

Research Insight

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Effects of Irrigation Frequency on Growth, Fruit Development and Fruit Quality in Melon

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Abstract Melon is a high-value horticultural crop whose market performance depends not only on yield, but also on sweetness, texture, appearance, and storability. Among irrigation variables, frequency is especially important because it controls how often the root zone is rewetted, how strongly soil or substrate moisture fluctuates, and how stable the physiological environment remains during flowering, fruit set, enlargement, and ripening. This review examines how irrigation frequency influences melon growth, fruit development, and fruit quality under open-field, protected, soil-grown, and soilless systems. The literature shows a clear pattern: very infrequent irrigation often restricts leaf expansion, photosynthesis, and fruit growth because melon is sensitive to sudden water deficits, particularly around flowering and early fruit enlargement. By contrast, overly frequent irrigation can sustain vegetative vigor and fruit enlargement but may dilute soluble solids, increase cracking risk in some systems, and reduce water productivity when total water input is excessive. Between these extremes, stage-specific scheduling tends to perform best. Studies from semi-arid and greenhouse systems consistently indicate that adequate or relatively frequent irrigation during flowering and early fruit growth is needed to protect yield, whereas mild deficit or reduced irrigation frequency during late maturation can improve soluble solids, vitamin C, antioxidant activity, firmness, and sometimes reduce cracking without a major yield penalty. Evidence from eastern China, including a two-year greenhouse muskmelon experiment in Haining, Zhejiang, indicates that a moderate irrigation regime can produce a better balance between yield, quality, irrigation water use efficiency, and nitrogen use efficiency than either lower or higher water inputs. In northwestern China and other water-limited regions, pulsed drip irrigation, sensor-guided scheduling, and regulated deficit irrigation have shown strong promise for sustaining fruit quality while reducing water use. Overall, the review argues that irrigation frequency should be treated as a developmental and quality-management tool rather than simply a calendar decision. Future research should separate the effects of frequency from total irrigation amount, compare cultivar-specific responses, and strengthen evidence from humid protected systems such as those common in the Yangtze River Delta.

Keywords Melon; Irrigation frequency; Fruit development; Fruit quality; Deficit irrigation; Drip irrigation; Protected cultivation; Water use efficiency

1 Introduction

Melon is one of the most commercially important fruit vegetables in warm and semi-arid production regions, and it is also widely grown in protected structures where fruit appearance, sweetness, and uniformity determine market value. Recent irrigation research continues to treat melon as a strategic crop because of its high economic return per unit area and its sensitivity to water management. A recent greenhouse-melon study in Taiwan, citing FAOSTAT, described worldwide melon production at roughly 29.48 million tons over more than 1.09 million hectares, while a greenhouse muskmelon study from southeast China emphasized that China remains the dominant producer and that melon occupies a central place in the country's protected horticulture systems. These studies are useful for a review because they connect agronomic management with market quality, not just yield. Melon also has a distinct position in horticultural research because fruit value is shaped by multiple traits at once. Consumers and supply chains judge melons by soluble solids, sugar-acid balance, firmness, flesh color, aroma, netting or skin appearance, and shelf-life behavior. This means irrigation research on melon rarely ends with a simple "more water versus less water" conclusion. Instead, the key question is how to regulate water in a way that preserves enough vegetative strength to fill fruit while also favoring the quality traits that make fruit saleable. Recent studies on fruit development, sugar metabolism, firmness, and ripening biology reinforce this point by

showing that fruit growth and quality formation are tightly linked developmental processes (Cheng et al., 2022; Gustani et al., 2024; Wang et al., 2025).

Water management in melon has become more difficult for two reasons. The first is the broad pressure of water scarcity in many melon-producing regions, including semi-arid Mediterranean zones, northwestern China, and dry parts of North America. The second is that melon quality responds not only to total irrigation amount, but also to the timing and rhythm of water delivery. A global meta-analysis of vegetable deficit irrigation showed that mild to moderate deficit can often preserve yield better than severe deficit, but melon-specific studies make clear that the developmental stage at which the deficit occurs is just as important as the severity itself (Fabeiro et al., 2002; Singh et al., 2021; Yavuz et al., 2021). In protected systems the challenge is even more delicate. Over-irrigation can reduce water use efficiency, increase nutrient leaching, dilute sweetness, and in some cases aggravate fruit cracking, while under-irrigation can suppress canopy development, reduce leaf gas exchange, and limit fruit growth. A two-year commercial melon study in Murcia showed that sensor-guided irrigation reduced water inputs by 27%-30% without yield loss and increased both water and nitrogen productivity, which suggests that a major part of the problem is not lack of technology but lack of precise scheduling. Likewise, a recent greenhouse muskmelon study reported that mild water deficit at fruit maturity significantly lowered cracking while improving commercial quality, showing that “too much” irrigation can be harmful late in the cycle (Zapata-García et al., 2023; Xue et al., 2025).

Irrigation frequency is the temporal dimension of irrigation management. Total seasonal water amount matters, but the interval between irrigation events determines how strongly roots experience drying cycles, how much oxygen remains in the root zone, how stable nutrient transport is, and how sharply the plant alternates between high and low water status. In melon, this matters because fruit growth depends on continuous assimilate supply and sustained cell expansion, while sweetness and firmness often improve when late-season water supply becomes slightly more restrictive. For this reason, frequency should not be treated as a secondary technical detail. It is a direct regulator of source-sink relations, root uptake, and final fruit quality (Sensoy et al., 2007; Li et al., 2012; Sun et al., 2024). The evidence now comes from several kinds of systems. Open-field work has compared longer and shorter irrigation intervals across fixed water amounts. Protected-environment studies have tested pulsed irrigation several times per day, especially in drip and soilless systems. Newer precision-irrigation studies go further by combining irrigation timing with plant-based or sensor-based signals, effectively turning irrigation frequency into a variable that changes with crop stage and crop stress rather than with a fixed calendar. This shift is particularly important for melon because the sensitive phases are not identical from transplanting to ripening (Chang et al., 2019; Zapata-García et al., 2023; Fang et al., 2026).

This study examines irrigation frequency from the perspective of three connected outcomes: vegetative growth, fruit development, and fruit quality. Instead of treating water management as a purely engineering issue, the discussion follows melon development across stages and asks how irrigation rhythm changes canopy formation, root activity, fruit set, fruit enlargement, ripening, and commercial quality traits. It also considers regional case studies, with special attention to eastern China and the Zhejiang-related context, because protected melon production in those regions makes irrigation scheduling especially consequential. The study finally summarizes sustainable strategies, recent technological advances, current research limitations, and practical directions for future work.

2 Water Requirements and Growth Characteristics of Melon

2.1 Growth and development stages of melon

Melon growth is typically divided into an early vegetative stage, a flowering and fruit-set stage, a fruit enlargement stage, and a maturation or ripening stage. Although these labels are simple, the physiological meaning of each stage is different. During early vegetative growth, the plant is building photosynthetic area and root capacity. During flowering and fruit set, reproductive stability becomes critical because water stress can interfere with flower function, fruit initiation, and the early cell division processes that largely determine later fruit size. During enlargement, fruit becomes a dominant sink for water and photoassimilates. During maturation, the

balance shifts from rapid accumulation of fresh mass toward sugar concentration, metabolic change, aroma formation, and tissue softening (Fabeiro et al., 2002; Liu et al., 2024; Wang et al., 2025).

Recent developmental studies support this stage-based view. Transcriptomic and metabolomic analyses show that melon fruit follows a strong developmental sequence in which early growth is associated with active cell division and expansion, and later stages are associated with sharp changes in sucrose, organic acids, texture-related pathways, and ripening regulation. A 2025 transcriptome-metabolome study described middle and late fruit development as a typical S-shaped growth process, while a 2024 time-series transcriptome study confirmed clear differences between earlier and later maturity stages in sugar and organic-acid metabolism. This matters for irrigation research because the same water regime cannot be expected to serve all developmental goals equally well (Liu et al., 2024; Wang et al., 2025).

2.2 Water demand during different growth stages

Melon does not demand water uniformly across the season. Early vegetative growth requires enough moisture to support establishment and leaf area development, but seasonal demand often peaks from flowering into fruit enlargement, when transpiration and sink demand are both high. Stage-based deficit irrigation experiments have repeatedly shown that water restriction during blooming or fruit set is more damaging to yield than comparable restriction imposed later. In the classic controlled-deficit study by Fabeiro and colleagues, deficits during blooming most strongly reduced production, deficits during setting affected both quantity and quality, and deficits during ripening had a stronger effect on quality than on yield (Fabeiro et al., 2002).

More recent work confirms that stage sensitivity remains a central principle. Yavuz and colleagues, working in a semi-arid environment, found the highest yields under stress-free irrigation across all stages, but they also showed that different stage combinations shifted quality and water use efficiency in different ways. Kuscu and Turhan later reported that maintaining full irrigation up to fruit ripening and then shifting to 50% ETc produced nearly the same three-year average yield as full irrigation while improving water productivity and several quality traits. In greenhouse substrate production, Xue and colleagues found that mild deficit during maturity reduced cracking and improved quality without a significant penalty in yield. Together these studies suggest that melon water demand is highest, and least negotiable, before and during early fruit growth, while the late stage offers more room for quality-oriented adjustment (Yavuz et al., 2021; Kuscu and Turhan, 2022; Xue et al., 2025).

2.3 Physiological responses of melon to water availability

When water becomes limiting, melon responds through declines in leaf water status, stomatal conductance, transpiration, and net photosynthesis. These are not abstract laboratory traits; they directly shape fruit growth because they determine how much carbon and water are available for sink tissues. Recent studies in field and greenhouse systems show that moderate water deficits can be tolerated if leaf gas exchange remains high enough and if the plant avoids prolonged turgor loss. Under severe or prolonged deficits, however, stomatal closure and reduced photosynthesis lead to smaller canopies, weaker fruit growth, and lower yield (Miceli et al., 2023; Panda et al., 2025; di Santo and Barrios-Masias, 2026).

At the same time, melon does show some capacity for acclimation. In a recent study combining deficit irrigation with biostimulant preconditioning, melon plants under a suppressed-irrigation treatment showed evidence of osmotic adjustment, and the biostimulated treatment further improved water uptake and irrigation water productivity while increasing phenolic compounds in fruit. This is important because it shows that the physiological response to irrigation frequency is not determined by water alone; root-zone conditions, stress history, cultivar traits, and biological inputs can all shift the plant's response threshold (Zapata-García et al., 2025).

2.4 Critical irrigation periods for melon production

The literature points to two especially critical periods. The first is flowering to early fruit enlargement, when water deficits can reduce fruit set, lower fruit number, and restrict the cell division and early expansion that underpin later fruit size. The second is fruit maturity, not because the plant becomes fragile in the same way, but because

water status at this stage strongly affects soluble solids, firmness, cracking risk, and market quality. This second period is therefore critical in a different sense: it is the stage where water can be adjusted most effectively to reshape quality (Fabeiro et al., 2002; Yavuz et al., 2021; Xue et al., 2025).

For growers, the practical implication is straightforward. Irrigation frequency should be higher or at least more stable when the crop is setting and enlarging fruit, especially in protected systems with shallow effective rooting or soilless substrate (Figure 1). Later, once marketable fruit size is largely established, reducing frequency or applying mild deficit can improve sweetness and reduce cracking, provided the stress remains controlled and does not become severe enough to depress yield. That principle appears consistently in studies from Spain, Turkey, Taiwan, and China despite differences in climate and production system (Kuscu and Turhan, 2022; Sun et al., 2024; Xue et al., 2025; Fang et al., 2026).

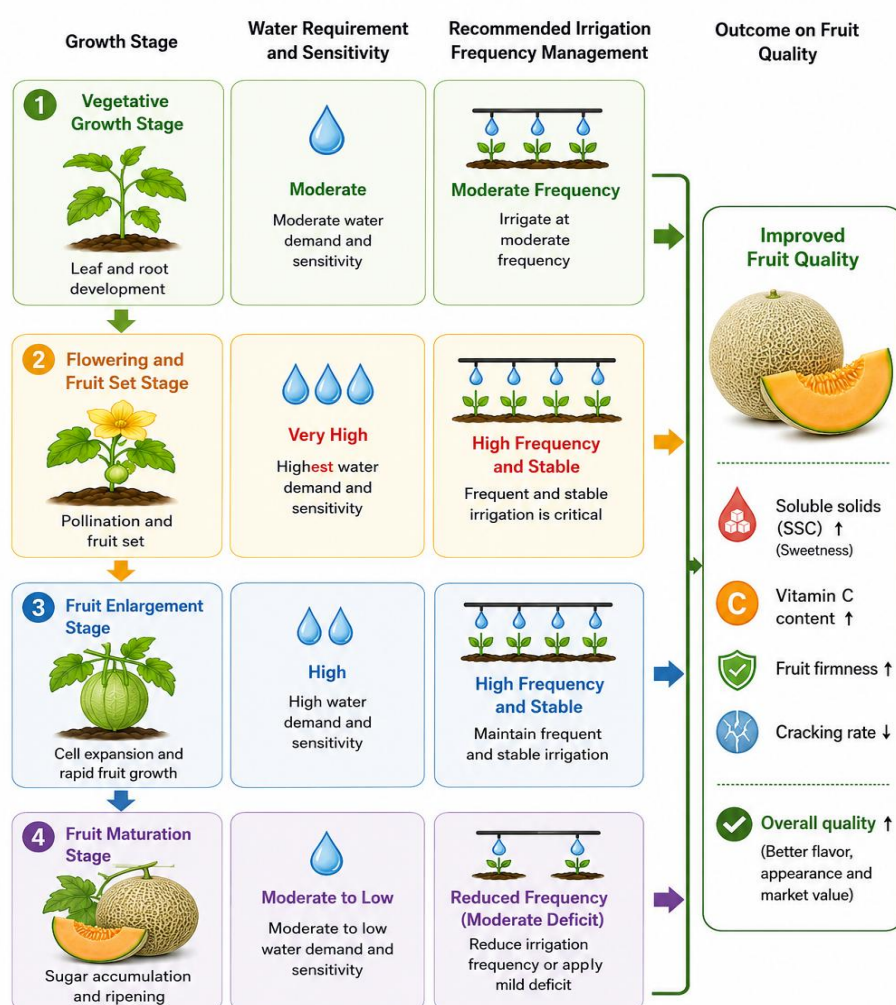


Figure 1 Framework of water sensitivity and irrigation frequency management across melon growth stages

3 Effects of Irrigation Frequency on Melon Growth

3.1 Influence on plant height and biomass accumulation

Vegetative growth is usually the first visible response to irrigation frequency. When irrigation is delivered in smaller, more frequent doses under drip systems, the root zone tends to experience fewer sharp moisture fluctuations, which often supports taller plants, thicker stems, higher fresh mass, and greater dry matter accumulation. In a net-house study from Cambodia, three drip irrigations per day produced the greatest plant height, stem diameter, biomass accumulation, and yield relative to one or two irrigations per day and hand watering, despite equal total water based on crop requirement. This is a useful reminder that frequency can change plant performance even when the seasonal water amount is similar (Nut et al., 2019).

Open-field evidence points in the same direction, although the optimum interval depends on climate and soil. Sensoy and colleagues found that a 6-day schedule with higher pan-based replacement produced the highest melon yield and strongly affected fruit traits, indicating that lower frequency combined with lower replacement was too restrictive. Similarly, greenhouse studies in southeast China have shown that low-water treatments can increase some quality attributes, but they also lower biomass accumulation and tend to suppress maximal yield. The main message is that adequate growth depends on keeping vegetative stress within a narrow range (Sensoy et al., 2007; Yue et al., 2023).

3.2 Effects on root development and water uptake

Root responses to irrigation frequency are more complex than shoot responses. In field-grown crops, less frequent irrigation can sometimes encourage deeper rooting, but in high-value melon systems, especially greenhouses and substrates, large drying cycles often reduce effective water uptake before any benefit from “hardening” appears. A recent cantaloupe study found that severe deficit weakened plant water status enough to trigger water-conservative behavior, while also suggesting reduced root hydraulic conductivity under stronger soil drying. By contrast, moderate deficit maintained functional performance much better (di Santo and Barrios-Masias, 2026).

Protected-environment studies show that root-zone physical conditions matter alongside watering rhythm. In a BMC Plant Biology study on greenhouse muskmelon, supplemental soil aeration under subsurface drip increased yield, leaf area index, dry matter, and irrigation use efficiency, showing that water-frequency effects cannot be separated from oxygen supply in the root zone. In other words, a frequent irrigation schedule is beneficial only if it avoids hypoxia and keeps the wetting pattern accessible to roots (Li et al., 2020).

Northwestern China adds another layer because high-EC irrigation water and protected production often require pulsed delivery rather than a few large applications. Sun and colleagues found that, in high-EC irrigation regions, irrigation frequency had a curvilinear effect, with integrated growth, water use efficiency, fertilizer use efficiency, and fruit quality improving and then declining as frequency increased; across their tested conditions, seven pulses per day emerged as the best compromise. This result is especially revealing because it shows that “more frequent” is not always better. There is an optimum beyond which additional pulsing adds management complexity without physiological gain (Sun et al., 2024).

3.3 Effects on leaf growth and photosynthetic performance

Leaf area is central to melon productivity because the fruit depends on a continuous supply of current photoassimilates rather than large stored reserves. Studies under deficit irrigation repeatedly show that reduced water availability lowers relative water content, stomatal conductance, and net photosynthesis, which then limits leaf expansion and canopy persistence. In inoculated and uninoculated melon plants, Miceli and colleagues observed that stronger deficits reduced stomatal conductance and fruit yield, while moderate deficit combined with mycorrhiza improved water use efficiency and preserved some quality traits (Miceli et al., 2023).

The same physiological pattern appears outside Mediterranean systems. Panda and colleagues reported that increasing water stress in a Mediterranean climate reduced yield and fruit traits and that the best outcomes for relative water content, stomatal conductance, and yield were associated with full irrigation and the milder reduction level. In Murcia, sensor-based precision irrigation improved water productivity without depressing stem water potential, photosynthesis, or stomatal conductance, suggesting that irrigation frequency can be reduced or adjusted only when plant status is monitored carefully enough to avoid a hidden physiological penalty. (Zapata-García et al., 2023; Panda et al., 2025).

3.4 Comparative responses under different irrigation frequencies

Taken together, the comparative literature suggests that the “best” irrigation frequency depends on production environment. In greenhouse and nethouse systems with localized drip or substrate culture, relatively frequent or pulsed irrigation often performs better because the effective root volume is smaller and the system dries quickly. That is why three irrigations per day improved growth under net-house conditions, and why seven pulses per day performed well in the high-EC greenhouse study from northwestern China (Nut et al., 2019; Sun et al., 2024).

In open-field systems, however, medium intervals can be appropriate when water amount is sufficient and soil water storage is greater. Sensoy's field study showed that 6-day irrigation outperformed a 12-day interval, but that does not mean "daily" irrigation is always needed outside a greenhouse. The broader point is that irrigation frequency must be interpreted relative to rooting depth, evaporative demand, substrate volume, and water quality. Reviews and greenhouse-irrigation syntheses increasingly argue that the real goal is not a fixed interval but a frequency that keeps plants away from both acute stress and prolonged oversupply (Figure 2) (Sensoy et al., 2007; Nikolaou et al., 2019; Fang et al., 2026).

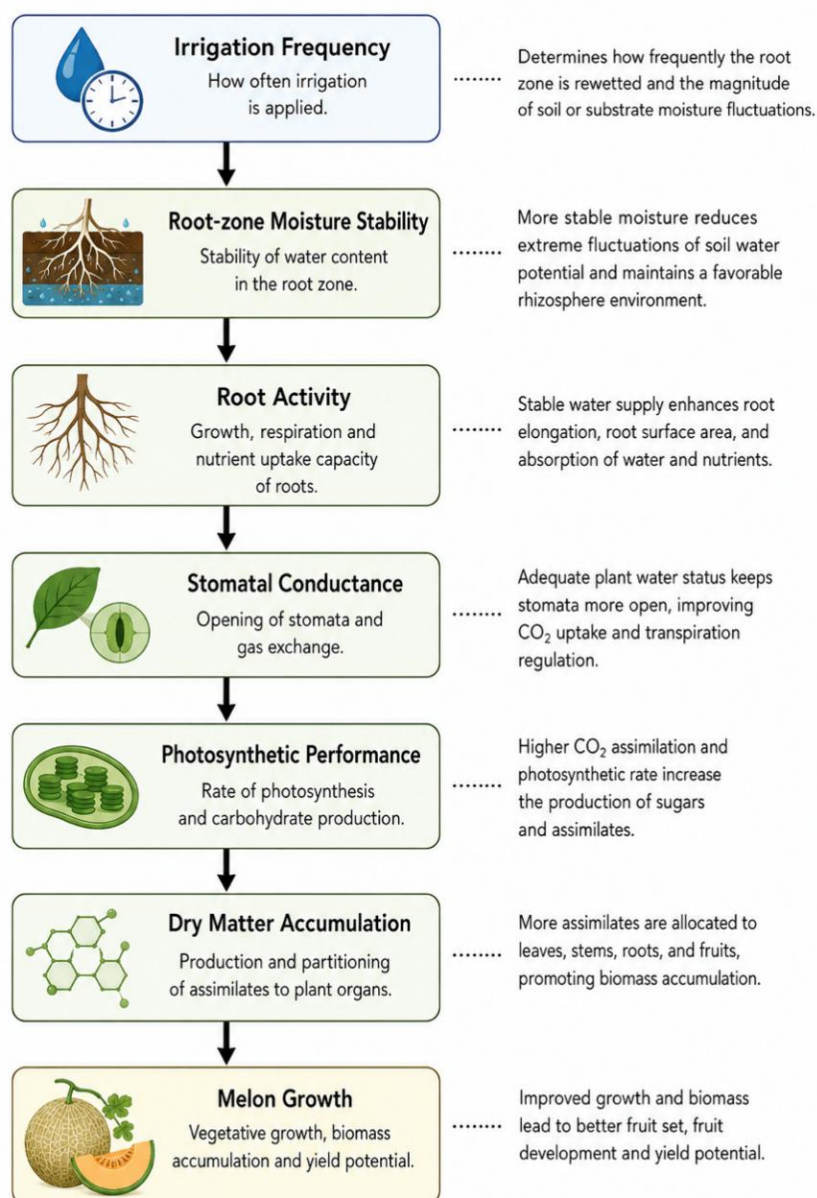


Figure 2 Physiological pathway through which irrigation frequency regulates melon growth

4 Effects of Irrigation Frequency on Fruit Development

4.1 Fruit set and early fruit growth

Fruit development begins with a fragile transition. At flowering and immediately after fruit set, the plant is deciding how many fruits it can support, and the developing fruit is establishing its sink strength through active cell division and early expansion. Water deficits at this stage can therefore reduce more than final fruit size; they can reduce the basic developmental capacity of the crop to produce marketable fruit. This principle has been clear since early controlled-deficit work, and it remains visible in current studies. Fabeiro and colleagues showed that

deficits during blooming had the lowest production, while Yavuz and colleagues found that treatments depriving the crop of stable water during reproductive development significantly reduced yield (Fabeiro et al., 2002; Yavuz et al., 2021).

Even in protected environments where daily irrigation can be precisely delivered, unstable moisture at this stage can be costly. The 2019 net-house experiment showed that more frequent drip events supported stronger vegetative development and higher yield, which likely reflects better protection of early sink establishment as well as better canopy support. More recent physiological work also indicates that flowering to early fruit enlargement is the point at which drops in plant water status can quickly translate into reduced stomatal conductance and weaker assimilate supply (Nut et al., 2019; di Santo and Barrios-Masias, 2026).

4.2 Fruit enlargement and weight accumulation

During enlargement, melon fruits become strong sinks for both water and carbon. This is the stage when irrigation frequency most directly affects fresh weight and marketable size. Field and greenhouse studies are remarkably consistent on this point: adequate irrigation during enlargement increases fruit weight, whereas stronger deficits reduce it. In the Haining greenhouse trial, higher water input increased yield, although the middle irrigation treatment proved better overall once quality and efficiency were considered. In Turkey, the highest average yields were achieved either with full irrigation or with a regime that delayed deficit until ripening, which implies that fruit enlargement was still protected by adequate water (Kuscu and Turhan, 2022; Yue et al., 2023).

Severe deficits during or before enlargement can also shrink fruit in greenhouse systems. The 2025 greenhouse muskmelon study found that deficits applied across both flowering-swelling and maturity stages reduced fresh and dry fruit weight, while field work in Nevada showed that severe deficit at 50% field capacity lowered yield by about 40% relative to full irrigation. These findings suggest that there is little agronomic value in letting fruit experience strong and repeated water shortages while they are still building mass (Xue et al., 2025; di Santo and Barrios-Masias, 2026).

4.3 Fruit maturation and ripening characteristics

The maturation stage is where irrigation frequency changes from being mainly a yield-management variable to being a quality-management variable. Many studies show that reducing irrigation or frequency late in development can raise soluble solids, improve the sugar–acid balance, and reduce disorders such as cracking. In northwestern China, Xue and colleagues found that mild deficit during maturity sharply reduced greenhouse muskmelon cracking while maintaining yield and improving quality. In Turkey, water stress treatments often improved quality traits even when they lowered yield, again indicating that the end of the cycle is the most responsive stage for targeted quality enhancement (Yavuz et al., 2021; Kuscu and Turhan, 2022; Xue et al., 2025).

The effect is not unlimited, however. If late deficit is too strong, fruit size and commercial acceptability can still decline. In Taiwan, Fang and colleagues reported that a plant-based regulated deficit strategy improved sweetness and reduced cracking in soilless systems, but it also reduced yield and fruit size there, while in soil-grown systems the same framework reduced irrigation by 19.3%-25.7% without compromising yield or fruit quality. This contrast is valuable because it shows that the same late-season deficit principle behaves differently in soil and soilless environments (Fang et al., 2026).

4.4 Physiological mechanisms linking water supply and fruit development

The physiological link between irrigation frequency and fruit development can be summarized in four connected steps. First, irrigation rhythm determines how stable soil or substrate moisture remains in the root zone. Second, root-zone stability shapes plant water status, stomatal behavior, and nutrient transport. Third, those whole-plant responses govern the amount and continuity of carbon and water delivered to the fruit. Fourth, fruit tissues translate those inputs into cell division, cell expansion, sugar concentration, acid metabolism, and mechanical integrity. This is why a small change in watering schedule can alter not just fruit size, but also cracking, sweetness, and firmness (Cheng et al., 2022; Gustani et al., 2024; Wang et al., 2025).

Melon fruit quality biology helps explain the stage effect. Integrated transcriptomic and metabolomic studies show that sucrose, glucose, organic-acid metabolism, and texture-related pathways all shift sharply across development and ripening. A review of melon firmness mechanisms similarly emphasizes that cell-wall remodeling during maturation is a major determinant of softening and storability. Therefore, when late irrigation frequency is reduced and fruit water influx becomes slightly more restricted, sugar concentration may rise and cracking pressure may fall, but if the stress is too strong, the fruit can lose mass and uniformity instead (Cheng et al., 2022; Gustani et al., 2024; Liu et al., 2024).

5 Effects of Irrigation Frequency on Fruit Quality

5.1 Soluble solids and sugar accumulation

Soluble solids concentration is the quality trait most consistently improved by mild water restriction in melon. This does not mean that drought “creates” sugar in a simple way. More often, reduced late-stage water supply limits further dilution and alters carbohydrate partitioning so that the concentration of sugars in the flesh becomes higher. In the Haining, Zhejiang greenhouse study, lower water treatments produced higher total soluble solids and vitamin C than the medium and high water treatments, even though they did not maximize yield. In the maturity-deficit study from China, mild deficit increased sugar-related quality and lowered cracking risk (Yue et al., 2023; Xue et al., 2025).

The pattern appears in other regions as well. Kuscü and Turhan reported that deficit treatments significantly affected soluble solids, total sugar, titratable acidity, vitamin C, and protein content, with quality traits generally improving under deficit irrigation. Miceli and colleagues similarly observed that moderate deficit combined with arbuscular mycorrhizal inoculation improved fruit soluble solids and the SSC/TA ratio. These results show why growers often accept slightly lower vegetative vigor or even a small yield penalty when the market strongly rewards sweetness (Figure 3) (Kuscü and Turhan, 2022; Miceli et al., 2023).

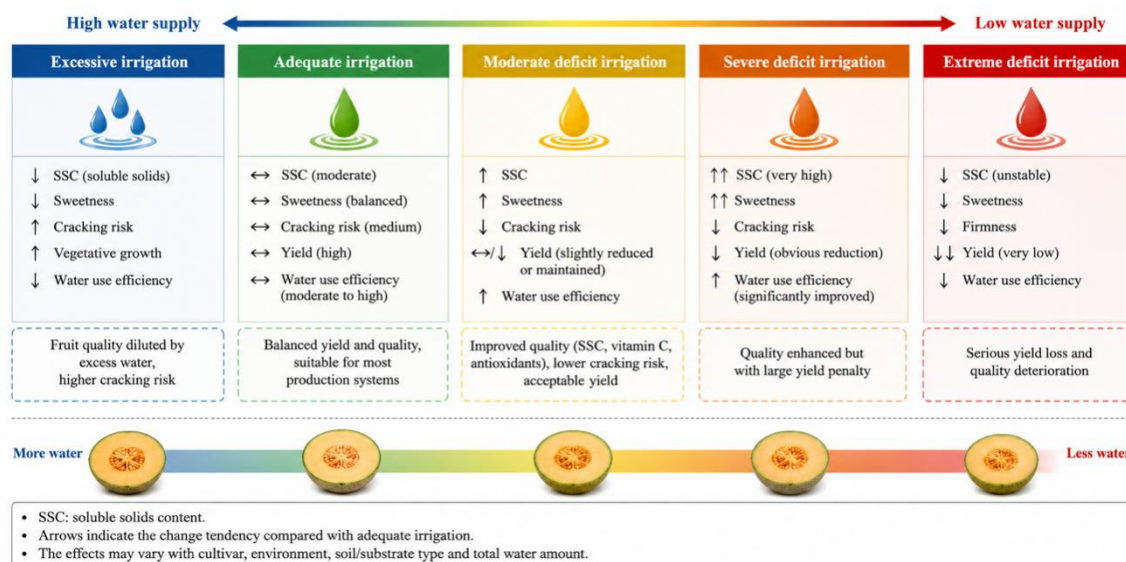


Figure 3 Quality formation of melon fruits under different water supply regimes

5.2 Organic acids and flavor formation

Flavor depends on more than sweetness. Organic acids help determine freshness, balance, and overall sensory character, and melon flavor is also shaped by volatile compounds that change across development and storage. Irrigation regime affects these traits by changing dilution, carbon metabolism, and ripening status. In a 2023 study of melon flesh and seeds under different irrigation regimes, sucrose, total sugar, titratable acidity, phenolic compounds, and antioxidant activity all responded significantly to how and when water was supplied. Notably, some deficit treatments improved phenolics and antioxidant activity while also shifting sugar composition (Ercan et al., 2023).

Molecular studies help explain why this happens. A Frontiers study comparing oriental melon cultivars found that sugar and organic-acid accumulation are developmentally regulated and tied to differential gene networks, while a 2024 maturity study showed strong changes in sucrose, citric acid, and related processes between 60% and 90% maturity fruit. From a practical perspective, this means irrigation frequency affects flavor most strongly when it modifies the developmental environment in which these pathways operate, especially late in fruit growth (Cheng et al., 2022; Liu et al., 2024).

5.3 Fruit firmness and shelf-life characteristics

Fruit firmness is a major commercial trait because it influences transport tolerance, shelf life, and susceptibility to mechanical damage and cracking. Irrigation affects firmness in two ways. First, it changes turgor and tissue hydration during growth. Second, it alters the pace of maturation and cell-wall remodeling. In greenhouse muskmelon, mild deficit during maturity reduced cracking substantially and improved the commercial balance between yield and quality, while a 2026 regulated deficit irrigation framework in Taiwan improved sweetness and reduced fruit cracking in soilless systems, even though yield trade-offs were observed (Xue et al., 2025; Fang et al., 2026).

The mechanistic literature adds depth to these agronomic findings. A recent review on melon firmness emphasized that maturation-related expression of cell-wall genes is central to texture loss and shelf-life decline. When irrigation is too frequent or too abundant late in the season, fruits may remain larger but structurally more vulnerable. When stress is mild and well-timed, fruits may become firmer, less crack-prone, and easier to store. In the mycorrhiza study, moderate deficit with AMF increased firmness and improved some quality traits, reinforcing the idea that firmness can be managed not only by less water, but by better physiological resilience (Miceli et al., 2023; Gustani et al., 2024).

5.4 Nutritional quality and bioactive compounds

Nutritional quality traits such as vitamin C, phenolics, antioxidant activity, and related bioactive compounds often rise under moderate water restriction. This pattern appears repeatedly in recent melon studies, although the response depends on cultivar, stage, and stress intensity. In Zhejiang, lower irrigation increased vitamin C in greenhouse muskmelon. In Murcia, sensor-based precision irrigation increased ascorbic acid by about one-third on average while also conserving water and improving water and nitrogen productivity. In the irrigation-regime quality study, deficit timing changed phenolic content and antioxidant activity as well as sugars (Ercan et al., 2023; Yue et al., 2023; Zapata-García et al., 2023).

This does not mean stronger stress always improves nutrition. Severe or poorly timed deficits can reduce size, yield, and sometimes firmness, which can offset any gain in concentration. The better interpretation is that mild, controlled deficit near the end of the fruit cycle often shifts fruit composition toward a denser nutritional and sensory profile. The biostimulation study strengthens this idea, because fruit from the biostimulated deficit treatment had higher phenolic concentration than fruit under precision irrigation alone (Zapata-García et al., 2025).

6 Representative Case Studies of Irrigation Management in Melon Production

6.1 Protected melon production in eastern china: implications for zhejiang province

For an author working from Zhejiang, the strongest directly relevant English-language case is the two-year greenhouse muskmelon experiment carried out in Haining, Zhejiang. The study tested three irrigation levels based on ETc and three nitrogen levels and concluded that the combination of 1.0 ETc with 95 kg N ha⁻¹ achieved the best compromise among yield, quality, irrigation water use efficiency, and nitrogen use efficiency. Low-water treatments improved vitamin C and soluble solids, but the balanced treatment was superior overall for production under local protected conditions. Because the work was conducted in Haining under a north subtropical monsoon climate and by a Zhejiang-based research team, it is especially appropriate as a regional anchor for review writing aimed at eastern China (Yue et al., 2023).

This case is valuable for another reason. It shows that, in humid and commercially intensive protected systems, the question is rarely whether less water improves sweetness. The real question is how to avoid the common farmer tendency toward excessive irrigation and fertilization while still keeping yield high enough for commercial greenhouse production. The Haining results suggest that irrigation in this region should be moderate rather than maximal, and that water scheduling should be coupled with nutrient management instead of treated independently. That conclusion fits well with the production realities of Zhejiang, where growers often target appearance and quality premiums in protected fruit (Yue et al., 2023).

6.2 Greenhouse melon irrigation management in the yangtze river delta region

Direct English-language field studies explicitly framed as “Yangtze River Delta melon irrigation” are still relatively limited, which is itself an important observation. However, existing evidence from the broader region still gives a useful picture. The Haining greenhouse case already belongs to the Delta’s eastern protected-horticulture context, and a Shanghai-based study on greenhouse netted muskmelon demonstrated that plant phenotyping and random-forest modeling could forecast substrate water status with high stage-specific accuracy, reaching 77.60%, 94.37%, and 90.01% at seedling, vine elongation, and fruit development stages, respectively. That work matters because greenhouse melon systems in the Delta are often technologically intensive and quality-oriented, making plant-based irrigation decision tools especially relevant (Chang et al., 2019; Yue et al., 2023).

The practical lesson for the Yangtze River Delta is not that every farm should adopt machine learning immediately. It is that regional melon systems are well suited to dynamic irrigation scheduling because they combine protected cultivation, high fruit value, and relatively strong technical infrastructure. In such a context, irrigation frequency can reasonably move away from fixed grower habit toward stage-specific decision rules tied to substrate water status, crop growth stage, and desired fruit quality. What is still missing is more field-validated, English-language, region-specific work that links these tools to final fruit quality and economic return under Delta humidity and greenhouse conditions (Chang et al., 2019; Fang et al., 2026).

6.3 Deficit irrigation practices in northwestern china

Northwestern China provides a contrasting environment in which water scarcity, salinity risk, and greenhouse or substrate production make irrigation frequency an even more technical issue. Sun and colleagues, working in high-EC irrigation water regions, evaluated irrigation amount, nutrient solution EC, and irrigation frequency together and found that integrated growth and efficiency rose and then fell with frequency, with seven irrigations per day emerging as the best option in their studied conditions. This is a clear case where pulsed irrigation is not merely a convenience; it is a way to manage salinity, root-zone conditions, and plant performance simultaneously (Sun et al., 2024).

Another northwestern case comes from soil-moisture-based furrow irrigation scheduling for melon in an arid region, which showed that moisture-based scheduling can improve the balance between yield and quality under water limitation. More recently, greenhouse substrate work found that mild deficit during fruit maturity significantly reduced cracking and improved fruit quality. Together, these studies show that northwestern systems often need two things at once: water-saving delivery and stage-targeted quality management. The frequency question therefore becomes highly practical—how small and how often should irrigation events be when water is limited but fruit quality must remain premium? (Wang et al., 2017; Xue et al., 2025).

6.4 Lessons from regional melon production systems

Across regions, one broad lesson stands out: irrigation frequency is not transferable in a simple calendar form. Humid eastern greenhouses, high-tech Delta systems, arid northwestern greenhouses, Mediterranean open fields, and North American semi-arid field systems all respond differently because evaporative demand, rooting volume, salinity, and market goals differ. Yet a common rule still emerges. Fruit set and enlargement need stable moisture; ripening can tolerate, and often benefit from, controlled reduction (Fabeiro et al., 2002; Kuscu and Turhan, 2022; Fang et al., 2026).

A second lesson is methodological. Regional case studies that treat frequency together with root-zone environment, nutrient supply, and plant status are more informative than studies that vary only seasonal water amount. This is why the Zhejiang greenhouse trial, the Shanghai phenotyping model, the northwestern pulsed-irrigation study, and the Taiwan plant-based RDI framework are especially useful references for a modern review. They move the discussion from “how much water?” to “how should the plant experience water over time?” (Chang et al., 2019; Yue et al., 2023; Sun et al., 2024; Fang et al., 2026).

7 Sustainable Irrigation Strategies for Improving Growth and Fruit Quality

7.1 Drip irrigation and water-saving technologies

Drip irrigation remains the most important base technology for melon water management because it allows both amount and frequency to be controlled accurately. The literature generally shows that drip systems outperform furrow or less localized methods in water use efficiency and often in yield when managed well. A recent northeastern/northern China study reported that plastic-mulched drip irrigation produced the highest greenhouse melon yield and sharply reduced water consumption relative to furrow-based control treatments. This confirms that the irrigation method itself conditions how frequency affects the crop (Liu et al., 2024).

Additional water-saving technologies refine this basic system. Subsurface drip can reshape the wetting pattern and reduce evaporation, but root-zone aeration may be needed to avoid oxygen limitations. Mulching reduces surface evaporation and stabilizes temperature, which often allows fewer or smaller irrigations without stronger plant stress. Reviews of greenhouse irrigation therefore emphasize that “efficient irrigation” is rarely a single device; it is a package that combines localized delivery, evaporation control, and scheduling logic (Nikolaou et al., 2019; Li et al., 2020).

7.2 Precision irrigation and smart agriculture

Precision irrigation is the natural next step because melon responds so strongly to stage and water status. Recent studies offer three promising routes. The first uses soil or substrate sensors to regulate irrigation based on allowable depletion, as in the Murcia studies that reduced water use and leaching while preserving yield. The second uses plant phenotyping or image-based information, as shown in the Shanghai muskmelon forecasting study. The third uses direct plant-based thresholds and crop coefficient calculations, as demonstrated by Fang and colleagues in Taiwan (Chang et al., 2019; Zapata-García et al., 2023; Fang et al., 2026).

These systems are attractive because they convert irrigation frequency from a calendar habit into a crop-response decision. Still, most are not yet effortless for commercial use. Plant-based monitoring can be expensive, image acquisition can be sensitive to greenhouse conditions, and some models still require manual or highly standardized measurements. Even so, the direction is clear: the future of melon irrigation lies in adaptive rather than fixed scheduling (Chang et al., 2019; Fang et al., 2026).

7.3 Integration of irrigation and nutrient management

For melon, irrigation frequency should rarely be discussed without nutrient management. Frequent irrigation changes nutrient residence time, fertigation uniformity, and leaching risk, while nutrient level changes the crop’s ability to convert water into biomass and fruit. The Zhejiang greenhouse case showed that water and nitrogen had to be optimized together, not separately. Likewise, the northwestern high-EC study identified the optimum only when irrigation amount, nutrient-solution EC, and irrigation frequency were evaluated jointly (Yue et al., 2023; Sun et al., 2024).

The same principle appears in commercial-scale precision irrigation. Zapata-García and colleagues demonstrated that sensor-guided irrigation reduced water use while improving both water and nitrogen productivity, meaning that the gain was not simply “less water,” but a better synchronization of water, root-zone retention, and nutrient availability. Biological complements may also help. In melon grown under deficit irrigation, AMF inoculation improved some quality traits and water-use indicators, which suggests that sustainable irrigation strategies can include microbial support as well as digital control (Miceli et al., 2023; Zapata-García et al., 2023).

7.4 Improving water use efficiency under climate change

Climate change intensifies the need to improve water use efficiency because higher evaporative demand makes fixed irrigation calendars less reliable. The broad vegetable literature suggests that moderate deficit irrigation often increases water productivity more reliably than severe deficit, but melon-specific work refines that conclusion by showing that deficit intensity must be matched to growth stage. Moderate deficit can be useful; severe, prolonged deficit frequently damages yield or fruit size (Singh et al., 2021; Panda et al., 2025; di Santo and Barrios-Masias, 2026).

Under climate uncertainty, the most resilient strategy for melon is probably a flexible system with three features: drip-based localized delivery, stage-specific irrigation frequency, and real-time adjustment by soil, substrate, or plant indicators. The recent Taiwan greenhouse study is particularly persuasive here because it reduced irrigation by about one-fifth to one-quarter in soil-grown systems without sacrificing yield or fruit quality. That is the kind of evidence needed for climate-adaptation arguments: not abstract efficiency, but water saving with maintained commercial output (Fang et al., 2026).

8 Future Perspectives and Conclusions

8.1 Current limitations in irrigation frequency research

Despite the growing literature, research on melon irrigation frequency still has several limitations. Many studies change both irrigation amount and frequency at the same time, which makes it difficult to isolate the independent effect of frequency. Others are highly system-specific, meaning that results from open-field loam soils cannot be transferred directly to substrate bags or peat-based troughs. Another limitation is that cultivar type is often underemphasized even though climacteric versus non-climacteric behavior, fruit size, netting, and cracking susceptibility may all influence the response to water scheduling (Singh et al., 2021; Xue et al., 2025; Fang et al., 2026).

There is also a regional imbalance in the evidence base. Semi-arid and water-limited regions are relatively well represented, but humid protected systems in eastern China, especially those typical of the Yangtze River Delta, still lack abundant English-language studies devoted specifically to irrigation frequency in melon. As a result, growers in these regions often have to infer management rules from studies designed for other climates or from experiments where water amount rather than frequency was the main focus (Chang et al., 2019; Yue et al., 2023).

8.2 Emerging technologies for irrigation management

The most promising new technologies are those that transform irrigation scheduling into a real-time, stage-aware process. Plant phenotyping, machine learning, soil-water sensors, plant water-status classification, and decision frameworks that combine crop coefficients with physiological thresholds have all reached a point where they can support serious greenhouse management. Their value is not only higher precision. They also make it possible to apply different irrigation frequencies at different stages without relying on intuition alone (Chang et al., 2019; Zapata-García et al., 2023; Fang et al., 2026).

At the same time, these technologies still need simplification. Models that depend on expensive instruments or highly standardized imaging environments are harder to scale commercially. The next practical gains will likely come from lower-cost sensors, easier interfaces, and integrated platforms that link environmental monitoring, crop stage recognition, and fertigation control in one system. For melon, this integrated approach is especially promising because quality and cracking risk respond so strongly to late-season water management (Zapata-García et al., 2025; Fang et al., 2026).

8.3 Future research directions

Future melon research should do three things more clearly. First, it should separate irrigation frequency from total water amount by using experiments in which seasonal water is held constant while interval or pulse structure changes. Second, it should compare responses across cultivars and production systems so that recommendations become more transferable. Third, it should move beyond yield and soluble solids to include cracking rate, firmness, aroma, shelf life, and economic return, because these are often the traits that determine whether a water-saving schedule is commercially acceptable (Sensory et al., 2007; Xue et al., 2025; Fang et al., 2026).

For eastern China and especially for Zhejiang-related production, more local greenhouse work is needed. The Haining study gives a strong starting point, but it does not answer every question about irrigation frequency under the humid, quality-oriented, protected systems common in the region. Future trials should compare daily versus pulsed scheduling, link irrigation rhythm with fruit cracking and flavor, and test whether sensor-based models developed in one Delta greenhouse can be transferred to another. That would make irrigation recommendations not only more scientific, but more regionally useful (Chang et al., 2019; Yue et al., 2023).

8.4 Conclusions

Irrigation frequency is one of the most practical and biologically meaningful levers in melon production. It shapes vegetative growth through its effects on root-zone stability, leaf expansion, and photosynthesis. It shapes fruit development by protecting or constraining fruit set and enlargement. And it shapes fruit quality by influencing sugar concentration, acidity, firmness, nutritional compounds, and cracking during maturation. The strongest overall pattern in the literature is not that frequent irrigation is always better or that deficit is always better. Rather, melon performs best when irrigation frequency changes with developmental stage.

Stable and adequate watering is most important from flowering through early fruit growth. This is the phase where poor scheduling most clearly reduces yield. Later, once fruit size is largely formed, a carefully controlled reduction in frequency or intensity can improve sweetness, nutritional density, and market quality, and may also reduce cracking. Greenhouse systems, soilless culture, and high-value protected production make this stage-specific logic even more important because the root zone is smaller and fruit quality premiums are higher.

Viewed this way, irrigation frequency is not simply a timing parameter. It is a developmental strategy. Good melon irrigation should therefore be dynamic, stage-specific, and increasingly data-informed. For growers and researchers alike, the practical goal is no longer just to apply enough water. It is to deliver water with the right rhythm, at the right stage, for the right fruit outcome.

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Conflict of Interest Disclosure

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

References

- Bustan A., Cohen S., De Malach Y., Zimmerman P., Golan R., Sagi M., and Pasternak D., 2005, Effects of timing and duration of brackish irrigation water on fruit yield and quality of late summer melons, *Agricultural Water Management*, 74(2): 123-134.
<https://doi.org/10.1016/j.agwat.2004.11.009>
- Cabello M.J., Castellanos M.T., Romojaro F., Martínez-Madrid C., and Ribas F., 2009, Yield and quality of melon grown under different irrigation and nitrogen rates, *Agricultural Water Management*, 96(5): 866-874.
<https://doi.org/10.1016/j.agwat.2008.11.006>
- Chang L., Yin Y., Xiang J., Liu Q., Li D., and Huang D., 2019, A phenotype-based approach for the substrate water status forecast of greenhouse netted muskmelon, *Sensors*, 19(12): 2673.
<https://doi.org/10.3390/s19122673>
- Cheng H., Kong W., Tang T., Ren K., Zhang K., Wei H., and Lin T., 2022, Identification of key gene networks controlling soluble sugar and organic acid metabolism during oriental melon fruit development by integrated analysis of metabolic and transcriptomic analyses, *Frontiers in Plant Science*, 13: 830517.
<https://doi.org/10.3389/fpls.2022.830517>
- di Santo H., and Barrios-Masias F., 2026, Implementation of deficit irrigation to improve crop water productivity in cantaloupe melons, *The Journal of Agricultural Science*, 164: e29.
<https://doi.org/10.1017/S0021859626100665>
- Ercan M., Çoklar H., Akbulut M., Yavuz D., Seymen M., and Yavuz N., 2023, Effect of irrigation regime on chemical, physico-chemical, and functional properties of melon fruits and seeds, *Gesunde Pflanzen*, 75(6): 2835-2845.
<https://doi.org/10.1007/s10343-023-00900-w>

- Fabeiro C., Martín de Santa Olalla F., and de Juan J.A., 2002, Production of muskmelon (*Cucumis melo* L.) under controlled deficit irrigation in a semi-arid climate, *Agricultural Water Management*, 54(2): 93-105.
[https://doi.org/10.1016/S0378-3774\(01\)00151-2](https://doi.org/10.1016/S0378-3774(01)00151-2)
- Fang S.L., Tsai B.Y., Chang S.C., Chang Y.L., Yao M.H., Chi M.K., Wang W.L., and Kuo B.J., 2026, Regulated deficit irrigation strategy for greenhouse melons based on water status classification model and crop coefficient-reference evapotranspiration approach, *Irrigation Science*, 44(2): 41.
<https://doi.org/10.1007/s00271-026-01082-9>
- Gustani F.M., Colodel C., and Ayub R.A., 2024, Unraveling the molecular mechanisms of melon fruit firmness: Insights into cell wall gene expression and regulation, *Phytochemistry Reviews*, 24(4): 3205-3220.
<https://doi.org/10.1007/s11101-024-10023-3>
- Kirmak H., Higgs D., Kaya C., and Tas I., 2005, Effects of irrigation and nitrogen rates on growth, yield, and quality of muskmelon in semiarid regions, *Journal of Plant Nutrition*, 28(4): 621-638.
<https://doi.org/10.1081/PLN-200052635>
- Kuseu H., and Turhan A., 2022, Yield, net return and fruit quality response of melon to deficit irrigation, *Gesunde Pflanzen*, 74(3): 647-659.
<https://doi.org/10.1007/s10343-022-00639-w>
- Li Y., Niu W., Cao X., Zhang M., Wang J., and Zhang Z., 2020, Growth response of greenhouse-produced muskmelon and tomato to sub-surface drip irrigation and soil aeration management factors, *BMC Plant Biology*, 20(1): 141.
<https://doi.org/10.1186/s12870-020-02346-y>
- Li Y.J., Yuan B.Z., Bie Z.L., and Kang Y., 2012, Effect of drip irrigation criteria on yield and quality of muskmelon grown in greenhouse conditions, *Agricultural Water Management*, 109: 30-35.
<https://doi.org/10.1016/j.agwat.2012.02.003>
- Liu F., Shao X., Fan Y., Jia B., He W., Wang Y., Wang F., and Wang C., 2024, Time-series transcriptome of *Cucumis melo* reveals extensive transcriptomic differences with different maturity, *Genes*, 15(2): 149.
<https://doi.org/10.3390/genes15020149>
- Liu S., Li J., Jia S., Dai Z., Du F., Zhao N., Fan F., Liu Z., and Zhao S., 2024, Effects of irrigation approaches and mulching on greenhouse melon production and water use in Northern China, *Water*, 16(14): 2013.
<https://doi.org/10.3390/w16142013>
- Long R.L., Walsh K.B., and Midmore D.J., 2006, Irrigation scheduling to increase muskmelon fruit biomass and soluble solids concentration, *HortScience*, 41(2): 367-369.
<https://doi.org/10.21273/HORTSCI.41.2.367>
- Miceli A., Vetrano F., Torta L., Esposito A., and Moncada A., 2023, Effect of mycorrhizal inoculation on melon plants under deficit irrigation regimes, *Agronomy*, 13(2): 440.
<https://doi.org/10.3390/agronomy13020440>
- Nikolaou G., Neocleous D., Katsoulas N., and Kittas C., 2019, Irrigation of greenhouse crops, *Horticulturae*, 5(1): 7.
<https://doi.org/10.3390/horticulturae5010007>
- Nut N., Phou K., Mihara M., Nuth S., and Sor S., 2019, Effects of drip irrigation frequency on growth and yield of melon (*Cucumis melo* L.) under net-house's conditions, *International Journal of Environmental and Rural Development*, 10(1): 146-152.
- Ozmen S., Kanber R., Sari N., and Unlu M., 2015, The effects of deficit irrigation on nitrogen consumption, yield, and quality in drip-irrigated grafted and ungrafted melon, *Journal of Integrative Agriculture*, 14(5): 966-976.
[https://doi.org/10.1016/S2095-3119\(14\)60870-4](https://doi.org/10.1016/S2095-3119(14)60870-4)
- Panda R.M., Matese A., Maachi D., and Aberkani K., 2025, Water stress impacts on the growth and productivity of melon crops in a Mediterranean climate, *Irrigation Science*, 43(5): 1159-1168.
<https://doi.org/10.1007/s00271-024-00972-0>
- Sensoy S., Ertek A., Gedik I., and Kucukyumuk C., 2007, Irrigation frequency and amount affect yield and quality of field-grown melon (*Cucumis melo* L.), *Agricultural Water Management*, 88(1-3): 269-274.
<https://doi.org/10.1016/j.agwat.2006.10.015>
- Sharma P.S., Leskovar D.I., Crosby K.M., Volder A., and Ibrahim A.M.H., 2014, Root growth, yield, and fruit quality responses of reticulatus and inodorus melons (*Cucumis melo* L.) to deficit subsurface drip irrigation, *Agricultural Water Management*, 136: 75-85.
<https://doi.org/10.1016/j.agwat.2014.01.008>
- Singh M., Singh P., Singh S., Saini R.K., and Angadi S.V., 2021, A global meta-analysis of yield and water productivity responses of vegetables to deficit irrigation, *Scientific Reports*, 11(1): 22095.
<https://doi.org/10.1038/s41598-021-01433-w>
- Sun T., Zhou D., Jia Y., Yang M., Hu X., and Zhang Z., 2024, Optimal nutrient solution management program for *Cucumis melo* L. growth by using a comprehensive evaluation method, *Irrigation Science*, 42(2): 401-418.
<https://doi.org/10.1007/s00271-023-00897-0>
- Wang J., Huang G., Li J., Zheng J., Huang Q., and Liu H., 2017, Effect of soil moisture-based furrow irrigation scheduling on melon (*Cucumis melo* L.) yield and quality in an arid region of Northwest China, *Agricultural Water Management*, 179: 167-176.
<https://doi.org/10.1016/j.agwat.2016.04.023>

- Wang Q., Tang L., He Y., Xu Y., Zhang J., Kong W., Hu K., Garcia-Mas J., Pujol M., and Zhao G., 2025, Comprehensive analysis of transcriptome and metabolome identified the key gene networks regulating fruit length in melon, *BMC Plant Biology*, 25(1): 442.
<https://doi.org/10.1186/s12870-025-06332-0>
- Xue Q., Li H., and Du T., 2025, Mild water deficit during maturity reduces cracking rate of greenhouse muskmelon while improving fruit quality, *Agricultural Water Management*, 313: 109465.
<https://doi.org/10.1016/j.agwat.2025.109465>
- Yavuz D., Seymen M., Yavuz N., Çoklar H., and Ercan M., 2021, Effects of water stress applied at various phenological stages on yield, quality, and water use efficiency of melon, *Agricultural Water Management*, 246: 106673.
<https://doi.org/10.1016/j.agwat.2020.106673>
- Yue W., Chen S., Gao L., Li N., and Liu L., 2023, Effects of water and nitrogen coupling on yield, quality, water and nitrogen use efficiencies of greenhouse muskmelon, *Water*, 15(14): 2603.
<https://doi.org/10.3390/w15142603>
- Zapata-García S., Temnani A., Berrios P., Espinosa P.J., Monllor C., and Pérez-Pastor A., 2023, Using soil water status sensors to optimize water and nutrient use in melon under semi-arid conditions, *Agronomy*, 13(10): 2652.
<https://doi.org/10.3390/agronomy13102652>
- Zapata-García S., Temnani A., Berrios P., Espinosa P.J., Monllor C., and Pérez-Pastor A., 2025, Deficit irrigation and biostimulation preconditioning to improve drought resistance in melon, *Agricultural Water Management*, 309: 109311.
<https://doi.org/10.1016/j.agwat.2025.109311>



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