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SUSTAINABLE WATER USE IN INTENSIVE HORTICULTURE: SMART IRRIGATION SYSTEMS AND THEIR EFFECTS ON FRUIT QUALITY — A REVIEW

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Abstract

Intensive horticultural systems rely on a precise water supply to achieve high yields and marketable fruit quality, while freshwater for agriculture is increasingly limited. This review examines how smart irrigation systems can support sustainable water use in intensive orchards and how they influence fruit quality. Twenty peer-reviewed publications were analysed and grouped into three themes: water-saving irrigation strategies, soil-based and plant-based monitoring technologies, and sensor-driven automation. The evidence shows that regulated and partial root-zone deficit irrigation can save water and control vegetative growth when applied at tolerant phenological stages, and that the effect on fruit size, soluble solids, firmness and storage behaviour depends on timing, severity and crop load. Plant-based indicators, such as stem water potential and trunk diameter variation, provide the most direct information on tree water status, whereas wireless sensor networks and thermal remote sensing improve spatial and temporal coverage. The main limitations are the need for local calibration, system cost and the scarcity of long-term, multi-site orchard trials. Integrating plant-based thresholds with automated sensor networks is the most promising route to sustainable irrigation of intensive orchards.

Keywords: smart irrigation; deficit irrigation; water use efficiency; fruit quality; intensive orchards; plant water status

1. Introduction

Intensive orchards are characterised by high planting density, dwarfing rootstocks, trained canopies and drip irrigation. Such systems reach high productivity early, but their shallow and limited root systems make them sensitive to even short periods of water imbalance. At the same time, irrigated agriculture is the largest consumer of freshwater, and competition from other sectors and increasing climate variability are reducing the water available for horticulture [1, 2]. Improving water use efficiency is therefore a condition for the long-term sustainability of intensive fruit production.

Water stress is not uniformly harmful to fruit trees. Its consequences depend on the phenological stage, the intensity and the duration of the stress, and some fruit quality traits may even benefit from a controlled water deficit [3, 4]. This has led to deficit irrigation strategies that deliberately reduce water

supply when yield and fruit growth are least sensitive. Applying these strategies safely requires reliable information on the actual water status of the orchard, which has stimulated the development of smart irrigation systems that combine sensors, plant-based indicators, remote sensing and automated control [5, 6].

Despite the growing number of studies, information on deficit irrigation, monitoring technologies and fruit quality is scattered across different disciplines. The aim of this review is to (i) summarise the main water-saving irrigation strategies used in fruit production, (ii) compare the monitoring and automation technologies that support them, (iii) synthesise their effects on fruit quality, and (iv) identify research gaps relevant to intensive horticulture.

2. Methods

A narrative literature review was conducted following the IMRAD structure. Publications were searched in Scopus, Web of Science and Google Scholar using combinations of the keywords “smart irrigation”, “deficit irrigation”, “regulated deficit irrigation”, “partial root-zone drying”, “plant water status”, “soil moisture sensors”, “wireless sensor networks”, “fruit quality” and “orchard”. Priority was given to peer-reviewed articles and review papers from established journals in horticulture, plant physiology, agricultural water management and agricultural engineering.

Publications were included if they (a) addressed irrigation management or water status monitoring in fruit trees or in horticultural crops more broadly, (b) reported or discussed effects on water saving, yield or fruit quality, or (c) described sensing and automation technologies applicable to irrigation scheduling. Conference abstracts, non-peer-reviewed reports and studies without an explicit link to irrigation management were excluded. Twenty publications, covering the period from 1995 to 2022, were retained. For each source, the irrigation strategy, species, monitoring technology and reported effects were extracted and then compared qualitatively. Because the studies differ in species, climate and experimental design, no quantitative meta-analysis was attempted. All sources are cited by number and listed in the References section.

3. Results

3.1. Water-saving irrigation strategies

Deficit irrigation supplies less water than the full crop requirement, with the aim of increasing water productivity while limiting yield loss [3, 7]. In regulated deficit irrigation (RDI), water is restricted only during phenological stages in which the crop tolerates stress, and full irrigation is applied in the remaining periods. In fruit trees, the rationale is based on the timing of shoot and fruit growth: restricting water during intensive shoot extension reduces vegetative vigour and pruning needs without necessarily reducing fruit growth [8–10]. Reviews of Mediterranean orchards and vineyards show that RDI can reduce irrigation volumes considerably, but its success depends on the species, the stage at which the deficit is imposed and the severity of the stress [2, 10].

Partial root-zone drying (PRD) and related alternate irrigation techniques keep one part of the root system wet and the other dry, and alternate them. The physiological explanation is that roots in drying soil send chemical signals, notably abscisic acid, that partially close the stomata, which can reduce water loss more than carbon assimilation [2, 11]. However, the advantage of PRD over conventional deficit irrigation applied at the same water volume is not consistent across reports [2]. In both approaches, the

practical difficulty is to maintain the stress within the intended limits, which is why monitoring is essential.

3.2. Soil-based and plant-based monitoring

Soil water sensors, such as tensiometers and dielectric probes, are widely used because they are easy to install and can be connected to data loggers and wireless networks [5, 12]. Their weakness is spatial variability: a point measurement may not represent the root zone of the whole tree, and the result depends on sensor placement, soil type and calibration.

Plant-based methods measure the response of the tree itself and thereby integrate soil, atmospheric and physiological effects [13]. Stem water potential is considered a reference indicator of tree water status, and threshold values have been proposed to guide irrigation scheduling in deciduous orchards [14]. Because it requires manual measurements, its use is limited to periodic checks. Continuous measurements of trunk or stem diameter variations offer an automatable alternative: indices such as maximum daily shrinkage and trunk growth rate have been used to schedule irrigation in tree crops [15, 16]. Nevertheless, reference values depend on species, tree age and crop load, and they must be established for each orchard type before being used in automatic control [14, 16]. Jones [13] emphasised that plant-based methods are advantageous but need a clear baseline and careful interpretation.

Remote sensing extends monitoring to the orchard scale. High-resolution thermal imagery acquired from unmanned aerial vehicles was used to assess the variability of water status within a commercial orchard in five fruit tree species, and canopy temperature-based indicators were related to physiological measurements of water status [17]. Such maps can identify irrigation zones that would be invisible to a few point sensors.

3.3. Sensor networks, IoT and automated control

Wireless sensor networks collect soil, plant and weather data and transmit them to a central unit, where decision rules or models determine when and how much to irrigate [12]. More recent reviews describe how threshold-based, model-based and feedback control strategies are being combined with Internet of Things platforms to automate irrigation and to improve water use efficiency [5, 6]. The reported barriers include sensor cost, energy supply, calibration drift, unreliable connectivity, lack of interoperability between devices and the limited number of long-term validations under commercial orchard conditions [6, 12]. Table 1 summarises the approaches discussed.

Table 1. Irrigation approaches and monitoring technologies in intensive orchards.

Approach	Main principle	Strengths	Limitations
Regulated deficit irrigation	Water restriction at stress-tolerant stages [3, 10]	Saves water; controls vegetative growth [8, 9]	Requires accurate stage timing and monitoring [7]
Partial root-zone drying	Alternate wetting of root zone halves; root-to-shoot signalling [11]	Reduces transpiration relative to assimilation [11]	Benefit over conventional deficit irrigation inconsistent [2]
Soil moisture sensors	Point measurement of soil water [12]	Easy to automate and network [5]	Spatial variability; calibration [12]

Approach	Main principle	Strengths	Limitations
Plant-based indicators	Stem water potential, trunk diameter variation [14, 16]	Direct tree response; integrates soil and climate [13]	Species-specific reference values; some methods are labour-intensive [14, 16]
Thermal remote sensing	Canopy temperature from UAV imagery [17]	Orchard-scale spatial maps [17]	Needs ground validation [17]
IoT and automated control	Sensor data combined with control algorithms [5, 6]	Real-time decisions; water efficiency [6]	Cost, connectivity, few long-term trials [6]

3.4. Effects on fruit quality

The effect of water supply on fruit quality is the result of two processes: changes in fruit water content and size, which alter the concentration of solutes, and metabolic changes that affect sugars, organic acids and secondary metabolites [4]. The outcome depends on the stage and severity of the stress, so the same water saving may improve one trait and impair another [4].

In apple, deficit irrigation applied at different periods modified fruit maturity and quality attributes in ‘Braeburn’, and the effects differed with timing [18]. Fruit size is particularly sensitive: it was shown to depend jointly on tree water status and crop load, which means that irrigation and fruit thinning should be managed together [19]. In peach, the effects of deficit irrigation during stage II of fruit growth and after harvest were evaluated both at maturity and after cold storage [20], which highlights that irrigation decisions should be assessed through postharvest quality as well as yield at harvest. These findings agree with general reviews of deciduous orchards, which conclude that moderate and well-timed deficits can maintain or improve some quality traits, whereas severe stress usually reduces fruit size and yield [9, 10].

4. Discussion

The reviewed literature shows a consistent logic: sustainable irrigation in intensive orchards means supplying water in the right amount at the right phenological stage, and verifying it with reliable measurements. Deficit strategies provide the water-saving potential [3, 7], plant-based indicators provide the physiological reference [13, 14], and sensor networks and remote sensing provide the spatial and temporal resolution needed to apply these references at orchard scale [5, 12, 17]. Smart irrigation systems are therefore most effective when they are not limited to soil moisture thresholds but are linked to the water status of the trees and to the fruit quality targets of the grower.

Several limitations should be noted. First, the experimental protocols differ greatly in the timing and severity of deficits, so results are difficult to compare and to transfer between species, cultivars and rootstocks [4, 10]. Second, most quality assessments are done at harvest, while information on storage behaviour, sensory quality and consumer acceptance remains limited. Third, the reviews on smart irrigation mainly describe technical potential, and the number of long-term validations in commercial orchards is small [6]. Economic analysis, including sensor costs and the benefit of improved fruit quality, is also rarely reported. Finally, this review is narrative and based on twenty sources, so it does not replace a systematic review with a formal quantitative synthesis.

For irrigation-dependent regions with limited water resources, including Central Asia, where intensive orchards are expanding, these findings imply that imported thresholds and control algorithms should be calibrated locally for each cultivar, rootstock and climate before being used for automation. Priority research areas are (i) site-specific plant-based thresholds linked to fruit quality targets, (ii) multi-year trials of automated systems under commercial conditions, (iii) combined management of irrigation and crop load, and (iv) low-cost, robust sensor solutions suitable for small and medium-sized farms.

5. Conclusions

Smart irrigation systems offer a realistic way to reduce water use in intensive horticulture while protecting fruit quality. Regulated deficit irrigation and partial root-zone drying can save water, but their results depend on timing and severity. Plant-based indicators currently provide the most direct basis for decision-making, and sensor networks, thermal remote sensing and automated control make it possible to apply them at orchard scale. Wider adoption requires local calibration, evidence from long-term commercial trials and cost-effective technologies.

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