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Morphological Characterization of High-Yield Bitter Gourd Populations under High-Density Planting and Drip Irrigation

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Abstract This study mainly examined the effects of high-density planting and drip irrigation combined management on the morphology and yield of bitter gourd, and analyzed the relationships between indicators such as vine length, branch number, leaf characteristics, flowering status, and fruit traits and yield. It was found that high-yield groups have advantages in canopy structure, water and fertilizer utilization, and disease control. Studies show that combining drip irrigation with reasonable planting density can significantly improve the utilization rate of water and fertilizer as well as market output. Meanwhile, this method can improve the quality of the fruit by adjusting the distribution of light and nutrients. This study aims to provide theoretical basis and technical reference for the bitter gourd industry to achieve sustained high yields.

Keywords Bitter gourd; High-density planting; Drip irrigation; Morphological traits; High-yield breeding

1 Introduction

Bitter gourd (*Momordica charantia* L.) is an important economic vegetable and is widely cultivated in tropical and subtropical regions of Asia and around the world. With the increase in population and the reduction of arable land, raising the per-unit yield has become the focus of bitter gourd production. In recent years, technologies such as drip irrigation, integrated fertilizer and water, and protected land have been increasingly applied in bitter gourd cultivation. These technologies can increase yield and quality, improve the utilization rate of water and fertilizer, and promote the sustainable development of the industry (Bahadur et al., 2021). High-density planting is a way to increase yield, but it also changes light, ventilation and nutrient distribution, and puts forward higher requirements for the growth and fruiting of bitter gourd (Seong et al., 2015; Abraham et al., 2017).

Under intensive models such as high density and drip irrigation, the morphological characteristics of bitter gourd, including plant height, branching, leaf area and fruit traits, will directly affect photosynthetic efficiency, nutrient utilization and yield. By systematically observing these morphological characteristics, the adaptability and high-yield reasons of bitter gourd under different cultivation conditions can be understood, providing a reference for variety improvement and precise management (Alhariri et al., 2021; Rao et al., 2021). Drip irrigation can improve water use efficiency, regulate the water environment in the root zone, promote the coordinated growth of the root system and the above-ground part, thereby improving fruit quality and yield (Mali et al., 2017; Bahadur et al., 2021). High-density planting can affect photosynthetic characteristics, root distribution and fruit development. Morphological analysis is needed to find high-quality and high-yield varieties that are most suitable for high-density drip irrigation conditions (Mehta et al., 2024).

This study summarized the main morphological characteristics of high-yield bitter gourd populations under high-density drip irrigation conditions, compared the differences among different populations, analyzed the relationship between morphological characteristics and yield, and identified the key indicators for high yield. This research aims to provide theoretical and technical support for the breeding of high-yield varieties and the improvement of efficient cultivation models.

2 Principles of High-Density Planting and Drip Irrigation in Bitter Gourd

2.1 Agronomic rationale and yield potential of high-density cultivation

High-density planting is achieved by growing more plants in the same area to increase yield. This can enhance the photosynthetic efficiency of the group and also make better use of the land. An appropriate density not only increases the number of fruits and the yield per unit area, but also improves ventilation and light transmission by adjusting the distribution of branches and leaves, thereby reducing diseases. For instance, the optimal density for grafting bitter gourd in a greenhouse is 70 to 100 plants per 667m². By pruning weak and low-lying branches in combination, the yield and fruit quality can be further enhanced. However, high density should also take into account the variety and growth environment. If the density is too high, it may cause the plants to compete for water and nutrients, resulting in smaller individual fruits.

2.2 Role of drip irrigation in optimizing water and nutrient delivery

Drip irrigation is a method that can precisely deliver water and fertilizer to the roots. It can enhance water use efficiency (WUE) and fertilizer utilization rate. Studies have shown that bitter gourd with drip irrigation combined with appropriate fertilization (such as NPK 150:120:120 kg/ha) can significantly increase yield and fruit weight, and the water productivity under drip irrigation is much higher than that under traditional irrigation (Turkar and Deshmukh, 2018; Bahadur et al., 2021). Drip irrigation can also reduce water evaporation and nutrient loss, lower the risk of soil salt accumulation, and improve the stress resistance and quality of crops (Singh et al., 2020; Soomro et al., 2021). If drip irrigation is combined with plastic film mulching, it can better retain moisture, suppress weeds, and promote early maturity and high yield (Kayande et al., 2016; Abraham et al., 2018).

2.3 Integration of planting density and irrigation scheduling for growth optimization

Combining high-density planting with drip irrigation is an important method for achieving high yields and efficiency of bitter gourds. Density, irrigation and fertilization should be properly coordinated to ensure that each plant receives sufficient water and nutrients and avoid excessive competition for resources. Studies have found that under drip irrigation conditions, irrigating at 100% crop evapotranspiration (ET) per day, combined with high-density planting, can significantly increase yield and water use efficiency (Singh et al., 2020; Bahadur et al., 2021). In addition, staged and batched water and fertilizer supply (such as NPK drip irrigation once every 7 days) can better meet the needs of different growth stages, enabling continuous growth and high yield of bitter gourd (Turkar and Deshmukh, 2018). In the specific implementation, it is also necessary to adjust the density and irrigation plan according to the variety, climate and soil conditions, so as to maximize the utilization of resources and achieve high yield (Xu et al., 2023).

3 Morphological Traits Related to High Yield

3.1 Vine length, branching patterns, and canopy architecture

The length of the vine and the number of branches are important foundations for high yield of bitter gourd. Plants with longer vine lengths and more branches usually have a larger photosynthetic area, stronger growth vigor, are more likely to bear more fruits, and increase the yield per plant (Gupta et al., 2016; Lavale et al., 2022). Under high-density planting and drip irrigation conditions, a reasonable canopy structure can make the light distribution more uniform, reduce leaf overlap, improve photosynthetic efficiency, thereby promoting fruit development and increasing yield (Selvam et al., 2020; Bahadur et al., 2021). Different branching types and canopy structures also provide abundant genetic materials for breeding high-yield varieties (Alhariri et al., 2021; Mallikarjuna et al., 2024).

3.2 Leaf morphology, chlorophyll content, and photosynthetic efficiency

Leaf morphology (such as leaf area, leaf shape, and leaf thickness) directly affects photosynthesis. High-yield groups usually have large leaf area and high chlorophyll content, which can increase the photosynthetic rate per unit area (Mehta et al., 2024). Drip irrigation can maintain the water content and chlorophyll content of leaves, further improving photosynthetic efficiency and dry matter accumulation (Bahadur et al., 2021). The research also found that the heritability of leaf traits is relatively high and the selection potential is large, which is an important direction for high-yield breeding (Panigrahi et al., 2024).

3.3 Flowering dynamics, sex ratio, and fruit set characteristics

Flowering time, the ratio of male to female flowers and fruit setting rate are the key reproductive traits that affect yield. The groups with early flowering, high proportion of female flowers and high fruit setting rate tend to have higher yield per plant (Moharana et al., 2022; Srinivasulu and Singh, 2024). QTL mapping and genetic analysis indicated that female flower nodes, the number of male and female flowers, and fruit setting were closely related to yield and controlled by multiple genes (Rao et al., 2021; Kaur et al., 2022). High-density planting combined with drip irrigation helps regulate the flowering rhythm and increase the fruit setting rate, thereby enhancing the total yield (Alhariri et al., 2021).

4 Influence of High-Density Planting on Morphology

4.1 Changes in plant height, internode length, and leaf arrangement

Under high-density planting conditions, bitter gourd plants will show obvious morphological changes. As the density increases, the competition among plants intensifies, their height will rise, and the internodes will become longer. This is to compete for more light resources. The leaves will be arranged more densely, and some leaves will overlap, thereby reducing the light-receiving area of a single leaf and lowering the photosynthetic efficiency (Seong et al., 2015). These changes are the adaptive responses of bitter gourd under limited light and space conditions.

4.2 Canopy closure effects on light penetration and air circulation

High density will cause the canopy of bitter gourd to close more quickly, and the light inside the canopy will be significantly reduced. Studies have found that under high-density conditions, the light intensity at the bottom of the canopy decreases significantly, and the net photosynthetic rate of leaves drops by 41% to 71%, affecting the photosynthesis of lower leaves (Seong et al., 2015). The closure of the canopy will also reduce air circulation and increase humidity, thereby raising the risk of diseases. Therefore, appropriately pruning low and weak branches can improve the ventilation of the canopy and the distribution of light.

4.3 Morphological adaptations to inter-plant competition

In high-density environments, bitter gourds will adopt various morphological adaptation strategies to cope with competition. The plants will exhibit characteristics such as longer main vines, fewer lateral vines, and reduced root weight in order to prioritize growth and obtain light and nutrients (Seong et al., 2015). At the same time, the leaf area index will increase, with more leaves concentrated at the top to better utilize the light from the top. Moderate dense planting combined with reasonable pruning can not only increase the yield per unit area, but also improve the commercial fruit rate.

5 Influence of Drip Irrigation on Morphology

5.1 Effects on root architecture and distribution

Drip irrigation can provide precise water supply, keep the moisture in the soil of the root zone evenly distributed, help the root system of bitter gourd expand to the surface and middle layers, and enhance the water and nutrient absorption capacity (Mali et al., 2017). Compared with traditional irrigation, drip irrigation reduces deep water seepage and surface evaporation. The root system will be concentrated in the water and fertilizer supply area, making it easier to efficiently utilize nutrients and water (Turkar and Deshmukh, 2018). If combined with bio-organic fertilizer or biostimulants, the root morphology and rhizosphere environment can be further improved (Wang et al., 2024).

5.2 Influence on vine vigor, leaf turgidity, and fruit development

Drip irrigation can significantly increase the vine length, branch number and dry matter accumulation of leaves of bitter gourd, making the plants grow more vigorously (Bahadur et al., 2021). When there is sufficient and uniform moisture, the turgor pressure of leaves is better, the photosynthetic efficiency is higher, the leaves will be thicker, and the chlorophyll content will also increase (Dolatmand-Shahri et al., 2024). In terms of fruit growth, drip irrigation can promote fruit enlargement, increase weight and uniformity, thereby improving the commercial fruit rate and total yield (Samad, 2018). High-frequency and moderate drip irrigation combined with reasonable fertilization can also enable fruits to ripen earlier and achieve high yields.

5.3 Interaction with nutrient uptake and morphological expression

Drip irrigation fertilization (integrated water and fertilizer) can greatly improve the efficiency of bitter gourd in absorbing nutrients such as nitrogen, phosphorus and potassium (Mali et al., 2017). This not only makes the root system absorb nutrients more efficiently, but also directly reflects in the plant morphology, such as thicker vines, thicker leaves, and better fruit development. Drip irrigation fertilization can also increase the dry matter and nutrient content of fruits. However, when the water and fertilizer levels are too high, it may reduce the content of some antioxidant substances (such as vitamin C) (Abraham et al., 2018). In addition, drip irrigation can also regulate the rhidal environment, promote the activities of beneficial microorganisms, and indirectly optimize the morphological performance of plants (Figure 1) (Wang et al., 2024).

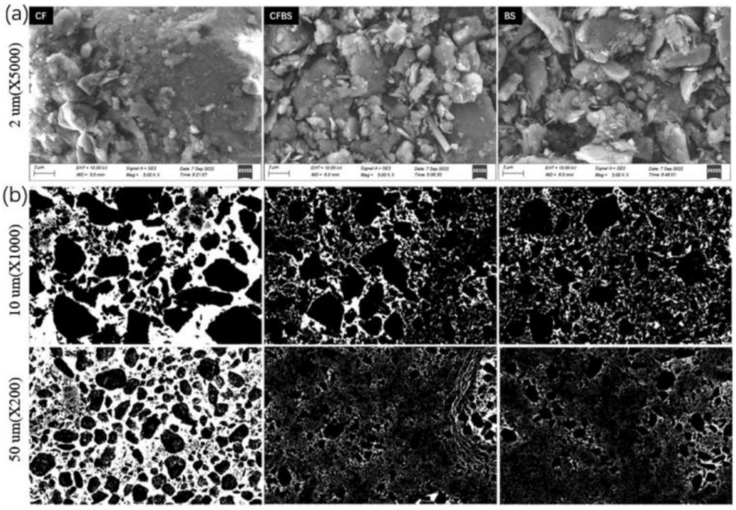

Figure 1 (a) Soil microstructure under different treatments and (b) distribution of soil pores under different treatments: white areas represent pores and black areas represent soil particles (Adopted from Wang et al., 2024)

6 Morphological Indicators of High-Yield Bitter Gourd Populations

6.1 Key morphological traits linked to yield performance

The yield performance of high-yielding bitter gourd is closely related to many morphological traits. It is generally believed that traits such as fruit weight, fruit length, fruit diameter, fruit quantity, flesh thickness and vine length are significantly positively correlated with the yield per plant and are important references for judging high yield (Iqbal et al., 2016; Yadagiri, 2017; Liu, 2024). Among them, fruit weight (r=0.81), fruit length (r=0.73), flesh thickness (r=0.65), and fruit diameter (r=0.63) had the strongest correlations with yield (Wan et al., 2022). In addition, early flowering and a high ratio of male to female flowers will also directly affect the yield (Prasanth et al., 2020).

6.2 Trait stability and variability under combined treatments

Under conditions of high-density planting and drip irrigation, these yield traits usually have high heritability and significant genetic progression, indicating that they are mainly controlled by genes and have less environmental influence, making them suitable for improvement through phenotypic selection (Panigrahi et al., 2024). For instance, the heritability of traits such as fruit weight, fruit length, fruit quantity and vine length all exceeds 90%, and they remain stable in different environments, which can be used as important selection indicators for high-yield breeding (Mehta et al., 2021). However, traits such as fruit surface nodules and fruit color are greatly affected by the environment. It is best to combine molecular marker-assisted selection to improve breeding efficiency (Mallikarjuna et al., 2024).

6.3 Potential morphological markers for selection in breeding programs

Overall, fruit weight, fruit length, fruit diameter, fruit quantity, flesh thickness and vine length are not only closely related to yield, but also have high heritability and improvement potential, and are ideal reference traits for high-yield breeding (Mehta et al., 2021; Mallikarjuna et al., 2024). In addition, early flowering, the ratio of male to female flowers, fruit nodules and fruit color, etc. can also be used as auxiliary references. Especially in molecular marker-assisted selection (MAS) and QTL mapping studies, these traits have been proved to be related to high yield (Alhariri et al., 2021). When these indicators are used in combination, new varieties of bitter gourd with high yield and strong adaptability can be screened out more quickly.

7 Case Study: Field Evaluation of High-Density + Drip Irrigation in Bitter Gourd

7.1 Site description, variety selection, and experimental design

This case study was conducted in the field plots of the main bitter gourd production areas. The soil was loam, and the drainage and irrigation conditions were relatively good. The experiment adopted high-density planting in combination with a drip irrigation system, mainly aiming to observe the impact of this model on the yield and morphological traits of bitter gourds. The selected varieties are high-yielding and highly resistant main cultivated varieties, such as ‘Preethi’ and ‘Reyan No.1’, etc. (Abraham et al., 2017). Random block design was used in the experiment, with different planting densities (70~100 plants /667m²) and drip irrigation treatment. Some were also combined with plastic film mulching and different levels of fertilizer and water management (Kayande et al., 2016; Abraham et al., 2018).

7.2 Morphological measurements and data collection protocols

The measured morphological traits include main vine length, number of primary branches, dry matter content of leaves, fruit length, fruit diameter, single fruit weight, number of fruits per plant, etc. (Samad, 2018). Part of the data was measured regularly, and the other part was determined centrally during the harvest period. All samples were collected according to a unified standard, ensuring the accuracy and comparability of the data. The parameters of the drip irrigation system (such as emitter flow rate, spacing, and irrigation frequency) and the fertilizer-water management schemes (such as NPK dosage and application frequency) are all recorded in detail (Mali et al., 2017; Singh et al., 2020).

7.3 Results: yield outcomes, morphological trait correlations, and farmer perspectives

The results show that high-density planting combined with drip irrigation significantly increases the market yield and water and fertilizer utilization efficiency of bitter gourd. Under drip irrigation conditions, traits such as the length of the main vine, fruit weight, and the number of fruits per plant were all improved, and were significantly positively correlated with the final yield (Samad, 2018; Singh et al., 2020). For example, under drip irrigation + high-fertilizer treatment, the market yield can reach 21.9~28.7 t/ha, the water productivity increases to 5.98~6.33 t/ha·mm, and at the same time, the fruit quality (length, diameter, single fruit weight) is also improved (Mali et al., 2017). Farmers have reported that this model not only saves water and labor, but also enables early maturity and increased income. The economic benefits are obvious, and the input-output ratio can reach up to 2.32 (Soomro et al., 2021). Some farmers suggest that the drip irrigation system and fertilizer and water management can be further optimized to adapt to different soil and climatic conditions (Turkar and Deshmukh, 2018).

8 Agronomic Implications and Recommendations

8.1 Best-fit planting densities for specific bitter gourd varieties

Studies show that the optimal planting density of bitter gourd varies depending on the variety and cultivation method. In greenhouses, a density of 305 plants per 10a can achieve the highest total yield and commercial fruit rate. When the density drops to 235 plants per 10a, the weight of individual fruits and roots will be higher, but the total yield will decline. When the density exceeds 305 plants per 10a, the photosynthetic rate will decline, the number of fruits will decrease, and the increase in yield will be limited (Seong et al., 2015). Grafting bitter gourd is suitable for a density of 70 to 100 plants per 667m². Combined with pruning weak branches and lower branches, it can enhance ventilation and light penetration, and increase yield. Therefore, it is recommended to select 305 plants per 10a or 70~100 plants per 667m² according to the variety and cultivation environment, and combine pruning management to optimize the population structure.

8.2 Drip irrigation scheduling tailored to morphological responses

Under drip irrigation conditions, bitter gourd is very sensitive to the frequency and volume of irrigation. The maximum yield can be achieved by replenishing 100% of the evapotranspiration (ET) every day. The irrigation of 75% ET every other day can achieve the highest water use efficiency (WUE) (Bahadur et al., 2021). If the underground drip irrigation pipes are buried to a depth of 10~15cm and combined with a high fertilizer-water level (NPK 150:120:120 kg/ha), both the yield and water productivity will increase significantly (Mali et al., 2017). Drip irrigation combined with plastic film mulching and high fertilizer and water management can also promote the growth of main vines, increase branching and dry matter accumulation, making bitter gourds mature earlier and have higher yields (Abraham et al., 2018). Therefore, it is recommended to choose the irrigation method of 100% ET per day or 75% ET every other day according to the growth stage of the variety and soil conditions, give priority to underground drip irrigation, and combine it with efficient integrated fertilizer and water management (Turkar and Deshmukh, 2018).

8.3 Integration into sustainable high-yield production models

High-density drip irrigation cultivation is best used in combination with organic and inorganic fertilizers, along with microbial agents (such as arbuscular mycorrhizal fungi) and mulching measures. This can improve resource utilization and stress resistance (Dolatmand-Shahri et al., 2024). The ratio of 50% organic fertilizer +50% inorganic fertilizer can significantly improve growth, yield and economic benefits (Ghimire et al., 2023). Drip irrigation not only saves water and labor, but also reduces salt accumulation and the occurrence of diseases. It is suitable for promotion in areas with limited resources and ecological sensitivity (Soomro et al., 2021). Therefore, it is suggested to promote the sustainable high-yield model of “drip irrigation + high-density + combination of organic-inorganic fertilizer” for bitter gourd, taking into account yield, quality and environmental friendliness.

9 Concluding Remarks

Under integrated management such as high-density planting and drip irrigation, high-yield bitter gourd groups showed obvious morphological differences and increased yields. Research has found that morphological traits such as fruit length, fruit diameter, single fruit weight, and the number of fruits per plant are closely related to yield, and these traits vary significantly among different genotypes. Some genotypes have higher yield potential due to the appropriate ratio of male to female flowers and good fruit development. Drip irrigation combined with reasonable fertilization can further increase the number of fruits and the weight of individual fruits, improve the efficiency of water and nutrient utilization, and thereby significantly increase the total output. By using molecular markers and QTL mapping, some key trait genes related to high yield can also be identified, providing a theoretical basis for molecular-assisted selection and precision breeding.

However, at present, research on the mutual influence among genotype (G), environment (E), and management (M) is still insufficient. Many studies are only conducted in a single environment or under a single management approach, lacking systematic comparisons under multiple environments and management conditions. The regulatory mechanisms of environmental factors and management measures on different genotypes are also not clear enough, which brings difficulties to precise management and variety adaptability evaluation. At the molecular level, whether high-yield-related QTLs are stable under different environmental and management conditions, as well as their expression regulatory mechanisms, also require further research.

Future research on the precise cultivation and breeding of bitter gourd requires the joint optimization of multiple aspects. Systematic experiments should be conducted under different environments and management models to deeply analyze the impact of G×E×M interactions on morphology and output. By integrating high-throughput phenotypic technology and molecular omics, superior genotypes with strong adaptability and stable yield can be screened out, and then combined with QTL mapping for molecular-assisted breeding. At the same time, it can promote the application of intelligent perception and machine learning in the growth monitoring, maturity judgment and precise management of bitter gourd, and improve the scientific nature of cultivation decisions. It is also necessary to enhance the integration of efficient cultivation measures such as drip irrigation and close planting with genetic improvement to achieve efficient utilization of water and fertilizer and simultaneous breeding of high-yield and high-quality varieties. These measures will provide technical support for the sustainable development of the bitter gourd industry and help achieve the goals of high yield, high quality and efficient utilization of resources.

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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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