgrading and income effects of intensive vegetable production: Evidence from Shouguang, China, Agricultural Economics, 53(5): 733-747.
https://doi.org/10.1111/agec.12701

Zhang M., Ma M., Lang H., and Jiang M., 2025, Research advances and perspectives on early flowering traits in cucumber, Plants, 14(8): 1158.

Zhou X., and Wu F., 2018, Effects of soil microbial community structure on cucumber yield and continuous cropping obstacle, Applied Soil Ecology, 126: 178-186.
https://doi.org/10.1016/j.apsoil.2018.02.011