unpollinated fruits rapidly cease growth, linking successful fruit set and early cell division to subsequent fresh weight accumulation. Broader studies in model species indicate that fruit development proceeds through fruit set, a growth phase dominated by cell division and then expansion, and maturation/ripening, all tightly regulated by phytohormones such as auxin and gibberellins (Fenn and Giovannoni, 2020). High-resolution analyses highlight that fertilization and seed-derived signals trigger a transition to cell expansion that drives post-fertilization fruit growth and final size, emphasizing that both cellular processes and hormonal regulation underpin fruit weight . In cucurbits and other fleshy fruits, early developmental windows are considered "critical periods" in which disturbances can irreversibly constrain final fruit size and yield potential (Gao et al., 2023).

Environmental factors strongly modulate these developmental processes, making research on their regulatory roles essential for understanding and predicting watermelon fruit weight. Light conditions, for example, have been shown to markedly alter fruit expansion: low-light or shading during 0-15 days after pollination reduces fruit size, soluble sugars, and amino acids, and affects expression of thousands of genes related to metabolism and transcriptional regulation in developing watermelon fruit. Greenhouse orientation and internal microclimate alter solar radiation, temperature, transpiration, and leaf gas exchange around the fruiting zone, which in turn influence fruit volume increase in seedless watermelon (Woo et al., 2022). Supplementary LED lighting and optimized temperature or nutrient regimes around the fruit set region significantly increase fruit mass, size, flesh thickness, and overall yield in plastic-house and winter or early-spring crops, highlighting light, temperature, and mineral availability as key environmental levers for fruit weight formation (Chamchum et al., 2023). Weather studies at field scale further show that precipitation and temperature patterns across seasons drive differences in yield and fruit quality, with drier seasons often associated with higher productivity (Bai et al., 2020).

Despite this growing body of work on environmental impacts, quantitative models that explicitly link dynamic environmental conditions to fruit weight formation in watermelon remain scarce. In other fruit and crop systems, nonlinear growth functions, Bayesian sigmoidal models, and process-based simulation models (e.g., modified WOFOST, SIMBA, or radial basis function neural networks) have been successfully used to describe fruit growth dynamics and predict yields based on time, physiological status, and environmental drivers. Such models capture characteristic sigmoidal or multi-phase growth curves and can integrate factors like temperature, radiation, and plant age to forecast final fruit weight or total yield with high accuracy. However, comparable modeling efforts tailored to watermelon, particularly under controlled-environment or protected cultivation where light, temperature, and supplemental energy inputs are actively managed, are largely absent. Given the demonstrated sensitivity of early fruit expansion and final fruit weight to radiation, temperature, and nutrient conditions in watermelon, there is a clear need to develop and validate models that mechanistically and quantitatively link environmental variables to fruit weight formation. Such models could support decision-making for greenhouse design and orientation, supplemental lighting strategies, temperature control regimes, and fertilization programs, enabling producers to optimize resource use while stabilizing or increasing yield and fruit quality under variable climatic and market conditions.

2 Biological Basis of Watermelon Fruit Weight Formation

2.1 Stages of watermelon fruit development

Watermelon fruit development proceeds through fruit set, a rapid expansion phase, and maturation, each characterized by distinct physiological and molecular changes. Early after pollination, rapid cell division in the young ovary and fruitlets establishes the basic cell number and tissue pattern, a phase tightly coordinated with ethylene- and hormone-related gene expression and high ethylene evolution in fruitlets (Anees et al., 2023). Following this, fruit growth switches to a prolonged cell expansion phase in which vacuolated parenchyma cells enlarge and accumulate sugars, pigments, and other solutes that drive osmotic water uptake and volume increase, forming the bulk of fruit flesh mass.

The expansion and maturation stages are marked by coordinated changes in gene expression and metabolites that define size, texture, color, and sweetness. Transcriptome and digital expression profiling across key developmental stages show thousands of differentially expressed genes related to cell wall metabolism, sugar