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Data-Based Analysis of Water Management Effects on Melon Growth and Fruit Quality

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Abstract Water management is a critical factor affecting melon (*Cucumis melo* L.) growth, yield formation, and fruit quality, particularly under conditions of increasing water scarcity and climate variability. However, the complex interactions between irrigation practices, environmental conditions, plant physiological responses, and fruit quality development remain insufficiently understood. This review focuses on the application of data-based approaches to analyze the effects of water management on melon production. The physiological mechanisms underlying water regulation of melon growth are first summarized, including the impacts of irrigation regimes on root development, photosynthesis, reproductive processes, fruit expansion, and quality formation. Subsequently, methods for collecting and integrating multi-source datasets, including irrigation information, soil moisture dynamics, climatic variables, plant growth parameters, and fruit quality indicators, are discussed. Statistical models and machine learning approaches, such as regression analysis, Random Forest, Support Vector Regression, and deep learning algorithms, are evaluated for their ability to quantify water-growth-quality relationships and predict crop responses. A case study framework is presented to demonstrate the evaluation of different irrigation strategies and the development of precision water management decision-support systems. Furthermore, the integration of IoT sensors, remote sensing, and artificial intelligence technologies is explored to improve irrigation efficiency and optimize fruit quality. Future research should focus on multi-dimensional data integration, explainable artificial intelligence, and region-specific modeling to achieve sustainable and intelligent melon production.

Keywords Melon; Water management; Fruit quality; Machine learning; Precision irrigation

1 Introduction

Melon production depends strongly on irrigation management because water availability directly shapes yield formation, fruit size, and market quality under the water-limited conditions common to major production regions. In semi-arid environments, melon has been shown to be sensitive to seasonal water stress, with full-season stress-free irrigation producing the highest fruit yield, while water deficits imposed at single growth stages caused significant yield losses and a whole-season yield response factor greater than 1.0, indicating substantial susceptibility to water shortage (Yavuz et al., 2021). At the same time, irrigation strategy is not simply a matter of maximizing water input, because field experiments have shown that moderate deficit irrigation can preserve most of the attainable yield while improving irrigation water use efficiency, whereas severe deficits reduce yield mainly through reductions in fruit weight. These findings make water management a central agronomic issue in melon production, especially where growers must balance productivity, fruit quality, and resource conservation under increasing climatic and economic pressure.

The importance of water management also lies in the fact that melon responses are stage-specific and cultivar-dependent, so irrigation decisions must be aligned with crop phenology rather than applied uniformly across the season. Seasonal irrigation experiments have shown that two-stage irrigation programs such as VF, VM, and FM can approach the performance of full-season irrigation, and that one treatment achieved water savings of about 47% without significant losses in irrigation water productivity relative to the fully irrigated control (Yavuz et al., 2021). More recent greenhouse evidence further indicates that irrigation timing during maturity is particularly important for fruit quality outcomes, because mild deficit irrigation at the maturity stage reduced fruit cracking by 73% without significantly affecting yield, while broader reproductive-stage deficit irrigation improved soluble solids accumulation but also risked reducing fruit size (Xue et al., 2025). Together, these results show that seasonal water management in melon should be treated as a dynamic scheduling problem in which the same water deficit can produce beneficial or harmful outcomes depending on when it is imposed.

The physiological basis for these agronomic effects is that water deficit alters core processes governing melon growth, including gas exchange, plant water status, assimilate production, and stress metabolism. Controlled studies of melon under drought have shown that water stress significantly reduces stomatal conductance, transpiration, net photosynthetic rate, chlorophyll fluorescence, relative water content, and intercellular CO_2 concentration, while increasing stress-associated biochemical indicators such as soluble sugars, soluble proteins, and malondialdehyde (Rehman et al., 2023). Similar physiological responses have been documented under irrigation gradients in cultivated melon, where reduced water supply lowered stomatal conductance, transpiration, net photosynthesis, and accumulated dry matter, and cultivar differences in photosynthetic adjustment revealed unequal tolerance to water stress. These mechanisms explain why water regulation affects not only vegetative growth and yield, but also fruit composition, because shifts in carbon assimilation, osmotic adjustment, and source-sink relations can alter sugar concentration, acidity, and other quality traits.

Against this background, a data-based analysis of water management is needed to move from general irrigation recommendations toward adaptive, evidence-driven decision support for melon production. Precision irrigation studies under commercial semi-arid conditions have shown that soil water status sensing can save 27-30% of irrigation water without reducing fruit load or fruit weight, while increasing water productivity, nitrogen productivity, and even ascorbic acid content, demonstrating the value of continuous field measurements for optimizing irrigation and fertigation decisions (Zapata-García et al., 2023). More broadly, data-driven irrigation research shows that modern control systems can use real-time measurements of soil moisture, environmental variables, and crop conditions to reduce water consumption while avoiding crop water stress, which provides a clear methodological foundation for integrating environmental and cultivation data into predictive analysis (Garcia et al., 2023). Accordingly, the objective of this study is to analyze how water management affects melon growth and fruit quality through a data-based framework that links seasonal irrigation practices, physiological responses, and production outcomes, thereby supporting more precise and sustainable melon cultivation.

2 Mechanisms of Water Management Effects on Melon Growth and Development

2.1 Effects of irrigation regimes on vegetative growth and photosynthetic performance

Water management affects melon growth first through its control over plant water status, canopy development, and carbon assimilation. Drought stress reduced shoot length, stem diameter, leaf width, and leaf length in melon seedlings, and it also decreased chlorophyll, carotenoids, relative water content, chlorophyll fluorescence, transpiration, stomatal conductance, net photosynthetic rate, and intercellular CO_2 concentration, showing that water shortage constrains both vegetative expansion and photosynthetic function (Rehman et al., 2023). Under field irrigation gradients, water stress likewise reduced stomatal conductance, transpiration, net photosynthesis, and accumulated dry matter, indicating that lower soil moisture suppresses biomass formation mainly by limiting gas exchange and assimilation.

These physiological effects depend on irrigation intensity, season, and genotype, rather than following a single uniform response. Under 50% ETc, deficit irrigation significantly decreased above-ground biomass, leaf area, leaf number, and specific leaf area in one season, while in a drier year it also significantly reduced net photosynthetic rate and stomatal conductance, showing that the same irrigation regime can shift from mainly morphological to both morphological and photosynthetic limitation depending on climate severity. Genotypic differences further modify this mechanism, because one study found that 'Piel de Sapo' had higher photosynthetic adjustment and greater tolerance to water stress than 'Amarelo', while another reported that the late-maturing honeydew cultivar Super Nectar appeared more drought-sensitive because of declines in leaf area and net photosynthesis (Figure 1).

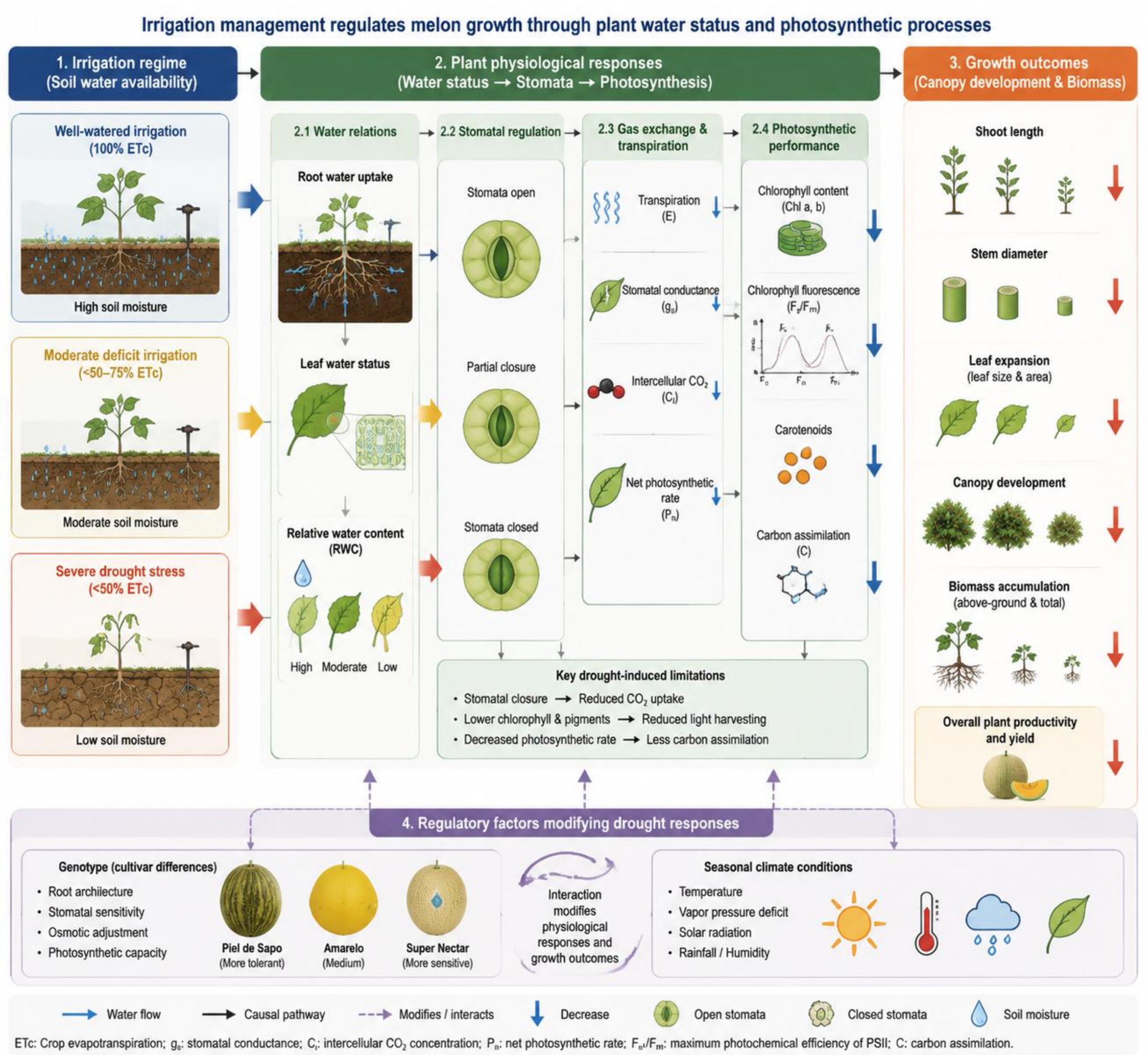

Figure 1 Conceptual framework illustrating the effects of irrigation management on melon growth and photosynthetic regulation

2.2 Water regulation of flowering, fruit set, and fruit development

The reproductive phase is especially sensitive to water regulation because the timing of deficit determines whether flowering, fruit set, or later fruit enlargement is most affected. In controlled deficit irrigation experiments, treatments with water deficit during blooming had the lowest production, and deficits during blooming mainly reduced quantity, whereas deficits during fruit setting affected both quantity and quality. A later field study similarly concluded that adequate production could be maintained with limited seasonal irrigation only if the fruit-setting stage, particularly its early part, was protected from water stress, confirming that this phase is a critical bottleneck for reproductive success (Yavuz et al., 2021).

Water supply during fruit development and maturity then governs fruit enlargement, cracking risk, and final marketable yield. Deficit irrigation at 50% ETc caused a 30% decrease in marketable yield in two seasons mainly because fruit size declined, and yield losses varied with cultivar, indicating that fruit growth is a major sink process disrupted by insufficient water. At the maturity stage, cracked fruit rate increased with irrigation amount, while mild deficit irrigation at maturity reduced cracking by 73% without significantly affecting yield or irrigation water productivity, suggesting that moderated water supply late in development can stabilize fruit tissues without sacrificing output (Xue et al., 2025).

2.3 Effects of water availability on fruit quality formation

Water availability influences fruit quality formation by altering the balance between dilution-driven fruit enlargement and concentration of soluble and bioactive compounds. Moderate water stress did not reduce melon yield and produced high irrigation water use efficiency, whereas severe deficit irrigation reduced yield mainly through lower fruit weight; at the same time, reduced irrigation increased flesh firmness and placenta and seed weight, indicating that quality-related structural traits respond differently from bulk yield. In another deficit irrigation study, fruit quality was not harmed overall and total soluble solids increased by 23% in one cultivar, showing that restricted water can enhance sweetness even when it reduces fruit size or economic yield.

The quality response is also strongly stage-specific, with later water restriction often favoring sugar accumulation and some functional traits. During fruit swelling and maturity, deficit irrigation had a positive effect on the accumulation of soluble solids such as sugars, and severe deficit during the reproductive period produced the best comprehensive quality score in greenhouse muskmelon (Xue et al., 2025). Chemical analyses across irrigation regimes further showed significant effects on sucrose, total sugar, phenolic compounds, antioxidant activity, and some color traits, while a water-fertilizer coupling study found that melon quality performed best under low to medium water and fertilizer inputs and recommended lower irrigation at maturity than at earlier stages, supporting the view that optimal quality formation requires dynamic rather than maximal water supply (Ercan et al., 2023; Yang et al., 2025).

3 Data Collection and Feature Construction for Water Management Analysis

3.1 Acquisition of irrigation and environmental monitoring data

Irrigation and environmental data acquisition should be built around continuous monitoring of the soil-plant-atmosphere continuum, because high spatiotemporal resolution is needed to replace low-resolution, labor-dependent observation with quantitative field intelligence (Chamara et al., 2022). In practical irrigation systems, core measurements commonly include soil moisture, air temperature, air humidity, and water level, and these variables can be calibrated before transmission and visualized in real time to support threshold-based or model-based irrigation control (Morchid et al., 2024).

A robust monitoring scheme should also integrate multiple sensing layers rather than relying on a single device class. Recent precision irrigation research shows that remote sensing can track spatial stress indicators, agro-meteorological inputs can drive evapotranspiration estimation, and wireless sensor networks can provide continuous localized measurements of soil moisture and canopy temperature, with integrated systems improving irrigation recommendations and reducing water use without yield loss (Fuentes-Peñailillo et al., 2025). At the hardware level, modern soil moisture monitoring increasingly combines on-the-go electrical, optical, and radiometric sensors with UAVs, satellite remote sensing, and IoT-based wireless networks to obtain timely, cost-effective, and spatially detailed water-status data for precision irrigation (Zhang et al., 2024).

3.2 Collection of melon growth and yield-quality data

Melon growth and yield-quality data should be collected across phenological stages and multiple seasons so that the analysis captures temporal variation in fruit development and harvest maturity. Multi-season melon trials have shown that maturity stage can be determined from rind color and net coverage, and that fruit length, fruit diameter, flesh thickness, fruit weight, and sugar content all change significantly across ripening stages. These results support a field protocol that records both morphological and compositional traits at repeated time points, especially because sugar content increased from 5.51 Brix at stage 2 to 8.18 Brix at stage 5 in the reported dataset.

For scalable data collection, manual measurements can be complemented by imaging and smart-farm records. UAV-based computer vision in melon achieved strong agreement between estimated and actual fruit counts and produced low total yield error through fruit detection and volume-based weight estimation, indicating that aerial phenotyping can support non-destructive yield monitoring at scale (Aldakn et al., 2026). In protected cultivation, smart-farm datasets from four oriental melon farms were used to model weekly yield from combined growth and environmental variables, while computer vision and logistic fruit modeling have also been used to quantify fruit morphology, net quality, and growth trajectories under different treatments (Moon et al., 2022; Yoon et al., 2023).

3.3 Data processing and feature selection strategies

Data processing should begin with standardization and dimensionality reduction so that heterogeneous irrigation, environmental, and crop variables can be used efficiently in predictive models. One recent agricultural prediction framework explicitly organized the pipeline into preprocessing, hybrid feature selection, and prediction phases, with normalization followed by K-means clustering and a correlation-based filter to generate a reduced dataset before model training. This logic is well suited to melon water-management analysis because irrigation studies typically combine many correlated inputs, including soil, climate, and groundwater or crop-state variables, that can otherwise introduce redundancy and unstable model behavior (Abdel-Salam et al., 2024).

Feature selection should then identify the smallest informative subset that preserves predictive accuracy while improving computational efficiency and interpretability. Relief-based feature selection and linear discriminant or principal-component extraction have already been used in crop prediction workflows, and these approaches improved downstream model performance by retaining variables most relevant to yield prediction (Gupta et al., 2022). In melon-related smart-farm modeling, principal component analysis was combined with distributed-lag and ARIMAX models to stabilize weekly yield prediction, while newer feature-selection work shows that combining correlation-based selection with neural-network-based transformation can reduce extraction time and improve prediction accuracy, supporting hybrid selection strategies for future melon water-management datasets (Moon et al., 2022; Hukare and Kumbhar, 2025).

4. Statistical and Machine Learning Approaches for Evaluating Water Management Effects

4.1 Statistical analysis of water-growth-quality relationships

Statistical analysis has been essential for quantifying how irrigation treatments alter melon growth, yield, and fruit quality across phenological stages. In field experiments, two-way ANOVA detected significant treatment-by-date relationships in photosynthetic energy use under 50%, 75%, and 100% irrigation, while split-plot analysis under varying irrigation and nitrogen levels identified significant irrigation-by-nitrogen interactions for yield, fruit weight, and irrigation water use efficiency (Panda et al., 2024). These results show that melon responses to water management are not static, but depend on both timing and interaction with other agronomic inputs. They also justify statistical designs that jointly evaluate irrigation, crop stage, and management covariates rather than testing each factor in isolation.

Multivariate statistical methods have further clarified the structure of water-growth-quality relationships by integrating many response indicators into a common framework. Principal component analysis showed that two-stage irrigation treatments such as VF and FM clustered near full irrigation when yield and quality traits were considered together, while structural equation modeling indicated that net photosynthetic rate regulated melon growth indirectly through total dry mass, and that growth was the most important direct determinant of yield and quality (Yavuz et al., 2021; Yang et al., 2023). Correlation analysis has also been used to identify the physiological variables most closely associated with final performance, and more recent multicriteria approaches combined 17 indicators spanning growth, yield, quality, efficiency, and soil residue to assess overall management benefit (Yang et al., 2025).

4.2 Machine learning models for predicting growth and fruit quality responses

Machine learning models are increasingly used to predict melon growth responses from environmental and cultivation data because they can capture nonlinear interactions that conventional regression often misses. In smart greenhouse studies, Linear Regression, Random Forest, XGBoost, and Support Vector Regression were trained on temperature, humidity, and cumulative solar radiation to predict melon length and width, and XGBoost achieved the strongest predictive accuracy among the tested models (Lim et al., 2025). A related greenhouse prediction study also found that XGBoost outperformed multiple linear regression, support vector machines, and artificial neural networks for forecasting internal temperature, humidity, and CO_2 30 minutes ahead, with R_2 up to 0.9929, indicating that tree-boosting approaches are especially effective for controlled-environment melon systems (Jeon et al., 2024).

For fruit quality prediction, machine learning has been combined with imaging and reduced feature sets to support early, non-destructive assessment. Snapshot hyperspectral imaging with standard normal variate preprocessing and variable importance in projection band selection produced solid models for oriental melon soluble solids concentration and moisture content, with support vector regression performing best and reaching R_2 values of 0.86 and 0.74, respectively (Cho et al., 2022). Integrated learning with gradient-boosted decision trees also predicted melon yield, sugar content, and hardness from reduced phenological, shape, and color features with R_2 above 0.90, while reducing training time and improving field applicability for early harvest evaluation (Qian et al., 2022).

4.3 Model interpretation and identification of critical water management factors

Model interpretation is necessary because high predictive accuracy alone does not reveal which water-management variables actually drive melon responses. SHAP provides a unified additive feature-importance framework for interpreting complex models, and recent agricultural applications show that SHAP can rank the contribution of individual predictors while preserving consistency across model explanations. In water-related prediction tasks, SHAP-based analysis has already identified the most influential inputs within deep learning systems, demonstrating that interpretability tools can isolate dominant hydrological or chemical variables rather than treating prediction as a black box (Hussein et al., 2024).

For melon-focused water management, interpretable models should be used to identify the environmental and physiological thresholds most relevant to irrigation scheduling and fruit-quality formation. Recent interpretable crop-coefficient modeling showed that LIME can expose actionable local thresholds for irrigation-relevant variables, while SHAP and Sobol analyses consistently highlighted antecedent crop coefficient and solar radiation as dominant drivers of daily water-demand prediction (Elbeltagi et al., 2025). Hybrid modeling evidence further suggests that weather variables alone are insufficient, because adding crop-model-derived hydrological features reduced prediction RMSE by 7%-20% and identified soil-moisture-related drought stress and water-table-depth variables as the most influential inputs, which is directly relevant to identifying critical water-management factors in melon systems.

5 Case Study: Data-Based Evaluation of Irrigation Strategies for Improving Melon Growth and Fruit Quality

5.1 Experimental design and data acquisition in melon production systems

A representative case study of data-based irrigation evaluation in melon production should combine multi-treatment field experimentation with continuous physiological and agronomic measurement. Recent melon trials used clearly structured irrigation gradients across seasons, including eight phenology-based treatments spanning planting to flowering, flowering to fruit swelling, and fruit swelling to harvest, as well as full-season and non-irrigated controls, while other studies adopted three fixed irrigation levels of 50%, 75%, and 100% with repeated monitoring of agronomic and physiological traits (Panda et al., 2024). Such designs are well suited to comparative analysis because they capture both stage-specific and intensity-dependent water responses under realistic production conditions (Yavuz et al., 2021).

Data acquisition in these systems should extend beyond final yield to include crop water status, environmental forcing, and fruit-quality endpoints. In semi-arid melon experiments, stomatal conductance and leaf temperature were tracked throughout the crop cycle and linked with harvest-time yield and postharvest quality, while greenhouse regulated-deficit studies combined crop coefficient estimation with growth-stage-specific stomatal conductance thresholds to classify water status and trigger irrigation timing. This integrated measurement framework supports a data pipeline in which environmental inputs, physiological indicators, and production outcomes are recorded together rather than treated as separate datasets (Figure 2) (Fang et al., 2026).

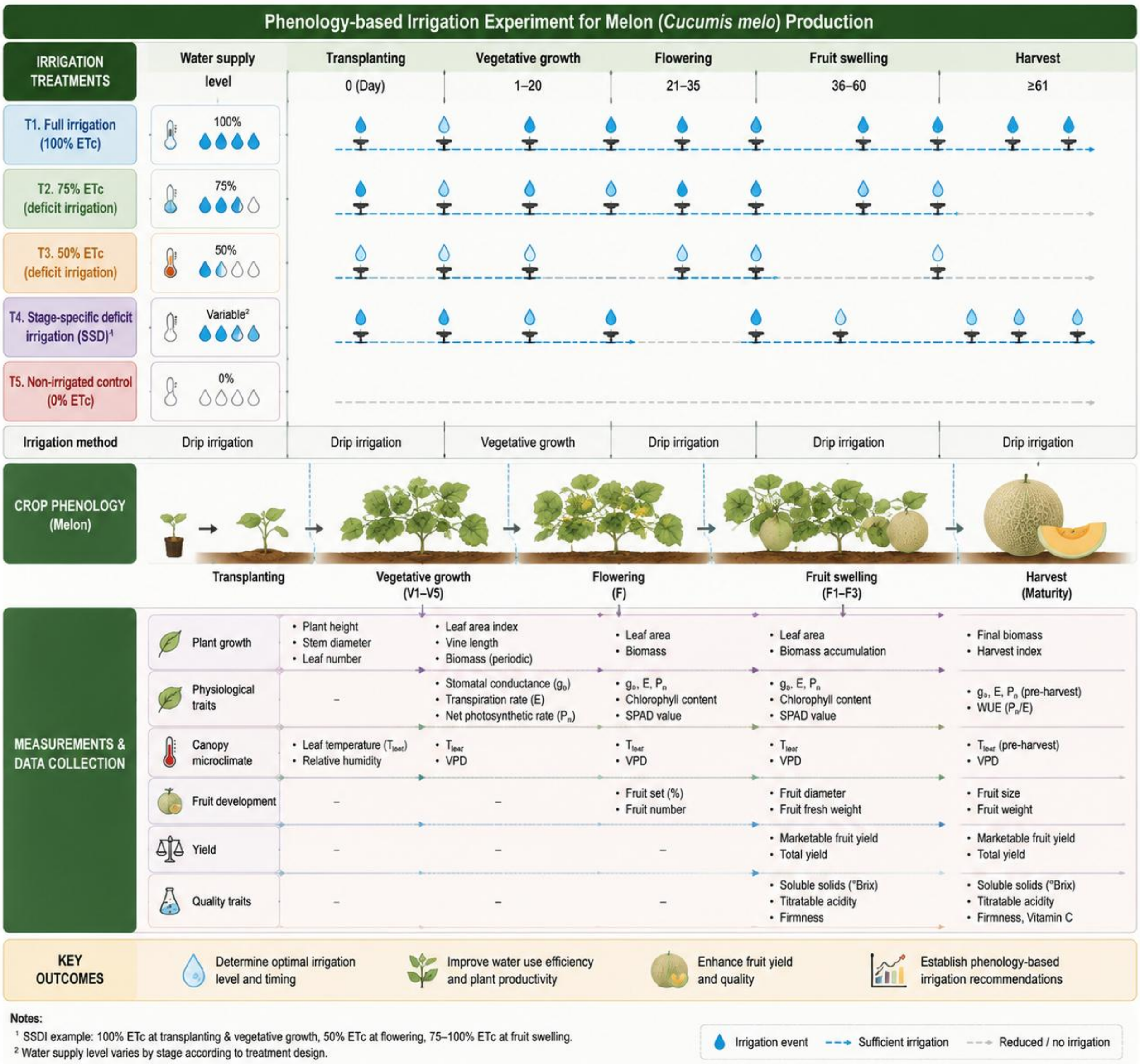

Figure 2 Phenology-based irrigation treatments and physiological response assessment in melon production systems

5.2 Comparative analysis of different water management strategies

Comparative evidence shows that moderate or stage-targeted deficit irrigation often preserves melon productivity better than uniform severe water restriction. In three-year field trials, full irrigation and the DI6 strategy produced similarly high yields, but DI6 delivered the highest net return per unit irrigation water and the highest water productivity, making it the strongest compromise between economic and water-saving goals (Kuşçu and Turhan, 2022). A newer cantaloupe study reached a similar conclusion: irrigation at 70% field capacity reduced water applied by 25% and maintained performance, whereas 50% field capacity lowered yield by 40% (Di Santo and Barrios-Masias, 2026).

Stage sensitivity is a recurring pattern in comparative irrigation studies, and later developmental periods often tolerate deficit better than earlier reproductive phases. In melon, principal component analysis showed that two-stage treatments such as VF and FM performed similarly to full-season irrigation when yield and quality were considered jointly, and VM saved about 47% of water without significant loss in irrigation water productivity relative to the fully irrigated control (Yavuz et al., 2021). Greenhouse regulated-deficit irrigation likewise reduced irrigation by 19.3% to 25.7% in soil-grown systems without compromising yield or fruit quality, while multicriteria evaluation confirmed a more favorable balance among water saving, quality, and yield maintenance than conventional irrigation (Fang et al., 2026).

5.3 Development of decision-support models for precision water management

Decision-support development for precision water management increasingly relies on models that translate sensor and field data into operational irrigation rules. A practical melon example used crop coefficient-reference evapotranspiration estimates together with water-status classification models based on stomatal conductance thresholds, then validated the resulting irrigation strategy across three seasons in both soilless and soil-grown systems (Fang et al., 2026). More broadly, irrigation decision-making has shifted from visual judgment toward machine-learning-based prediction of crop water needs, although current field-scale adoption remains constrained by limited data availability, poor data sharing, and insufficient uncertainty quantification (Umutoni and Samadi, 2024).

The next step is to build decision-support systems that are both data-efficient and agronomically interpretable. Reviews of smart irrigation systems emphasize flexible platforms that combine weather information, field data collection, crop coefficients, soil water balance, and scheduling outputs, while recent AIoT work shows that dimensionality reduction and time-series learning can support highly accurate water-stress detection for automated irrigation control (Saggi and Jain, 2022; Lin et al., 2025). For melon production, this implies that precision water-management tools should integrate stage-specific irrigation targets, physiological thresholds, and real-time monitoring into a unified recommendation engine that supports water saving without sacrificing fruit growth or quality (Abioye et al., 2022).

6 Integration of Digital Technologies for Intelligent Melon Water Management

6.1 Application of IoT and remote sensing technologies in irrigation monitoring

Digital irrigation monitoring increasingly combines in-field sensing with remote observation so that water status can be tracked continuously across both plant root zones and canopy conditions. IoT-based systems provide real-time measurements of soil moisture, weather, and plant-related variables that support timely irrigation decisions, while remote sensing adds spatial information on crop stress through multispectral and thermal indicators such as the Crop Water Stress Index (Abdelmoneim et al., 2025). This combination is especially relevant for melon because precise water control is needed throughout growth, yet point sensors alone cannot capture field-scale variability or canopy-level responses.

The practical architecture of these systems usually links field sensors, wireless transmission, and cloud dashboards into one monitoring chain. Recent implementations used temperature, humidity, soil moisture, and water-level sensors connected to embedded controllers and cloud platforms for real-time visualization, while melon-specific IoT systems have also integrated soil moisture, temperature, air humidity, and light sensors with automated watering and image-based fruit monitoring in a single connected platform (Sarosa et al., 2024). For protected or small-scale melon cultivation, this architecture can extend further to pH, total dissolved solids, and greenhouse microclimate sensing, allowing irrigation monitoring to be coupled with broader crop-environment surveillance.

6.2 Development of data-driven irrigation decision systems

monitoring becomes agronomically useful only when the incoming data are transformed into irrigation recommendations or automated control actions. Data-driven irrigation systems increasingly combine soil and environmental sensing with weather forecasts and machine-learning or rule-based algorithms to predict water demand, schedule irrigation, and operate pumps or valves in closed-loop mode (Nsoh et al., 2024). This shift moves irrigation management away from static thresholds alone toward adaptive systems that update decisions as field and atmospheric conditions change.

Several studies show that such systems can already support practical automation, although the sophistication of decision logic varies. IoT-based irrigation platforms have used weather-linked smart algorithms, cloud data pipelines, and autonomous water-supply control, while melon-focused fuzzy-logic drip systems adjusted solenoid valve opening times dynamically from soil-moisture and temperature inputs and maintained soil moisture within an optimal 60%-80% range (Alif and Pertiwi, 2025). More advanced digital farming frameworks also integrate machine learning with mobile or web interfaces so that farmers can interpret raw field data, receive actionable schedules, and manage irrigation remotely rather than manually (Abioye et al., 2022).

6.3 Challenges in data integration and field application

The main barriers to intelligent irrigation are no longer sensing alone, but the integration, reliability, and scalability of heterogeneous digital components under real field conditions. Reviews consistently identify data integration complexity, fragmented analytics pipelines, and weak interoperability across sensor suites as major obstacles, with current systems often addressing isolated functions instead of seamless end-to-end irrigation management (Nsoh et al., 2024). These limitations are important in melon systems because irrigation decisions often depend on combining soil, weather, crop-status, and quality-related data rather than any single variable.

Field deployment also faces practical constraints involving connectivity, calibration, cost, uneven actuator performance, and data governance. Rural internet limitations and cybersecurity concerns remain widespread, while melon greenhouse evaluations have shown that online monitoring can fail when connectivity drops and that automation performance can be reduced by sensor issues and uneven dripper discharge (Prasetyo and Khoiri, 2025). Broader precision-agriculture reviews add that high initial investment, technical expertise requirements, and privacy concerns still restrict adoption, so future melon water-management platforms will need affordable hardware, better standardization, stronger local edge processing, and more robust calibration and maintenance protocols (Mansoor et al., 2025; Miller et al., 2025).

7 Future Perspectives and Research Directions

7.1 Multi-source data integration for comprehensive water management assessment

Future melon water-management research should move from single-source monitoring toward integrated platforms that combine soil sensing, agro-meteorological observations, and remote sensing. Integrated systems reduce uncertainty in irrigation decisions because remote sensing captures spatial canopy variability, agro-meteorology explains atmospheric drivers of evapotranspiration, and wireless sensor networks provide localized real-time field information (Sharad et al., 2024). For melon production, this means that water assessment can evolve from plot-level irrigation records to a more complete representation of soil-plant-atmosphere interactions across phenological stages and management zones.

The next step is not only collecting more data, but harmonizing heterogeneous data streams into interoperable digital platforms. Current evidence emphasizes that future research should develop standardized protocols for data harmonization and stronger links between science and practice, while also expanding spatial and temporal data coverage by combining satellite observations with additional field sensors and climatic variables (Torres-Quezada et al., 2025). For melon systems, such integration would support comprehensive assessment of water demand, stress development, yield formation, and fruit quality under both field and greenhouse conditions.

7.2 Advanced artificial intelligence for predictive irrigation management

Advanced artificial intelligence is likely to become central to predictive irrigation management because it can integrate nonlinear soil, weather, crop, and irrigation information more effectively than conventional scheduling tools. Reviews of drought-focused agricultural AI show that models such as Random Forest, Gradient Boosting, ANN, and CNN can combine weather, soil, crop, and irrigation management data to predict crop performance under water stress, but there is still no clear consensus on one universally best model (Fares et al., 2026). In melon research, this suggests that future model development should compare algorithms across different production environments rather than assuming one architecture will generalize everywhere.

The strongest research direction is toward hybrid and temporal deep-learning models linked to irrigation decision-support systems. CNN-LSTM and related models can capture both spatial and temporal stress dynamics and have reached about 90% prediction accuracy for crop water stress, while sensor-assimilation studies show that ensemble and boosting approaches can forecast evapotranspiration and crop water stress accurately enough to support automated irrigation scheduling (Illakiya et al., 2025). Future melon applications should therefore prioritize explainable, field-validated AI systems that translate predicted evapotranspiration and stress into stage-specific irrigation recommendations.

7.3 Sustainable water management strategies for high-quality melon production

Sustainable melon water management will likely depend on stage-specific deficit irrigation rather than season-long full irrigation. In melon, two-stage irrigation treatments such as VF and FM performed similarly to full irrigation when yield and quality were evaluated together, and VM achieved about 47% water saving without significant loss in irrigation water productivity relative to the fully irrigated treatment (Yavuz et al., 2021). These results indicate that future research should refine phenology-based irrigation strategies that protect sensitive reproductive stages while allowing moderate restriction during more tolerant periods.

Future sustainability studies should also expand beyond water amount alone to include fruit quality, stress-mitigation inputs, and broader resource efficiency. Moderate deficit irrigation combined with optimized biostimulant application maintained melon fruit quality under semi-arid saline conditions, while mycorrhizal inoculation under 80% ETc allowed water savings without reducing yield and improved irrigation water use efficiency and some quality traits such as firmness and soluble solids (Miceli et al., 2023). Overall, the most promising direction for high-quality melon production is an integrated strategy that combines regulated deficit irrigation with biological or physiological stress-buffering practices to improve resilience, water productivity, and market quality.

8 Conclusions

Recent work shows that melon quality prediction has moved from simple end-point measurement toward integrated, data-based inference from environmental, physiological, and imaging signals. In greenhouse melon systems, machine learning models using temperature, humidity, radiation, and related cultivation variables predicted growth and environmental states with high accuracy, while hyperspectral imaging enabled non-destructive estimation of soluble solids concentration and moisture content that are directly relevant to harvest quality assessment. Together, these results show that quality prediction is becoming both earlier and less destructive, with increasing capacity to link fruit outcomes to real-time cultivation conditions rather than postharvest testing alone. This progress is strengthened by evidence that quality traits can be modeled from broader biochemical and nutritional predictors, not only from visual maturity cues. Hyperspectral field phenotyping predicted nitrogen, potassium, and sucrose in melon tissues with R^2 up to 0.958, and machine learning analysis of grafted melon cultivars showed that sucrose, glucose, fructose, and fruit weight were strong predictors of Brix, whereas titratable acidity contributed little. The conclusion is that environmental and cultivation data now support a more mechanistic view of fruit quality, where sugar accumulation, nutrient status, and fruit development can be quantified and translated into predictive indicators for management.

The main contribution of data-based water management to precision horticulture is that irrigation can now be adjusted to crop demand with measurable gains in efficiency. In commercial melon production under semi-arid conditions, precision irrigation guided by soil water status sensors saved 27%-30% of water without reducing yield, while increasing water productivity, nitrogen productivity, and ascorbic acid content; in greenhouse melon, regulated deficit irrigation reduced irrigation amounts by 19.3% to 25.7% in soil-grown systems without compromising yield or fruit quality. These findings show that data-driven irrigation is no longer only a monitoring tool, but a practical method for maintaining melon productivity while reducing resource inputs. Digital technologies also extend precision horticulture by making irrigation control more continuous, automated, and accessible across different production scales. IoT-based smart irrigation systems can maintain melon soil moisture within a target range of 60%-80%, and broader cloud-connected irrigation platforms have shown that real-time sensing and automated control reduce water waste while remaining economically feasible for small and medium-sized farms. In this sense, the contribution to sustainable production is both agronomic and operational: better water-use efficiency is coupled with lower labor demand, remote supervision, and more reproducible management under variable climatic conditions.

Despite clear progress, the main limitations are still integration, robustness, and transferability under field conditions. Reviews of advanced irrigation monitoring emphasize that the strongest systems are those that combine soil, plant, and weather data in closed-loop control, yet current adoption remains constrained by technical complexity, interoperability needs, and the difficulty of scaling integrated platforms beyond controlled test settings. For melon research, this means that predictive performance alone is not enough; models and sensor networks must also remain stable, interpretable, and deployable across greenhouses, open fields, and diverse production environments. Future opportunities lie in combining low-cost sensing, multi-source data fusion, and AI-based decision systems that can support real-time irrigation recommendations at farm scale. Integrated smart irrigation platforms for melon and other crops have already combined evapotranspiration models, wireless sensor networks, and advanced control algorithms to cut water use by 50% in one season, while broader reviews identify AI integration, remote control, and historical-plus-real-time analytics as the next step for adaptive irrigation scheduling.

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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.

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