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Data-Driven Irrigation Management in Controlled Environment Agriculture: A Three-Tier Integration Model

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ABSTRACT

Modern greenhouse operations collect diverse environmental and substrate data at high temporal resolution, yet most irrigation decisions still depend on a single measured variable. Peer-reviewed literature documents individual sensor technologies and control algorithms in detail but offers no systematic framework for evaluating how multiple data streams are, or could be, combined within a single irrigation decision. To propose a structured classification of data-driven irrigation approaches based on the number of integrated data streams and the temporal horizon of the resulting control decision. An analytical review of published sensor-based, radiation-based, and model-based irrigation strategies was combined with retrospective operational observations from commercial hydroponic strawberry cultivation on coir substrate. A three-tier integration model is introduced, progressing from single-parameter threshold control (Tier 1) through dual-parameter coordination (Tier 2) to multi-parameter feed-forward architectures that couple environmental anticipation with root-zone feedback (Tier 3). Most peer-reviewed implementations operate at Tier 1 or Tier 2; Tier 3 configurations appear in proprietary commercial platforms but lack open documentation. The proposed classification identifies a persistent gap between available sensor infrastructure and the decision logic that utilizes it, and positions multi-parameter feed-forward integration as a priority for further applied research. The analytical observations presented in this article were informed by the author's operational management of commercial hydroponic strawberry production in Kyiv Oblast, Ukraine, involving up to 10 hectares of greenhouse area and approximately 640,000 plants cultivated under closed-loop fertigation systems. The operational experience referenced throughout this work is used as contextual support for interpretation and discussion and is not presented as controlled experimental evidence.

KEYWORDS

data-driven agriculture, irrigation control systems, sensor-based irrigation, greenhouse automation, precision irrigation, real-time monitoring, decision support systems.

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Управління зрошенням на основі даних у сільському господарстві з контрольованим середовищем: трирівнева модель інтеграції

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СТАТТЯ

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АНОТАЦІЯ

Сучасні тепличні господарства збирають різноманітні дані про навколишнє середовище та субстрат з високою часовою роздільною здатністю, проте більшість рішень щодо зрошення все ще залежить від однієї вимірюваної змінної. Рецензована література детально документує окремі сенсорні технології та алгоритми керування, але не пропонує систематичної основи для оцінки того, як кілька потоків даних об'єднуються або можуть бути об'єднані в одному рішенні про зрошення. Запропонувати структуровану класифікацію підходів до зрошення на основі даних, на основі кількості інтегрованих потоків даних та часового горизонту результуючого рішення про керування. Аналітичний огляд опублікованих стратегій зрошення на основі датчиків, випромінювання та моделей був поєднаний з ретроспективними оперативними спостереженнями за комерційним гідропонним вирощуванням полуниці на кокосовому субстраті. Введено трирівневу інтеграційну модель, яка переходить від однопараметричного порогового керування (рівень 1) через двопараметричну координацію (рівень 2) до багатопараметричних архітектур прямого зв'язку, які поєднують передбачення навколишнього середовища зі зворотним зв'язком кореневої зони (рівень 3). Більшість рецензованих реалізацій працює на рівні 1 або рівні 2; конфігурації рівня 3 з'являються на власних комерційних платформах, але не мають відкритої документації. Запропонована класифікація визначає постійний розрив між наявною сенсорною інфраструктурою та логікою прийняття рішень, яка її використовує, а також позиціонує багатопараметричну інтеграцію прямого зв'язку як пріоритет для подальших прикладних досліджень. Аналітичні спостереження, представлені в цій статті, були засновані на оперативному управлінні автором комерційного гідропонного виробництва полуниці в Київській області, Україна, що охоплює до 10 гектарів тепличної площі та приблизно 640 000 рослин, вирощених у системах фертигації із замкнутим циклом. Операційний досвід, на який посилається в цій роботі, використовується як контекстуальна підтримка для інтерпретації та обговорення і не представлений як контрольовані експериментальні дані.

КЛЮЧОВІ СЛОВА

сільське господарство на основі даних, системи управління зрошенням, зрошення на основі датчиків, автоматизація теплиць, точне зрошення, моніторинг у режимі реального часу, системи підтримки прийняття рішень.

1. Introduction

Greenhouse crop production within controlled environment agriculture (CEA) generates a continuous stream of operational data. Environmental sensors measure air temperature, relative humidity, and photosynthetically active radiation (PAR) at intervals of seconds to minutes; substrate sensors report volumetric water content (VWC) and pore-water electrical conductivity (EC) at comparable frequencies; and drainage collection systems record leachate volume and nutrient concentration after each irrigation event [2; 10]. Commercial greenhouse platforms now routinely aggregate these measurements on a single dashboard, making raw data more accessible than at any earlier point in the history of soilless cultivation [4; 10]. Acquiring individual measurements is no longer the central challenge; what remains unresolved is how multiple data streams should jointly inform a single irrigation decision.

Capacitance-based and frequency-domain reflectometry sensors suitable for soilless substrates became commercially viable in the early 2010s, and wireless sensor networks (WSN) enabled real-time data collection across spatially distributed greenhouse zones at costs accessible to medium-scale growers [7; 11]. Automated systems that trigger irrigation when substrate VWC falls below a grower-defined threshold have since demonstrated measurable reductions in water use compared with fixed-timer schedules [3; 8]. Ion-selective electrode arrays have extended the monitoring scope to individual macronutrient concentrations in recirculating nutrient solutions, adding yet another data stream to the operational environment [5]. In most documented implementations, however, only VWC crosses the threshold between measurement and action; EC, radiation, and drainage data remain on the monitoring screen without entering the control loop [2; 11]. A single-variable trigger cannot distinguish a moisture deficit caused by high transpiration on a sunny afternoon from one caused by declining hydraulic conductivity in an aging substrate, and it cannot anticipate demand before depletion occurs.

An alternative scheduling approach links irrigation frequency to accumulated solar radiation rather than to substrate state. A pyranometer integrates incident energy over time, and an irrigation event fires each time the cumulative sum exceeds a predefined threshold [9]. Because transpiration correlates with intercepted light energy, the resulting event frequency tracks actual plant demand: shorter intervals on high-radiation days, longer ones under overcast conditions [2; 9]. Nikolaou et al. [9] note the method's widespread adoption in commercial soilless production across southern Europe. In control-architecture terms, radiation sum scheduling shifts the irrigation trigger from a post-depletion substrate variable (VWC) to a pre-depletion energy variable (PAR), representing a partial move from reactive toward anticipatory logic. Radiation sum scheduling operates without reference to root-zone conditions, though; identical radiation will produce identical irrigation events regardless of whether substrate EC has risen or drainage fraction has declined.

Hierarchical control architectures that integrate economic objectives, crop-growth models, and real-time sensor feedback within a unified optimization loop have been formalized for over fifteen years [12]. Sensor platforms, communication protocols, and decision-support software for such integration are well documented [10], and advanced control strategies ranging from proportional-integral-derivative (PID) controllers to fuzzy-logic and model-predictive approaches have been tested at prototype scale [1]. Yet existing literature does not offer a classification that maps documented irrigation approaches according to (a) the number and type of data streams they integrate and (b) the temporal horizon over which the resulting control decision operates. Without such a framework, it is difficult to locate a given system on the continuum from single-threshold reactive control to multi-parameter anticipatory management, or to identify which integration steps remain underdeveloped.

2. Literature Review

2.1. Control paradigms in greenhouse irrigation

Van Straten et al. [12] formalize greenhouse control as a three-layer hierarchy. At the strategic layer, economic and agronomic objectives are defined over the full crop cycle. The tactical layer translates those objectives into daily setpoints for environmental and irrigation parameters. An operational layer executes real-time adjustments by comparing sensor readings against the tactical setpoints. Each layer operates on a distinct time scale: weeks to months at the strategic level, hours to days at the tactical level, and seconds to minutes at the operational level [12]. In principle, data from all three layers feed back into one another; in documented practice, however, the tactical and strategic layers remain theoretical constructs, with no peer-reviewed case study describing their operational deployment in a commercial greenhouse irrigation system [1; 10].

Shamshiri et al. [10] trace the progression of CEA automation through four stages: manual operation, timer-based scheduling, sensor-triggered control, and model-integrated management. Each stage corresponds to a qualitative increase in the amount of data entering the irrigation decision. Manual operation uses no instrumented data; timer-based scheduling uses clock time alone; sensor-triggered control incorporates at least one real-time measurement; and model-integrated management combines multiple sensor inputs with a predictive or optimization algorithm. Field surveys cited by Shamshiri et al. [10] indicate that the majority of commercial greenhouse operations in Asia and parts of Europe remained at the second or third stage as of 2018. Abioye et al. [1] confirm a similar distribution for research prototypes: among the advanced control strategies they review, including PID, fuzzy-logic, and artificial neural network controllers, most were validated under laboratory or small-scale greenhouse conditions with one or two measured variables, and few incorporated more than two data streams simultaneously.

2.2. Sensor deployment and data acquisition challenges

Capacitance and frequency-domain reflectometry (FDR) sensors measure substrate volumetric water content by detecting changes in the dielectric permittivity of the growing medium. Van Iersel et al. [11] demonstrate that these sensors can maintain VWC within a narrow target range in container-grown ornamentals when connected to a simple threshold controller. Ferrarezi et al. [3] extend the approach to ebb-and-flow subirrigation, showing that even low-cost capacitance sensors reduce water input by 23 to 50 percent compared with grower intuition alone. Both studies also identify a practical constraint: sensor readings are substrate-specific: a capacitance sensor calibrated for peat-based media will produce inaccurate VWC values when placed in coir or perlite without recalibration. Substrate-specific calibration curves must account for particle size distribution, bulk density, and wetting-agent residues, all of which vary among commercial batches of the same nominal product [3; 11].

Kim et al. [5] describe an automated nutrient-sensing array based on ion-selective electrodes capable of measuring concentrations of nitrate, potassium, calcium, and phosphate in recirculating hydroponic solutions at intervals of ten to fifteen minutes. Electrode drift and biofouling required weekly recalibration under the conditions tested. Lea-Cox [7] addresses spatial variability: in a nursery setting, VWC differed by up to 15 percentage points between containers located at the center and the edge of the same irrigation zone, and a single sensor per zone underestimated or overestimated zone-average moisture by a margin sufficient to trigger unnecessary irrigation events or delay necessary ones. Wireless sensor networks (WSN) mitigate this problem by distributing multiple nodes across the production area; Lea-Cox et al. [6] report that a WSN-based irrigation system reduced water use by 40 to 70 percent over a three-year trial across multiple nursery and greenhouse sites, partly because spatial resolution improved irrigation uniformity.

2.3. Radiation-based scheduling: operational parameters and constraints

Nikolaou et al. [9] document crop-specific radiation sum thresholds ranging from 100 to 300 J/cm^2, with the value depending on crop species, substrate type, container volume, and growth stage. A pyranometer or quantum sensor positioned above the canopy records incident PAR; the choice between the two instruments affects spectral sensitivity and calibration requirements but not the accumulation logic itself. Lower thresholds are associated with high-frequency, low-volume irrigations suited to shallow substrates, while higher thresholds align with less frequent, larger-volume events in deeper containers [9]. After each irrigation event, the radiation counter resets, and a new accumulation cycle begins. Growers typically adjust the threshold seasonally: a lower value during early vegetative growth, when root volume is limited and substrate dries quickly, and a higher value during full canopy, when transpiration per unit radiation stabilizes [9].

A key advantage of radiation-based triggering is its implicit linkage to plant water demand. Transpiration rate correlates positively with intercepted radiation, and under stable vapor pressure deficit (VPD) conditions, cumulative PAR serves as a proxy for cumulative transpirational water loss [2; 9]. On overcast days, the accumulation rate slows, and irrigation frequency decreases accordingly, reducing the risk of overwatering that fixed-timer systems produce under low-light conditions. Adeyemi et al. [2] note that this correlation weakens when VPD fluctuates independently of radiation, as occurs during periods of high humidity combined with moderate light. In such conditions, radiation-driven irrigation may overestimate water demand because accumulated PAR continues to rise while actual transpiration remains suppressed by the high ambient humidity. Nikolaou et al. [9] further observe that radiation sum scheduling does not incorporate root-zone feedback between events. Over several consecutive high-radiation days, each radiation-triggered irrigation event delivers a nutrient solution at the same target EC, but concentration effects between events allow pore-water EC to drift progressively upward; without an independent EC-based correction mechanism, this cumulative salt loading may persist across an entire production week before a grower intervenes manually.

2.4. Economic evidence and adoption constraints

Lichtenberg et al. [8] analyze the economics of sensor-based irrigation in greenhouse and nursery operations across the eastern United States. Using a partial-budget framework, the authors estimate that replacing conventional timer-based irrigation with soil-moisture-sensor control yields a net benefit of USD 1,400 to USD 4,200 per hectare per year, depending on crop value and baseline water use efficiency. Payback periods for the sensor hardware ranged from less than one production cycle to approximately two years. Benefits were derived primarily from reduced water and fertilizer input, lower disease incidence attributable to more consistent substrate moisture, and improved crop uniformity. Despite favorable economics, adoption remained low among the surveyed operations. Growers cited three principal barriers: uncertainty about sensor calibration for their specific substrate and crop combination, lack of technical support for integrating sensors with existing irrigation controllers, and concerns about sensor reliability over multi-season use [8].

Kaya et al. [4] extend the discussion to AI-augmented control in plant factories, where the capital cost of sensor infrastructure is higher but the potential for data integration is also greater due to the fully enclosed and environmentally stable production space. Reported systems in plant-factory settings incorporate up to eight measured parameters feeding into centralized control algorithms, but most documented implementations remain experimental, and commercial deployment data are limited [4]. Lea-Cox et al. [6] address scalability by reporting that sensor network costs decreased substantially over the three-year trial period as hardware prices declined and installation protocols became standardized; the authors note, however, that the data interpretation step, converting sensor output into an actionable irrigation decision, still required trained personnel and was identified by participating growers as the most persistent operational bottleneck.

Across the reviewed literature, individual data streams and control strategies are characterized in considerable depth. Substrate moisture sensors, nutrient monitors, radiation integrators, and environmental controllers each have a documented evidence base regarding accuracy, economic return, and operational constraints. What remains largely unexamined is cross-stream coupling: the operational effect one irrigation-related variable exerts on another through the act of irrigation itself. No reviewed source documents how a VWC-triggered irrigation event alters pore-water EC trajectory over the following hours, or how radiation-driven scheduling interacts with drainage fraction dynamics across a multi-day production cycle. Published studies evaluate parameters individually or, at most, in pairs; the downstream consequences of one control action on the variables governed by another remain outside the scope of current documentation.

3. Problem Statement

The present article proposes a three-tier classification of data-driven irrigation approaches in CEA, organized by data-integration complexity and decision-time horizon, and maps published implementations onto the resulting framework.

Tasks: (1) classify the data inputs currently available for greenhouse irrigation decisions by category, sensor type, and temporal resolution; (2) compare open-loop, closed-loop, and feed-forward control architectures and their relationship to data-stream complexity; (3) evaluate the role of accumulated solar radiation as a transitional mechanism between reactive and anticipatory scheduling; (4) construct a three-tier integration model and position existing literature within it; (5) identify the integration gap at the highest tier and outline directions for further applied research.

4. Methods and Materials

The present study is an analytical review combined with an original classification framework. It does not report primary experimental data. Published literature was sourced from Scopus, Web of Science, and Google Scholar using keyword combinations including "greenhouse irrigation control", "sensor-based irrigation soilless", "radiation sum irrigation scheduling", "CEA automation", and "decision support irrigation greenhouse". Inclusion criteria required peer-reviewed publication in English, relevance to soilless or hydroponic cultivation under controlled-environment conditions, and explicit description of the data inputs and control logic used in the irrigation decision. Conference proceedings and book chapters were included when they provided technical detail not available in journal articles. Sources published between 2010 and 2025 were considered; preference was given to the most recent review within each thematic strand.

A total of twelve sources were selected for detailed analysis. Each source was classified according to three criteria: data-stream profile (number and type of inputs feeding the irrigation decision, categorized as environmental, substrate, plant-based, or derived), control logic (open-loop, closed-loop with reactive threshold, or feed-forward with anticipatory input), and temporal decision horizon (intra-event, daily, or seasonal). Sources that did not specify one or more of these criteria were classified based on the operational description provided in the methods or results sections of the original publication.

The three-tier integration model was constructed by arranging the classified approaches along two axes: data-stream complexity (number and diversity of inputs) and decision-time horizon. Tier boundaries were placed at natural discontinuities in data-stream count and decision-time horizon identified during the classification process; specific tier definitions and the rationale for each boundary are presented in Section 4. Retrospective operational observations from the author's experience managing commercial hydroponic strawberry production on coconut coir substrate (drip fertigation, greenhouse area up to approximately 10 hectares) informed the practical dimension of the tier descriptions. Field-level observations from the author's production practice are explicitly identified as such throughout the text and are not presented as controlled experimental results.

5. Results and Discussion

5.1. Data input classification

Classification of the data inputs available for greenhouse irrigation decisions yields four categories distinguished by the origin and processing stage of the signal: environmental parameters measured in the aerial zone of the greenhouse, substrate parameters measured within the root zone, plant-based parameters derived from direct contact with or proximity sensing of the crop, and derived parameters computed from two or more primary measurements. Table 1 presents ten representative inputs organized by these categories, together with the sensor type typically used, the temporal resolution at which data is acquired, and the functional role each input plays in an irrigation decision.

Table 1. Classification of data inputs for greenhouse irrigation decisions

Category	Parameter	Sensor type	Resolution	Role in decision
Environmental	Air temperature	Thermocouple/RTD	Minutes	Transpiration context, VPD input
Environmental	Relative humidity	Capacitive	Minutes	VPD calculation, condensation risk
Environmental	PAR / solar radiation	Pyranometer/quantum	Seconds	Energy accumulation trigger
Substrate	VWC	Capacitance/FDR	Minutes	Moisture threshold, dry-back tracking
Substrate	Pore-water EC	Dielectric	Minutes	Salinity indicator, nutrient balance
Plant-based	Leaf temperature	IR thermometer	Minutes	Transpiration proxy, stress detection
Plant-based	Stem diameter	LVDT dendrometer	Minutes	Water status proxy
Derived	Radiation sum (J/cm^2)	Computed from PAR	Event-based	Feed-forward irrigation trigger
Derived	VPD	Computed from T + RH	Minutes	Transpiration rate estimate
Derived	Drainage % and EC	Volume + EC sensor	Per event	Leaching fraction, nutrient loss

Source: Formed by the author.

Among the ten inputs listed, environmental and substrate parameters dominate the peer-reviewed literature on sensor-based irrigation. Van Iersel et al. [11], Ferrarezi et al. [3], and Lea-Cox et al. [6] base their control systems on VWC alone or on VWC combined with a timer override. Radiation sum, classified here as a derived parameter, appears in the scheduling literature reviewed by Nikolaou et al. [9] but is rarely described as an input to a closed-loop controller; it functions instead as an alternative trigger in place of, not in coordination with, substrate data. Plant-based parameters (leaf temperature, stem diameter variation) are well established in ecophysiological research but remain marginal in operational irrigation control: no reviewed source documents their integration into a greenhouse irrigation algorithm at commercial scale [2; 4].

5.2. Control architecture comparison

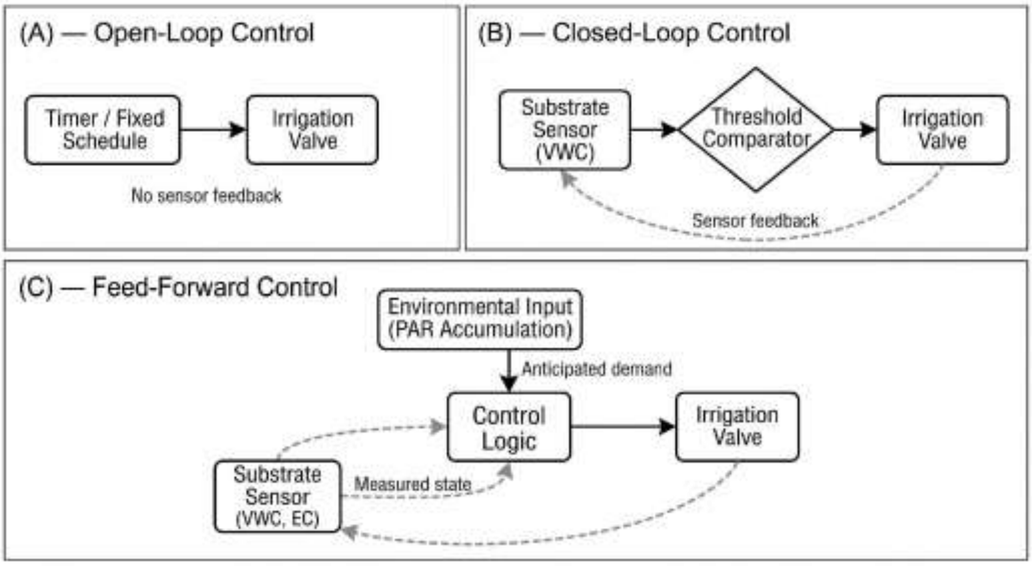

Figure 1. Comparison of three irrigation control architectures: (A) open-loop, (B) closed-loop, (C) feed-forward

Source: Built by the author.

Figure 1 illustrates the data flow in three control architectures applicable to greenhouse irrigation. In an open-loop configuration (A), a timer or fixed schedule activates the irrigation valve at predetermined intervals without receiving any measurement from the production environment. If environmental conditions change between programming events, the system has no mechanism to adjust; overwatering under low-demand conditions and underwatering under high-demand conditions occur silently, without generating an error signal.

A closed-loop architecture (B) introduces sensor feedback. Substrate VWC is compared against a predefined setpoint, and irrigation activates or deactivates when the reading crosses that boundary. Correction occurs only after the deviation has already taken place: the plant experiences a period of declining moisture before the threshold is crossed and irrigation is initiated. Response latency depends on the sensor sampling interval and the communication delay between sensor and actuator. A shorter sampling interval reduces latency but increases data volume and, in wireless deployments, power consumption [4, 7].

A feed-forward architecture (C) adds an anticipatory input. An environmental signal, such as cumulative PAR, enters the control logic alongside the substrate sensor feedback. Instead of waiting for VWC to decline past a threshold, the controller estimates future water demand on the basis of accumulated radiation energy and initiates irrigation before measurable depletion occurs. Substrate sensors remain in the loop as a verification channel: if the feed-forward prediction overestimates demand and VWC rises above an upper boundary, feedback suppresses the next scheduled event. The critical distinction between architectures is not merely the direction of data flow but the temporal relationship between the control action and the physiological event it addresses. Open-loop acts independently of the event, closed-loop reacts after the event, and feed-forward acts in anticipation of the event.

5.3. Radiation sum as transitional control mechanism

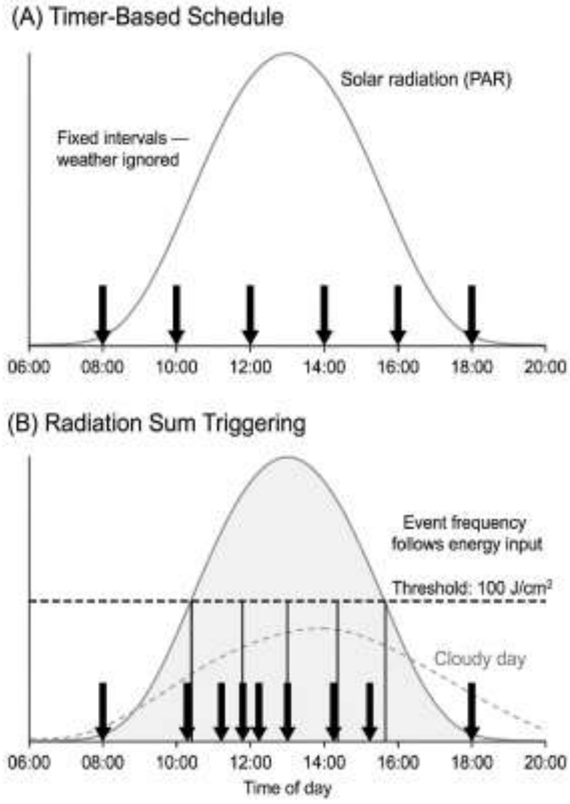

Figure 2. Comparison of irrigation event distribution: (A) timer-based schedule, (B) radiation sum triggering

Source: Built by the author.

Figure 2 contrasts the temporal distribution of irrigation events under a fixed-timer schedule (A) and a radiation-sum trigger (B). In panel A, six events are distributed at equal intervals across the daylight period; the PAR curve, drawn above the events, has no influence on their timing or frequency. In panel B, event frequency tracks the PAR curve: events cluster during midday when radiation accumulation is fastest, and spacing increases during early morning and late afternoon. A cloudy-day overlay (dashed curve) demonstrates that lower radiation input reduces total daily events from approximately seven to three, a self-regulating response absent from timer-based systems.

Within the tier framework developed in this article (Section 4.4), radiation sum occupies a transitional position. When used as the sole trigger, it operates as a single-parameter approach corresponding to Tier 1: one computed variable governs the decision independently of root-zone state. When paired with a VWC threshold, so that irrigation fires only when both the radiation criterion and a minimum-depletion condition are met, the combination constitutes a Tier 2 configuration in which two data streams coordinate the same decision.

During commercial strawberry production managed by the author, clear June days produced eight to ten radiation-triggered events between 09:00 and 16:00, while overcast days of comparable length produced three to four; a 90-minute fixed timer would have delivered six to seven events on both days regardless of radiation conditions. Pairing radiation sum with a VWC floor of 45 percent prevented unnecessary events on days when substrate moisture remained above the depletion threshold despite reaching the radiation trigger. On such days, the VWC condition effectively overrode two to three radiation-triggered events that would otherwise have added excess water to an already saturated substrate.

5.4. Three-tier data integration model

The classification of reviewed approaches along the two axes defined in Section 3, data-stream complexity and decision-time horizon, produces a three-tier structure. Tier boundaries correspond to qualitative shifts in both the number of inputs and the logic governing their combination. Figure 3 presents the model schematically; Table 2 maps published approaches and commercial systems onto the tiers.

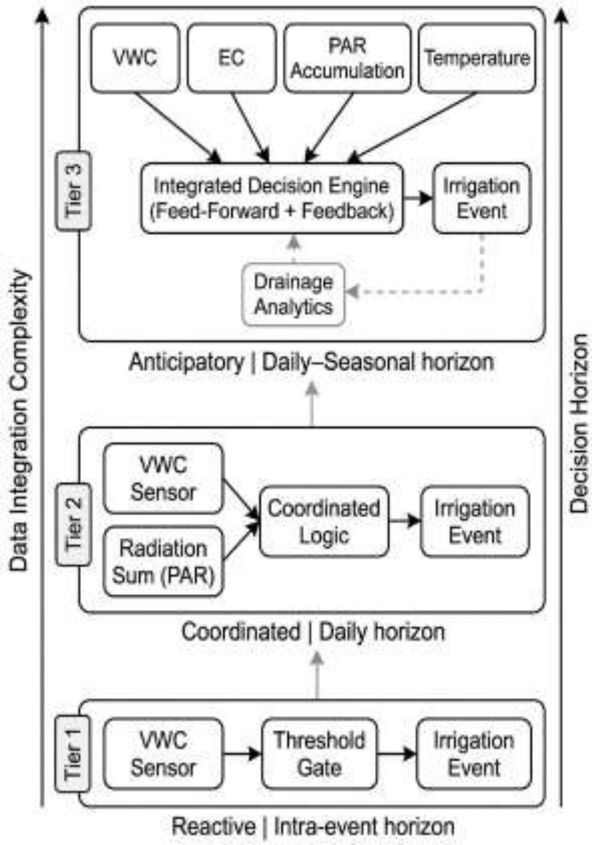

Figure 3. Three-tier data integration model for greenhouse irrigation decisions
Source: Built by the author.

Tier 1 (single-parameter threshold). An irrigation decision depends on one measured or computed variable. Control logic is reactive: a threshold crossing initiates or terminates the event. Decision horizon is intra-event; each threshold crossing is evaluated independently, without reference to prior events or anticipated future conditions. Examples include VWC-only threshold controllers [3; 11] and standalone radiation-sum triggers [9] when not coordinated with substrate feedback.

Tier 2 (dual-parameter coordinated). Two data streams enter the same decision. Coordination may be conjunctive (both conditions must be met), compensatory (one input modifies the threshold of the other), or sequential (one input determines whether to evaluate the second). Decision horizon extends to the daily scale because the interaction between the two variables unfolds over hours. Examples include VWC paired with radiation sum [9], where irrigation fires only when both the energy threshold and the moisture-depletion criterion are satisfied, and VWC paired with EC, where elevated EC triggers a supplementary leaching event even if VWC remains within the target range [1; 2].

Tier 3 (multi-parameter integration with feed-forward logic). Three or more data streams, spanning at least two of the four categories in Table 1, are processed by a decision engine that incorporates both feedback (sensor-measured state) and feed-forward (anticipated demand based on environmental inputs). Decision horizon extends from daily to seasonal: irrigation strategy adapts to diurnal radiation and temperature cycles as well as to crop-growth stage, cumulative drainage trends, and substrate aging effects. No peer-reviewed source documents a fully reproducible Tier 3 implementation. Commercial greenhouse control platforms, including Priva Connext, Ridder HortiMaX, and similar proprietary systems, integrate environmental, substrate, and drainage data within centralized software, but their internal decision algorithms are not published and cannot be independently replicated [4; 10].

The proposed tier framework is intended as a conceptual classification model for irrigation decision-making and data integration rather than a software architecture, proprietary control platform, or patented technology.

Table 2. Mapping of published approaches and commercial systems onto integration tiers

Tier	Data streams	Control logic	Time horizon	Literature / system examples
1	Single (VWC or radiation sum alone)	Reactive threshold	Intra-event	Van Iersel et al. [4]; Ferrarezi et al. [5]; Nikolaou et al. [3] (radiation-only mode)
2	Dual (VWC + radiation, or VWC + EC)	Coordinated threshold	Daily	Nikolaou et al. [3] (radiation + substrate); Abioye et al. [8] (review of multi-input controllers)
3	Multi (VWC + EC + PAR + T + drainage)	Feed-forward + feedback	Daily–seasonal	Priva Connext, Ridder HortiMaX (proprietary; not peer-reviewed)

Source: Complited by the author.

A consistent pattern emerges from the mapping: the density of peer-reviewed evidence decreases as tier level increases. Tier 1 is supported by controlled experiments with quantified water savings and crop-response data [3; 8; 11]. Tier 2 is represented in review articles and scheduling guidelines but lacks comparative trials isolating the effect of dual-parameter coordination against single-parameter control under otherwise identical conditions [1; 9].

In the author's operational experience, all data streams necessary for Tier 3 operation, including VWC, EC, PAR, air temperature, and drainage volume, were physically collected by the same greenhouse monitoring system during commercial strawberry cultivation. These streams were displayed on parallel dashboards and evaluated by production staff, but they did not feed into a single automated decision algorithm. Irrigation events were triggered by a radiation sum controller operating independently of EC data, and drainage fraction was reviewed manually at the end of each production day. Data availability did not translate into data integration: the sensing infrastructure supported Tier 3, but the operational logic remained at Tier 1.

6. Discussion

Section 4 established where the integration gap sits within the tier structure. Understanding why the gap persists despite favorable economics [8] and widely available sensor technology [6; 11] requires looking beyond hardware availability toward the institutional and commercial forces that shape how irrigation systems are designed, sold, and operated.

Sensor manufacturers market individual measurement devices, each optimized for a specific parameter: a capacitance probe for VWC, a dielectric sensor for EC, a pyranometer for radiation. Integration between these devices is left to the greenhouse control platform or to the grower. Academic research reinforces parameter isolation for methodological reasons: controlled experiments vary one or two factors while holding others constant, which generates clean causal evidence for individual sensor-response relationships but does not test multi-stream coordination. Commercial control platforms do integrate multiple streams, but their decision algorithms are closed-source, inaccessible for independent validation, and non-transferable between vendors. These three forces, product-level specialization in sensor manufacturing, variable isolation in academic research, and algorithmic enclosure in commercial software, converge to maintain the gap identified in the tier mapping.

For greenhouse operations currently managing irrigation with a single-parameter threshold (Tier 1), radiation sum coordination represents the most accessible upgrade path toward Tier 2. Most greenhouse climate controllers already include a pyranometer for temperature management and ventilation control; enabling radiation-based irrigation triggering may require only a software configuration change, not additional hardware investment. Combining the radiation trigger with an existing VWC sensor, so that irrigation fires only when both criteria are satisfied, adds a coordination layer at minimal marginal cost. Lichtenberg et al. [8] document favorable economics even for single-sensor upgrades; a Tier 2 configuration built on existing infrastructure could improve the cost-benefit ratio further by reducing overwatering events on low-demand days without requiring new sensor installations.

Advancing from Tier 2 to Tier 3 demands a qualitatively different approach. Adding a third or fourth data stream to an irrigation decision is insufficient if the decision logic remains a collection of independent thresholds evaluated in parallel. A functional Tier 3 system requires cross-stream coordination rules: for example, a rising EC trajectory over three consecutive days might progressively lower the VWC threshold at which a leaching event is triggered, even if VWC itself remains within the normal operating range. Similarly, the radiation sum threshold could be adapted to growth stage, set lower during early vegetative development when root volume limits water uptake capacity, and raised during full-canopy fruiting when transpiration per unit radiation stabilizes. Seasonal adaptation of this kind is absent from any documented single-tier system. Implementing such rules requires temporal memory within the control system: decisions informed by multi-day trends in drainage fraction, EC trajectory, and cumulative water balance, not merely by the current sensor reading at the moment of the threshold crossing.

Publication of open, reproducible Tier 3 decision frameworks would benefit both research and commercial practice. Researchers could benchmark integration strategies against documented baselines. Growers operating vendor-configured platforms could evaluate whether the installed algorithms match the operational logic their specific crop, substrate, and climate conditions require. Independent comparison across platforms would become possible for the first time. Without open documentation, growers remain dependent on vendor support for algorithm optimization, and the scientific community cannot validate, critique, or improve integration approaches it cannot examine.

7. Limitations

Several constraints limit the scope of the conclusions drawn in this article. First, the study is an analytical review, not a controlled experiment; the three-tier model is derived from published literature and the author's production-floor experience, not from comparative trials testing tier-level performance under standardized conditions. Second, the author's retrospective observations originate from a single production context: hydroponic strawberry cultivation on coconut coir substrate with drip fertigation in a greenhouse environment located in the Kyiv Oblast of Ukraine. Generalizability to other crops, substrates, climatic regions, or irrigation methods (e.g., ebb-and-flow, NFT) cannot be assumed without further validation.

Third, the literature base of twelve sources, while covering the principal thematic strands of data-driven irrigation in CEA, does not constitute a systematic review with predefined inclusion and exclusion protocols. Relevant work published outside the databases searched, or in languages other than English, may have been omitted. Fourth, tier boundaries are qualitative, defined at observed discontinuities in data-stream count and decision logic; no statistical criterion was applied to determine where one tier ends and the next begins. Fifth, descriptions of commercial Tier 3 platforms are based on publicly available documentation and product specifications; the internal decision algorithms of these systems were not directly inspected. All claims regarding cross-stream coupling and feed-forward logic are correlational and should not be interpreted as establishing causal relationships.

8. Conclusions

Data inputs available for greenhouse irrigation decisions were classified into four categories (environmental, substrate, plant-based, and derived), comprising ten representative parameters that differ in sensor type, temporal resolution, and functional role within the decision process. Comparison of open-loop, closed-loop, and feed-forward control architectures established that the three approaches differ fundamentally in the temporal relationship between the control action and the physiological event it addresses, progressing from weather-independent scheduling through post-deviation correction to anticipatory demand estimation.

Accumulated solar radiation occupies a position between single-parameter reactive control and coordinated anticipatory scheduling, making it the most accessible entry point into multi-stream integration. Operating alone, it constitutes a Tier 1 single-parameter approach; combined with a substrate moisture threshold, it enters Tier 2 by coordinating two data streams within a daily decision horizon. Field data from commercial strawberry production confirmed that radiation-VWC coordination measurably reduced unnecessary irrigation events on high-moisture days, demonstrating the practical value of even a minimal Tier 2 configuration.

The proposed three-tier integration model positions published and commercial approaches along axes of data-stream complexity and decision-time horizon. An inverse relationship emerges between integration complexity and documentation quality: the more data streams a system coordinates, the less openly its decision logic is described in peer-reviewed literature. At the highest tier, proprietary commercial platforms fill the functional role but leave the scientific record without a reproducible reference implementation. The principal gap is not in sensing infrastructure but in open, reproducible decision logic capable of coordinating multiple data streams with feed-forward anticipation across daily and seasonal time scales.

Directions for further research include: (a) controlled comparative trials measuring resource efficiency and crop response at each tier level under otherwise identical conditions; (b) publication of documented, reproducible Tier 3 architectures; (c) evaluation of cross-stream coordination rules, particularly the interaction between EC trajectory and VWC threshold adjustment, across different crop-substrate combinations; and (d) integration of plant-based sensing (leaf temperature, stem diameter variation) as a real-time crop-status input that could enrich Tier 3 decisions beyond environmental and substrate parameters alone.

Author's Contribution

This article introduces the Three-Tier Data Integration Model, an original classification framework for evaluating data-driven irrigation decision systems in controlled environment agriculture. The author developed the model, the ten-parameter data input taxonomy (Table 1), the control architecture comparison scheme (Figure 1), and the literature mapping matrix (Table 2) based on structured analysis of published sources and retrospective observations from commercial hydroponic strawberry production at greenhouse scale.

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