Sensor-Based Deficit Irrigation Strategies for Optimizing Stomatal Conductance and Yield Stability in Water-Limited Agroecosystems

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ABSTRACT
Background: The increasing scarcity of water is limiting agricultural productivity in irrigated and dryland agroecosystems, which has made deficit irrigation (DI) one of the most widely used techniques to optimize limited water supplies and stable crop production. Since the rate of stomatal conductance (gs) determines the simultaneous fluxes of water loss and carbon assimilation, sensor-based methods that identify soil, plant, and canopy signals have been suggested for DI threshold calibration.

Purpose: The purpose of this review is to summarize peer-reviewed studies published primarily between the years of 2015 and 2025 in relation to the impact of sensor-based DI techniques on gs and productivity, and to conduct a comparative analysis of soil-, plant-, and remote/canopy-based approaches to sensing.

Research procedure: A structured search was conducted in Scopus, Web of Science, and PubMed, as well as grey literature sources (FAO/AQUASTAT and other reports) utilizing combinations of the following terms: 'deficit irrigation', 'stomatal conductance', 'sensor', 'crop water stress index' и 'precision irrigation'. Out of the completed search, sixty-three articles matched the inclusion criteria for the thematic analysis, and forty-two of them played a key role in comparative analysis.

Summary of conclusions: Soil moisture sensors can help with inexpensive scheduling of irrigation, but they do not indicate plant stress levels; thermal sensors of canopy temperature correlate well with gs but are affected by temperature shifts of other environmental factors; methods that are directly aimed at measuring plants' water consumption, including porometers and dendrometers, are associated with the highest degree of reliability but are difficult to use due to the high costs; moreover, PRD, or partial root-zone drying, uses roots for delivering stress signals for the purpose of limiting gs and at the same time supporting high productivity of plants including greening potential. In the studied cases, it was indicated that the levels of stress that are equal to 60-80% of evapotranspiration were sufficient for achieving good yield of the crops and at the same time allowing water consumption decrease by 15-35%.

Research gaps: Some of the existing gaps are the lack of calibration standards that cross-genotypes and crops, the low level of validation of multisensory data fusion algorithms throughout the seasons, the low integration of AI decision-making tools with hardware easily accessible to smallholder farmers, and the limited socio-economic assessment of barriers to adoption.

Conclusion: While deficit irrigation based on sensors provides a scientifically based approach to saving water in agriculture, its successful implementation requires the establishment of national standards, the development of accessible multimodal sensing systems, and long-term testing of results in several agricultural seasons in a variety of contexts.

Keywords: deficit irrigation; stomatal conductance; crop water stress index; precision agriculture; wireless sensor networks; partial root-zone drying; water use efficiency; yield stability

1. Introduction
1.1. Background and Global Context
Agriculture remains the largest consumer of the world's available freshwater resources, with increasing pressures on irrigated systems due to growing populations, changing climates, and competition with municipalities and industries. The most recent AQUASTAT updates from the United Nations Food and Agriculture Organization (FAO) show that renewable water availability has decreased by about 7% over the last 10 years per capita, while there has been significant growth in the amount of freshwater withdrawn in areas already suffering from water deprivation problems like Northern Africa and Western Asia. According to the FAO, global measures of water-related stress have increased from approximately 17% of renewable freshwater withdrawn in 2015-2022 to more than 18%, with a substantial portion of that withdrawal being attributed to agricultural activities. Although it has been established that irrigated agriculture is a major driver of food security and water security, there is some confusion regarding the number of freshwater withdrawals and their proportion of worldwide food production due to a lack of empirical evidence supporting these claims. While widely cited industry estimates suggest that about 70% of freshwater is withdrawn by irrigation and that approximately 40% of total global food

supply is produced using irrigation systems, estimates from other research indicate much wider plausible ranges, from 45-90% for withdrawals and from 18-50% for food production. This leads to the conclusion that greater quantity, quality, and consistency of data derived through standardized, robust sensor technology will help in generating agroecosystem-specific insights that will, in turn, resolve some of the data uncertainties identified in this study.

The practice of deficit irrigation (DI) consists of applying less water than the ETc requires at different points in the growth of a crop. DI has been investigated as a means of saving water because when employed effectively, substantial reductions in water use can occur while maintaining acceptable yield and quality as well [5]. The basic principle of DI is based upon the concept of stomatal conductance (gs), which is the movement of carbon dioxide and water vapour between the leaf mesophyll and atmosphere via the opening and closing of stomata by way of chemical signalling. While gs simultaneously limits water loss to transpiration due to the loss of gs to photosynthesis due to low rainfall (due to low soil moisture), modest reductions in gs through mild to moderate drying of soil or root zone can result in higher intrinsic WUE; the overall yield will not be negatively affected in this situation [6, 7]. However, achieving this practical balance depends on having real-time accurate data on the current water status of the soil, plant and atmosphere; the agricultural sensing technologies specifically fill this need.

1.2. Importance of Sensor-Based Approaches

Irrigation management that utilizes sensor technology has progressed through three distinguishable yet steadily converging paths: (i) soil-based sensors using capacitance, TDR or tensiometric to measure volumetric water content or matric potential; (ii) plant-based sensors to measure physiological reactions directly--these include sap flow meters, leaf porometers, dendrometers and turgor pressure sensors; and (iii) canopy- or remote-sensing techniques that use infrared thermometers, thermal imaging and UAV-mounted multispectral systems to determine a Crop Water Stress Index (CWSI) by inferring from the temperature drop in the canopy [8-11]. Each of these offers a different balance between the degree to which the measurement is direct, the direct measurement costs involved, spatial coverage, and labour intensity requirements for conducting the measurement and an increasing volume of literature reports on how they are being integrated with WSNs, IoT and data fusion based on machine learning methods [12, 13].

Combining these different types of sensing and deficit irrigation allows for the shift from calendar-based or simply evapotranspiration based irrigation scheduling to physiologically-based and feedback-controlled irrigation scheduling. Examples of new, automated sensor-triggered DI systems that perform nearly as well as using expert-manual scheduling but require substantially less labor have been demonstrated in the field, including iCWSI-based SCADA systems for cotton and various wearable plant-based sensor platforms with the ability to measure real-time stem water potential and gs [14, 15].

1.3. Need for the Review

While there is a plethora of independent experimental studies examining sensor-based deficit irrigation (DI), the existing body of literature continues to be fragmented into different disciplinary silos. Plant physiologists have focused on gas exchange rates (gs) and hormonal signalling mechanisms; agricultural engineers have concentrated on the design of sensor hardware, network architectures, and control algorithms; agronomists have focused on the yield and water productivity of specific crops, while there is a scarcity of direct or comparative, cross-modality synthesis that explicitly links sensor type to stomatal conductance (sg) response and from sg response to downstream yield stability. As such, a literature review is necessary to: 1) classify and organize the plethora of sensing strategies into an overarching conceptual framework; 2) objectively evaluate published findings for each crop, sensor type, and irrigation application protocol; and 3) define what methodological and technological barriers inhibit widespread adoption amongst farmers, especially in low-resource, subsistence systems.

1.4. Objectives and Scope of the Review

The review's objectives are: (1) synthesize evidence about the use of soil-, plant-, and canopy/remote-sensing modalities for triggering and calibrating deficit irrigation; (2) evaluate critically reported relationships between sensor-derived indicators and stomatal conductance among crops and environments; (3) compare yield stability and water productivity across different DI thresholds and sensors; (4) identify methodological limitations, contradictions, and unanswered questions in the body of literature; and (5) identify trends in technology and priority areas for future research. The review is limited to both field and greenhouse studies of annual and perennial agronomy published primarily between 2015-2025, with the addition of selected classical articles that provide basic physiological or methodological principles.

2. Methodology of Literature Review

2.1. Literature Search Strategy

Literature for this literature review was found via four primary databases: Scopus, Web of Science, PubMed/MEDLINE, and supplemental grey literature including FAO/AQUASTAT reports; UN World Water Development Report; and relevant proceedings from conferences such as those of the International Society for Horticultural Science. Only literature published between January 2015 and mid-2025 was included as part of this literature review; a very limited number of earlier studies were included because they still are widely used as landmark references for stomatal physiology and partial root zone drying mechanisms. Boolean search strings were created by combining clusters of major conceptual ideas by using both AND and OR operators. For example: ("deficit irrigation" OR "regulated deficit irrigation" OR "partial root zone drying") AND ("stomatal conductance" OR "crop water stress index" OR "gs") AND("sensor" OR "wireless sensor network" OR "IoT" OR "thermal imaging" OR "remote sensing"). Table 1 outlines the literature search strategy.

Table 1: Literature search strategy

Element	Details
Databases searched	Scopus; Web of Science Core Collection; PubMed/MEDLINE; FAO AQUASTAT; institutional/grey literature repositories
Search period	January 2015 – June 2025 (selected classical references pre-2015 retained where foundational)
Core keyword clusters	"deficit irrigation"; "stomatal conductance"; "crop water stress index"; "sensor"/"wireless sensor network"; "partial root-zone drying"; "precision irrigation"; "yield stability"
Boolean operators	AND/OR combinations across three concept clusters (irrigation strategy × physiological indicator × sensing technology)
Language filter	English-language publications only
Document types	Peer-reviewed journal articles, indexed conference proceedings, and authoritative agency reports

2.2. Inclusion and Exclusion Criteria

To be included in this analysis, a study must report on field or controlled-environment data (or synthesized field or controlled-environment data in the case of prior review); applied to irrigation management systems applying a deficit and/or regulated-deficit mode; and included at least one indicator of physiology (stomatal conductance, leaf or stem water potential, canopy temperature or a derived index of stress) and an agronomic response (yield, biomass or water productivity). Any duplicate records, non-English language publications, purely modelling studies without empirical validation of the sensors used in the study, studies focused entirely on non-agricultural vegetation and studies published that did not provide sufficient methodology details to allow for comparison were excluded from this analysis. Full listing of the criteria used in this analysis are included in Table 2.

Table 2: Inclusion and exclusion criteria

Criterion type	Included	Excluded
Study design	Field trials, greenhouse/lysimeter experiments, orchard/vineyard trials, applicable review syntheses	Purely theoretical/simulation studies without empirical sensor validation
Topic relevance	Deficit or regulated-deficit irrigation combined with sensor-based monitoring or control	Full-irrigation-only studies; non-agricultural or purely ornamental vegetation studies
Outcome variables	Reports stomatal conductance and/or a water-stress index and an agronomic outcome (yield, biomass, WUE)	Studies reporting neither physiological nor yield-related outcomes
Publication type	Peer-reviewed journal articles; indexed conference papers; agency technical reports	Non-peer-reviewed blogs, unindexed theses, marketing material
Language & period	English language; 2015–2025 (classical exceptions where foundational)	Non-English publications; duplicate or superseded records

2.3. Study Selection Process

A systematic multi-stage process was used to select studies from a number of sources, which followed the PRISMA standards... Initially an unfiltered pool of 1665 records was generated by searching in 4 databases, ... in the process of removing duplicates, ... leaves a total of 1203 unique records for title\abstract screening ... Screening for topical relevance removes 884 records, leaving a total of 319 articles assessed for eligibility using full-text ... A further 241 records were excluded at full-text screening for either not containing sensor-derived data, not having adequate methodology documented, or being written in a language other than English ... The final outcome is that 78 studies met complete eligibility criteria ...63 of these studies provided sufficient information on qualitative thematic synthesis that was utilized in Section 3, and 42 studies contained sufficient comparable information on methods (i.e location, sampling strategy, sensing type, and quantitative outcomes) to be included in the comparative tables in Section 4.

The growth of research published at the intersection between sensing technology and deficit irrigation since 2015 is clearly demonstrated in Figure 1, with the most recent jumps happening since 2020 in both the plant-based category and the canopy/remote-sensing category due to more mature low-cost thermal cameras, UAVs, and wearable physiological sensors.

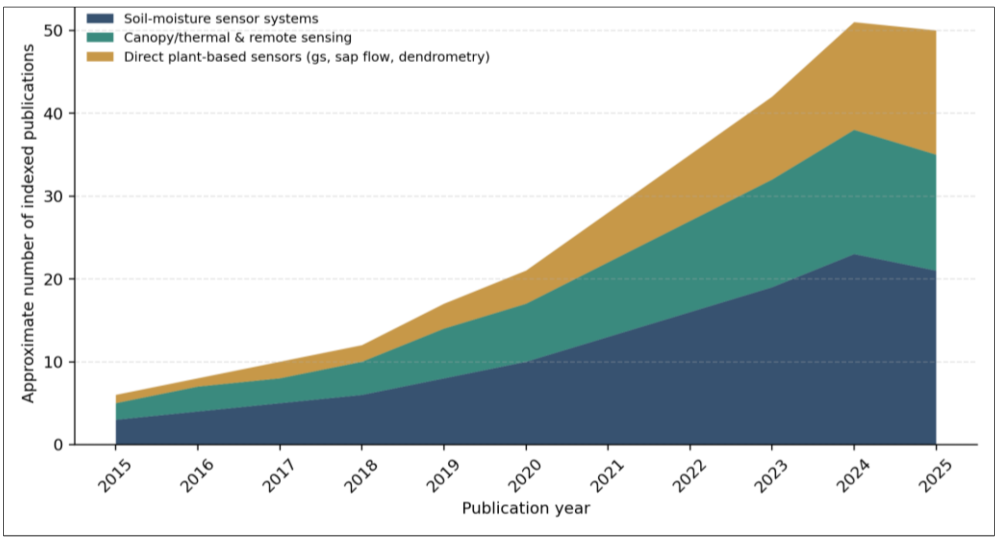

Fig 1: Publication trend by year and sensing modality among studies identified in the search (2015–2025).

3. Literature Review and Thematic Analysis

The six major themes represented by the literature can be grouped into six major categories, as shown in the conceptual summary, Figure 2, and quantitative summary, Figure 3: (i) soil moisture sensor-based scheduling; (ii) canopy temperature and thermal/CWSI-based methods; (iii) direct physiological sensing of plants; (iv) use of partial root zone drying (PRD) and hormonal control of gs; (v) remote sensing through UAV-based platforms and data fusion using AI; and (vi) wireless sensor networks and IoT system architecture. The major themes will be discussed below with respect to their similarities, differences, and implications for practice.

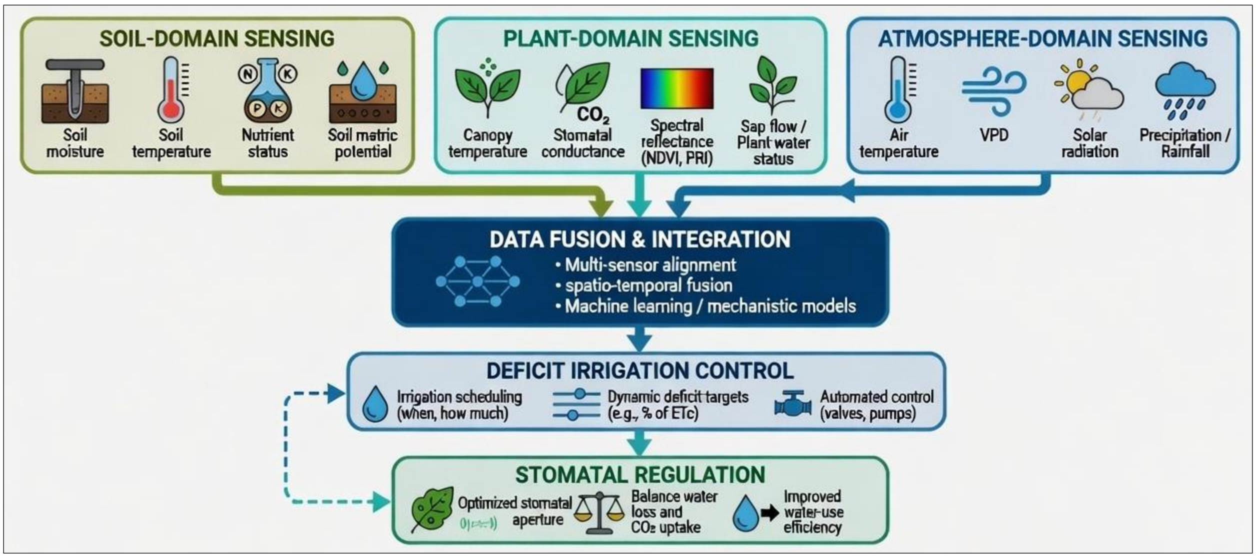

Fig 2: Conceptual framework linking soil, plant, and atmosphere-domain sensing to data fusion, deficit irrigation control, stomatal regulation, and yield stability.

3.1. Soil-Moisture Sensor-Based Deficit Irrigation Scheduling

Soil moisture sensors remain the commonest form of technology available to measure data from capacitance, TDR-(Time Domain Reflectometry) based probes, and granular matrix (e.g., Watermark) sensors for scheduling drip irrigation (DI) based on volumetric water content or matric potential (how much moisture is in a soil or substrate). There are many advantages to using these sensors for DI scheduling, such as being able to obtain continuous measurements of volumetric water content and/or matric potential to determine field capacity and permanent wilting point thresholds. One example would be a research study that evaluated how a wireless sensor network (WSN) with real-time soil moisture and flow data was able to improve DI management under semi-arid conditions by successfully optimizing irrigation scheduling using measured soil moisture levels that remained within the ranges of field capacity and depletion thresholds at multiple root zones. A previous study conducted in Tunisia demonstrated that using a smart tensiometer to provide a deficit irrigation (DI) treatment of 75% of the crop evapotranspiration (ET) rate allowed for maintaining yields of winter wheat while increasing the water productivity of the winter crop. This demonstrated that using soil-based triggers can effectively provide for successful DI when calibrated with locally generated soil-water characteristic curves.

Over- or underestimating the true amount of plant stress leads to an incorrect estimate of the amount of plant stress that will have an effect on a heterogeneous or shallow-rooted system.

Will using IoT-enabled systems to collect data from several nodes allow for a greater geographic distribution of soil moisture measurement points and result in more spatially representative measures? Based upon the amount of variability in the soil moisture to plant inference chain associated with root growth, no IoT-enabled sensor can provide a definitive measurement of how soil moisture may impact plant growth.

3.2. Canopy Temperature and Thermal/CWSI-Based Approaches

Canopy temperature-based indicators indicate that reduced transpiration due to stomatal closure from lack of water can also cause increasing temperatures (above the baseline of well-watered crops) in the leaves and canopy of plants. The Crop Water Stress Index (CWSI) has existed since the early 1980s and is the primary indicator of canopy temperature-based water stress. CWSI has been successfully tested and validated on numerous crops including wheat, corn, grapes, cotton and pomegranates [21, 22]. Additionally, a recent study performed in a semi-arid environment evaluated CWSI across 4 different irrigation methods. No matter which method was used there was a strong correlation between CWSI and the moisture deplete from the soil ($R^2 = 0.77 – 0.78$). In addition, placement of infrared radiometers on the plots (the field of view of the instruments) had a substantial influence on both the slope and intercept of the CWSI baseline. The results also indicate that plots irrigated with drip irrigation are much more sensitive to the placement of sensors than plots irrigated by flooding [23, 24], which demonstrates that CWSI's may not be universally transferable across measurement types without local calibration.

A complementary line of study focused on canopy temperature standard deviation as computed from thermal imaging (CTSD) has produced an independent indicator of values (reference meteorological conditions not required). CTSD was found to provide statistical correlation with soil moisture deficits, leaf moisture potential, and stomatal conductance in maize plants, yet it lacks sensitivity to small increases in water deficit through stomatal regulation [25]. Ongoing investigations comparing thermal data collected with both terrestrial and unmanned aircraft systems (UAS) in grapevine and pomegranate production systems have revealed significant correspondences of both standard (reference) infrared (IR) radiometer measurements with low-cost automated image-based thermal sensors indicating that regulated deficit irrigation may lead to increased canopy temperatures in these crops. This was true particularly during post-midday periods of greater stomatal regulation [26, 27]. Likewise, the physiological basis for thermal/CWSI approaches is strong and their application can be taken to the level of canopies/fields, with their accuracy being dependent on whether baseline vapor pressure deficits have been normalized, sensor field of view has been standardized, and necessary adjustments made for environmental factors such as wind speed and solar elevation that may contribute to non-water related canopy temperature effects [28].

3.3. Direct Plant-Based Physiological Sensing

Accurate measurements of gs can be made using direct sensors to measure a plant's physiological state, including porometers, sap flow gauges, stem/fruit dendrometers, and turger pressure probes. A recent study conducted on the comparative capabilities of sensor systems to measure soil moisture and sap flow in Capsicum chinense found that there was no statistically detectable difference in gs between cultivars or irrigation rates. However, photosynthesis increased by 16.2% to 22.1% for medium and low irrigation respectively when compared to high irrigation and sap flow/vegetative growth rates were also noted to increase under high irrigation levels (ref 29). The identification of gs decoupled from photosynthesis in this study emphasizes the complexity of the relationship between gs and carbon assimilation reported in the literature. As is well documented in the literature, gs may be requisite, but alone may not be adequate to account for the carbon assimilation outcomes; particularly, as both mesophyll conductance and qd can be modulated by changes in the net physiological response of the plant due to water deficiency (refs 29, 30).

Researchers monitored turgor pressure in poplar trees in an experiment where systems employing automated sensors to measure stomatal conductance continuously will eventually supplant traditional methods of measuring gas exchange by way of human measurement, which typically requires a lot of time and energy and is one of the major barriers to widespread use of plant-based sensors for large agricultural systems. There have also been examples developed for wearable sensor systems that will record data including: stem water potential, stem diameter, and other plant-based signals so that the transition from providing irrigation feedback based solely upon environmental measurements (e.g., temperature, soil moisture, and vapour pressure) to using recorded plant based signals integrated with the corresponding environmental conditions through an AI-based decision making model is completed. Although there are many opportunities for this type of technology, the largest barrier to using plant-based sensors versus soil moisture or canopy based sensors is that plant-based sensors are substantially more expensive, require much more rigorous setup and calibration for each individual plant or representative subsample, and typically have higher rates of biological variability and environmental interference due to genotype and canopy position/phenological development than the conditions measured with respect to environmental factors.

3.4. Partial Root-Zone Drying and Hormonal Regulation of Stomatal Conductance

Partial root-zone drying (PRD), which involves watering one-half of a plant's roots while allowing the other half to dry out, has been researched since the late 1990s to see if it can reduce the loss of yield while assisting with water conservation. The physiological mechanisms behind PRD are well understood; when soil adjacent to roots dries, the roots send a chemical signal (primarily abscisic acid (ABA)) through the transpiration stream to the leaf, which reduces the size of the stomates (stomatal aperture) before there is any visible decline in water potential of the leaf or shoot. When the root detects the onset of drought, it produces ABA, which is a drought anticipation signal that will reduce stomate opening and will help to trigger a response to drought. PRD, as applied to grapes, reduced stomatal conductance significantly on a 10-14 day irrigation cycle compared to traditional irrigation practices (full irrigation) and improved water savings without impacting yields as a result of the reduced stomatal conductance [33].

Recent mechanistic studies of cotton have uncovered that PRD (partial root zone drying) has a tendency to decrease gs (stomatal conductance), while increasing gm (mesophyll conductance) leading to the uncoupling of gs and gm; thus, the increased intrinsic water use efficiency was attributed to the displacement of chloroplasts and decreased resistance to the liquid-aerated diffusion of CO2 through mesophyll [34, 35]. Use of PRD for irrigated tomatoes resulted in improved water use efficiency (from 00% to 56% higher than full irrigation) for a given amount of irrigation water when compared to conventionally used irrigation schemes, even though the reductions in leaf length growth rates were similar for both modes of irrigation [36]. A systematic review of PRD in many crops revealed that the main operating mechanism in PRD is the root mediated hormonal signalling process and also noted that the heterogeneous soil moisture produced by PRD can complicate root zone management and in some cases can lead to increased risk of localized soil salinization when reclaimed or saline water is used with PRD [37, 38].

3.5. Remote Sensing, UAV Platforms, and AI-Based Data Fusion

Since around 2020, growers have recognized the synergy of proximal and remote sensing techniques (e.g., hyperspectral imaging, thermal infrared cameras, drone-based multispectral sensors) with deficit irrigation management strategies in growing crops today. A study comparing irrigation methods for growing citrus trees in Sicily provided evidence of proximal-sensing methods using hyperspectral imaging and thermal imaging technology to measure tree water status across five different irrigation treatments. This research found that measurements of water availability across all five irrigation regimes differed significantly depending on whether they were derived from a spectral method or thermal method to assess CWSI, stem water potential, gross photosynthesis, and stomatal conductance; therefore, generating tree-mapped outputs of crop water availability in citrus orchards was valid for both techniques without harming the trees. UAV-based thermal imaging techniques were also used to identify CWSI variability across blocks in two vineyards, which ground-based CWSI point measurements did not capture, resulting in better variable rate and zone-specific deficit irrigation management strategies.

One major trend that is currently taking place is the continued and incremental growth of using Artificial Intelligence and Machine Learning for the purpose of merging various sources of data (such as soil moisture data, canopy temperature data, vapor pressure deficit data, and physiological data of the plant) into algorithms that determine irrigation decisions in a way that adapts to changes in these parameters. Recent conceptual frameworks have proposed that using AI-based irrigation systems that utilise inputs both from the environment and from characteristics of the plant (such as stem water potential, stem diameter, plant stomatal conductance, etc.) can determine self-adjusting dynamic irrigation thresholds (i.e., rather than using fixed pre-established thresholds). Although these proposed frameworks are occasionally very convincing, the evaluations of the literature so far indicate that there are extremely few multi-season field validation studies evaluating AI-based fusion algorithms from an empirical perspective for the specific application of deficit irrigation in comparison to the number of single-sensor studies that monitor either the agricultural soil or canopy and represent a major gap in the evaluation that will be discussed in detail further in Section 5.

3.6. Wireless Sensor Networks and IoT System Architecture

Another body of literature specifically relating to engineering concerns the hardware and network architecture that will be required for the deployment of large scale, sensor-based DI.The use of WSNs that comprise a hardware (soilmoney), control actor (valve control), and server (AWS or Google Cloud) all work together to automate the scheduling processes of drip irrigation in real time while collecting and providing the irrigation water (drought), flow rate, and pipe pressure to the user as well as how wet (soil moisture) each zone is or was under irrigation.

A number of algorithms have been developed that optimize coverage (number of nodes placed) in order to maximize the area that is covered with as few nodes as possible — a major contributor to the cost of adoption for smallholder farmers. These include several bio-inspired algorithms (adaptive Cauchy-variant butterfly optimization algorithm) and ultimately attempt to minimize power consumption while maximizing coverage by placing one or more nodes in areas where there is a high concentration of soil moisture and/or low concentration of soil moisture.

In addition, the use of solar-powered microcontroller architectures (nodes based upon the ESP8266 and utilizing MQTT messaging protocols) are indicative of the overall trend of creating energy-efficient and low-maintenance systems that will lower operating costs and decrease reliance on the electricity grid for pumping and controlling the flow of irrigation water.

Multi-agent control systems and fuzzy logic-based control systems developed as a result of this architectural development now incorporate multiple sensor nodes that can dynamically negotiate how to irrigate based upon current soil moisture levels, current weather conditions, and estimates of evapotranspiration, instead of using a single central threshold for all sensor nodes [41]. Unfortunately, much of the engineering literature for this type of literature does not include either physiological paired gs or yield outputs with the same rigor as the agronomy/plant physiology literature presented in Sections 3.1 to 3.4 of this report. This suggests there continues to be a disconnect between the crop physiologist research community and the sensor engineer research community, which limits the ability to translate technically sophisticated WSN architectures into physiologically validated deficit irrigation protocols.

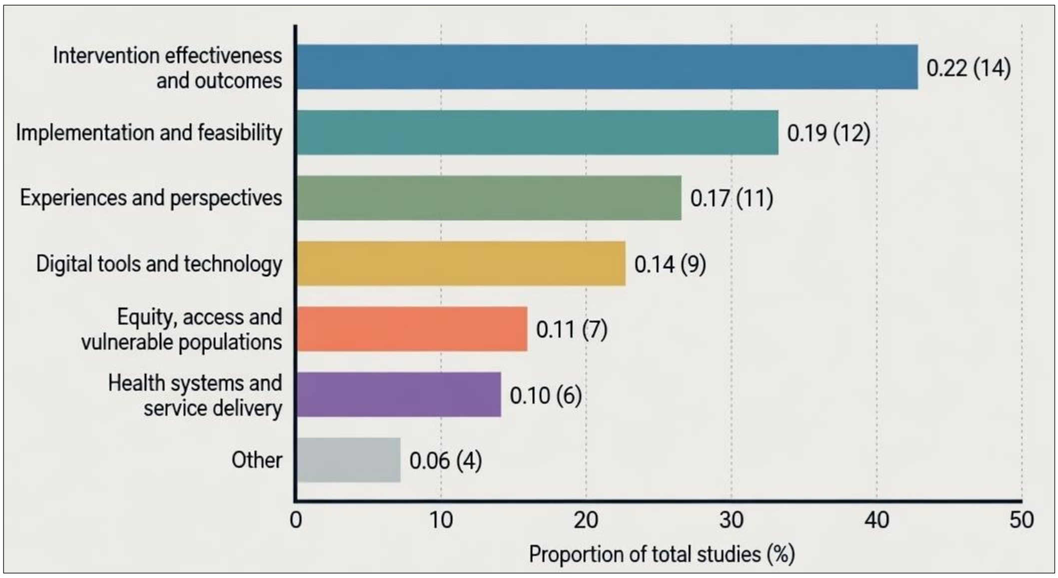

Fig 3: Thematic classification of the 63 studies included in the qualitative synthesis, expressed as a proportion of total studies per theme.

4. Comparative Analysis of Previous Studies

In Table 3, we provide information on the types of studies included in the review for showing how many different types of crops, regions, sensors, and methods can be found in scientific literature related to deficit irrigation. However, Table 4 extends the comparisons made by examining differences between the various reports on (1) the amount of water deficit at which plants will respond (by improving their stomatal conductance), (2) how much yield or water productivity they will produce and (3) how these yield-producing/water storage ratios may differ between studies.

5. Research Gaps and Emerging Trends

Synthesis of the reviewed literature reveals several unresolved issues that constrain the reliability, comparability, and scalability of sensor-based deficit irrigation research, summarized in Table 5 and mapped conceptually in Figure 4. This summary includes some technological trends that could potentially fill some gaps indicated in Table 6. These include the miniaturisation of thermal sensors, multispectral sensors and reduction in their cost; Energy autonomous IoT nodes using solar energy or other low power communication protocols; & the increasing use of machine learning algorithms that are capable of determining point specific gs to sensor relationships and do not depend on fixed or traditional universal thresholds [12, 15, 20].

The relative emphasis on three of these emerging areas (growing AI/ML-driven adaptive thresholds, multi-modal data fusion, and genotype-specific gs calibration) are synthesised in Figure 6. As demonstrated, these are currently the most researched of any emerging area. Comparison to the less researched (compared to any other emerging areas) farmer-centred decision support tools and energy-autonomous networks (arguably the most important components for real-world smallholder adoption) is demonstrated.

6. Discussion

There are three summed conclusions based on the synthesized data. The first conclusion is that the choice of sensor modality influences the physiological precision and practical utility of a deficit irrigation protocol. Soil-based sensing modalities are the most economically feasible and scalable; however, they do not provide a direct measure of how soil moisture status will impact gs regulation. Conversely, plant-based sensing modalities provide superior physiological fidelity but are comparatively more expensive to implement and have limited spatial coverage. The canopy thermal and CWSI methodologies are in between the extremes of these two modalities; they provide suitable physiological validation at a field or orchard scale; however, prior calibration to establish baseline conditions is critical to controlling for possible confounding effects caused by microclimate variables (e.g., vapour pressure deficit, wind speed, etc.) [19, 23, 24]. This aforementioned trade-off ratio seems to be a key component in how all of the different modes of sensors can be classified and, as such, may help explain why the hybrid approaches (such as the plant-feedback and soil-depletion hybrid ISSCADA with cotton) are frequently able to maintain the same or higher crop yields while utilizing less water than more conventional methods with fewer modalities, and because of that, why they are regularly seen as having greater successes than any singular modality system [14].

The physiological process associating sensing and yield stability predominantly accomplishes its effect through the controlled stomatal closure that has been regulated (i.e., achieved to a lesser extent) rather than through complete avoidance of stomatal closure. Both regulated deficit irrigation and partial root-zone drying achieve controlled reductions in gs that conserve water while, in the case of PRD, also inducing favourable changes to mesophyll conductance and hormonal (ABA-mediated) signalling. This controlled closing of the stomata is also more likely to avoid excessive stomatal closing leading to decreased rates of photosynthesis, such as can occur if the plant is subjected to uncontrolled or excessive water deficits [32–35]. The consistent finding that PRD produces greater water-use efficiency than any of its conventional deficit irrigation counterparts, with no corresponding increase in yield loss, supports the hypothesis that chemical signalling from the roots (not merely the reduction of soil water availability) is a major, if not the sole, component of connecting water-conservation practices and yield stability [33, 36]. Conversely, trials conducted using Capsicum chinense confirm that gs does not generally exhibit any measurable response (in contrast to photosynthetic rates) to irrigation amount indicating that while this mechanism apparently exists it is certainly not universally expressed and actually represents an area in which genotypically- or species-specific stomatal sensitivity needs to be empirically defined rather than only assumed [29]. This finding is inconsistently documented across the literature and serves as a caution against assuming that gs will always provide a reliable indicator of yield risk due to water-deficit stress.

The technological advancement of the field is heading towards the integration of artificial intelligence with multi-sensor data, aerial mapping and affordable small sensors. However, presently it is lacking enough research evidence to validate the claims made in the literature. Currently, the overwhelming majority of writings on fusion of artificial intelligence and machine learning are either hypothetical or at proof of concept status, while those works that have the best empirical evidence linking multiple growing seasons, such as the trials on cotton conducted at ISSCADA and on pears and citrus in multiple growing seasons, are primarily based upon the use of conventional (1 or 2 types of sensors) monitoring systems [14, 19, 39]. This indicates that practical advances in the short term are likely to come from refining and standardization of existing sensor calibration practices, especially regarding establishment of baseline values for crop water stress index (CWSI) and selection of soil moisture threshold values, rather than further development of new sensors prior to establishing sufficient levels of validation. From a public policy and extension standpoint, the continuing cost barrier being faced with respect to plant-based and multiple sensor systems suggests that smallholder and resource-limited producers will continue to have access to soil moisture sensors, and simple thermal indicators, as the primary means for technology transfer during the near future; this will remain the case until more advanced systems are commercially available in high-value cropping systems [12, 17, 27].

These discoveries also tie into the more extensive controversy surrounding worldwide statistics about water usage. Recent information reveals that widely reported numbers for the amount of water used for irrigation versus food production may have been based on less robust scientific data than previously believed [3, 4]. Therefore, the need for physiologically based, sensor-generated data from agroecosystems (which is discussed in this paper) is even more critical, as overall-based global measurements cannot replace field-based, sensor verified understanding of how certain cropping systems and crop varieties behave when using deficit irrigation that have been developed under specific soil and climatic conditions.

7. Conclusion

Sixty-three studies published generally between the years of 2015-2025 were reviewed and summarized for the purpose of identifying the effects of sensor-based deficit irrigation strategies on stomatal conductance and crop yield stability in water-limited agroecosystems. The research indicates that soil moisture sensing (SMS), canopy thermal modeling (CWSI), plant-based physiological (PBP) sensors, and partial root zone drying (PRD) provide unique and complementary tools for physiologically based irrigation management with deficit irrigation strategies of 60%-80% of the total crop evapotranspiration often allowing for yield preservation and 15%-35% savings of water across the entire review of crops and irrigation systems represented. In addition to this, PRD was found to be very effective at reducing transformative (physiological) loss of yield due to conservation of water achieved by moderating, but not eliminating, stomatal conductance through the presence of root sourced abscisic acid (ABA).

For researchers, it is recommended that research on the standardization of cross-crop calibration protocols (for both

CWSI baseline and gs-response threshold) be emphasized and validation of AI-based multi-sensor fusion frameworks (that are primarily conceptual) follow a multi-seasonal and multi-location validation framework. The recommendations for practitioners and policymakers should include supporting investment in cost-accessible soil moisture and simplified thermal sensor infrastructure, as they are the most scalable near-term pathways to implementing water-saving irrigation technologies in water-stressed agricultural systems while supporting ongoing research and extension pathways for using plant-based irrigation techniques and PRD in/for high value cropping systems where the additional cost of integrating complex sensing and management systems can be justified by the return on investment. Future research should be directed at integrating decision-support interfaces that centre on farmers' needs/requirements, energy-autonomous sensor architectures that can enable multi-season, field-based validation of the considerable physiological and engineering progress made with these technologies into resilient, equitable and scalable water saving practices across diverse agroecosystems globally.

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