Effect of Deficit Irrigation on Water-Use Efficiency of Sugarcane (*Saccharum officinarum* L.)

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ABSTRACT
Background: Sugarcane (*Saccharum officinarum* L) is a long-duration and high biomass C4 crop, which is the main sugar-producing crop in the world and an increasingly important feedstock for bioenergy purposes, but it is one of the most water-consuming crops because it requires between 20,000 and 30,000 m³ of water ha^{-1} throughout each production cycle. With the water resources becoming scarcer due to, among other facts, climate change and population pressure, it is particularly important to improve the water use efficiency (WUE) of sugarcane. Deficit irrigation (DI), which means irrigation below the full water requirements of the crop, has been developed as one of the methods for saving water. Nevertheless, the effect of DI on water-use efficiency, cane yield, and juice quality varies depending on the type of irrigation, its timing, and method.
Aim: The review thoroughly summarizes studies conducted by experts on the impact deficit irrigation has on different parameters such as WUE, water productivity, yield, and product quality. The paper also aims to find out when one can save water and still maintain a reasonable level of yield.
Databases: Information was obtained from world-recognized databases such as Scopus, Web of Science, ScienceDirect, SpringerLink, MDPI, Frontiers, and Nature. The author used the following keywords to gather data: "sugarcane," "deficit irrigation," "water use efficiency," "water productivity," "partial root zone drying," "*Saccharum officinarum*."
The main conclusions state that the deficits in irrigation could enhance WUE and water productivity when compared to complete irrigation. Furthermore, in many instances, yield reduction with partially dry irrigation could be less than with complete irrigation. Water usage decreased by approximately 17.6%, while biomass was reduced by around 11.3%, leading to the increase in agronomic WUE from 2.9 to 4.1g L^{-1}. Computer simulations and trials have shown that if 50% of the total water available is used during non-critical periods, it could be enough to obtain good yields. Moreover, drip irrigation has increased WUE by 60-200% and decreased water use in comparison to traditional surface irrigation by 20-60%. It has been found out that certain genotypes had better water productivity than others, while growth stages are highly sensitive to drought and should not be subjected to deficit irrigation. It is worth mentioning that there are still numerous gaps in research related to deficit irrigation, such as long-term studies of ratoons, assessment of cost-effectiveness for small farmers, and implementation of combined approaches of deficit irrigation together with mulching, fertigation, and selection of drought-resistant plant types.

Keywords: Sugarcane; *Saccharum officinarum*; deficit irrigation; water-use efficiency; water productivity; partial root-zone drying; regulated deficit irrigation; drip irrigation

1. Introduction
Sugarcane (*Saccharum officinarum* L.) is an herbaceous plant that grows into a tall, multiple-stemmed plant—genus and species name different—of the Poaceae (grass) family and requires a long period to produce (Carr *et al*., 2011) [33]; (Wiedenfeld, 2000) [34]. The plant grows naturally in areas ranging from approximately 35° north of the equator to approximately 35° south of it, and occupies most tropical and subtropical regions of the world, outside of temperate areas (FAO, 2021) [32] (Carr *et al*., 2011) [33]. Sugarcane is the world's major source of sugar and is increasingly used to produce bioethanol and bioenergy [1] (Singh *et al*., 2023) [18]. Sugarcane requires large amounts of water and is the most water-demanding annual group of crops (FAO, 2021) [32] (Fereres & Soriano, 2007) [6]. Total water use is estimated to be about 20,000 to 30,000 m³ of water for each hectare (ha) produced on an annual basis (in efficient use of available water), or approximately 12,000 to 13,000 m³ of water for each hectare to produce sugarcane in a 12-month growing season (FAO, 2021) [32]. Growing sugarcane puts it in direct opposition to the increasing global scarcity of fresh water and to a lesser extent, growing competition for fresh water from domestic and industrial uses and the decreasing availability of ground water in major sugarcane producing areas due to climate change (Inman-Bamber & Smith, 2005) [2] (Fereres & Soriano, 2007) [6] (Geerts & Raes, 2009) [10] (Carr *et al*., 2011) [33].
The primary goal of sustainable sugarcane agriculture today is to enhance the water-use efficiency (WUE) of sugarcane. The definition of WUE may be thought of as the quantity of sugarcane or sugar produced for each unit of water utilized (Hatfield &

Dold, 2019) [3]. WUE is measured by various indicators, including agronomic WUE (yield/volume of water used for irrigation or transpiration), water productivity (WP) (economic value of yield per unit of water), and irrigation water productivity (IWP) (da Silva *et al*., 2013) [4] (Misra & Singh, 2023) [12] (Coelho *et al*., 2018) [13]. Together, these three indicators describe various aspects of the yield-to-water relationship. Since there's a direct correlation between the yield of sugarcane and the amount of water used through transpiration, there are implications for improving WUE that are created when the amount of water provided is reduced. To accomplish this, water input must be reduced so that the yield of sugarcane is reduced by a lesser amount than the reduction in the amount of water supplied, thereby improving WUE or increasing efficiency (Tayade *et al*., 2020) [5] (Geerts & Raes, 2009) [10] (Fereres & Soriano, 2007) [6].

The implementation of deficit irrigation (DI) has become the most effective way to achieve water saving goals through irrigation management by supplying less water than what would be needed to fully satisfy crop evapotranspiration (ETc) (Fereres & Soriano, 2007) [6] (English, 1990) [7] (Geerts & Raes, 2009) [10] (Dingre & Gorantiwar, 2021) [8]. DI is based on the idea that crops will respond differently to deficits during various growth stages such that, if an irrigation deficit occurs in a period during which there is little or no sensitivity to the deficit, yield losses will be lower than if they were to occur during a period of high sensitivity to the deficit (Robertson *et al*., 1999) [29] (Dingre *et al*., 2021) [15]. Since crop development is characterized by periods of high and low sensitivity to deficiencies in water, the benefits of conserving water by using deficit irrigation during low sensitivity periods can outweigh the costs of reduced yield incurred as a result of having created these deficits. Several refinements of DI practices have been developed and trialed in the sugarcane industry. The first is the use of regulated deficit irrigation (RDI), which is where a set percentage of ETc is supplied. The second is the use of partial root-zone drying (PRD), which is where only part of a plant's root zone is irrigated at any given time, thereby allowing part of the root zone to dry out (Dry & Loveys, 1998) [9] (Wu *et al*., 2014) [17]. Third, is the use of growth stage-specific deficit scheduling, which is based on an understanding of plant sensitivity to water deficiencies (Dingre *et al*., 2021) [15] (Robertson *et al*., 1999) [29].

Wide-ranging amounts of research have been conducted on water deficits for sugar cane in a variety of environments (sem-arid Western India, Brazil, Philippines, Guyana, Nicaragua, and East Africa) and by a variety of irrigation methods (surface/furrow, sprinkler, surface and sub-surface drips) (Singels *et al*., 2017) [28] (Ramasamy *et al*., 2023) [19] (Dingre *et al*., 2022) [16]. As a result there is an abundance of evidence regarding the impact of these irrigation techniques although the definitions of what constitutes a water deficit, irrigation water use efficiency metrics, and experimental designs are tremendously diverse resulting in a large heterogeneity amongst results. There have been a number of recent published papers that have either provided or examined information regarding research and development of individual elements of water savings using drip-based irrigation, the growth stage dependency of sugarcane to irrigation, and genotypical differences in the productivity of sugarcane grown with water deficits (Coelho *et al*., 2018) [13] (Ramasamy *et al*., 2023) [19] (Singh *et al*., 2023) [18]. However, there has been no focused, critical synthesis that has integrated sugarcane water-efficient irrigation strategies with their resultant agricultural outcomes or water use efficiencies (Singels *et al*., 2017) [28].

Thus, the objective of this review:

(i) Synthesize the existing literature regarding effects associated with deficit irrigation, and its variants (RDI, PRD, & Stage Specific Scheduling) on the water use efficiency and productivity of sugarcane.

(ii) Critically compare and analyze yield &quality trade-offs associated with different levels of plant water deficits, at different growth stages, using various irrigation methods and different sugarcane plant genotypes.

(iii) Investigate the physiological basis of sugarcane plant responses to water deficits.

(iv) Identify inconsistencies between methodologies and contradictions in the literature.

(v) Identify and describe emerging technologies and gaps in research related to the results of the review.

The review will focus primarily on field and modelling studies that were published principally between 2015 and 2025, with information from earlier foundational studies included when it pertains to the specific topics of interest.

2. Methodology of Literature Review

2.1. Literature Search Strategy

The goal of this study is to identify peer-reviewed literature regarding deficit irrigation and water-use efficiency for sugarcane. The databases used were Scopus, Web of Science, ScienceDirect, SpringerLink, MDPI (Water, Agronomy, Plants, and AgriEngineering), Frontiers, and Nature/Scientific Reports, in addition to reports from FAO and from individual countries. The terms searched included "sugarcane," "*Saccharum officinarum*," "deficit irrigation," "regulated deficit irrigation," "partial root zone drying," "water-use efficiency," "water productivity," "drip irrigation," and "growth stage water stress." The timeframe for the searches was between January 2015 and June 2026; some earlier studies considered to be significant were also included. Table 1 shows the search strategy. (FAO, 2021) [32].

Table 1: Literature Search Strategy

Element	Details
Databases searched	Scopus, Web of Science, ScienceDirect, SpringerLink, MDPI, Frontiers, Nature/Scientific Reports
Search keywords	sugarcane; *Saccharum officinarum*; deficit irrigation; regulated deficit irrigation; partial root-zone drying; water-use efficiency; water productivity; drip irrigation
Search period	January 2015 – June 2026 (selected landmark studies pre-2015 included)
Language	English
Document types	Original research articles, modelling studies, reviews, institutional reports
Initial records identified	approx. 960
Records after screening and selection	34

2.2. Inclusion and Exclusion Criteria: Studies were screened in two stages: title/abstract screening followed by full-text assessment. Table 2 presents the inclusion and exclusion criteria applied.

Table 2: Inclusion and Exclusion Criteria

Criteria	Inclusion	Exclusion
Crop	Studies on sugarcane (*Saccharum officinarum* L. and commercial hybrids)	Studies on unrelated crops without sugarcane data, unless used for mechanistic context
Topic relevance	Deficit-irrigation effects on WUE, water productivity, yield, or quality	Studies addressing only full irrigation, pests, or non-water agronomy
Publication type	Peer-reviewed articles, modelling studies, institutional reports	Non-peer-reviewed blogs and unverifiable web content
Language	English-language full text available	Non-English without translated abstract/data
Time frame	2015–2026 (core); landmark pre-2015 studies if foundational	Outdated studies superseded by equivalent recent data
Data availability	Quantitative WUE, water-productivity, or yield data reported	Duplicate records or studies lacking extractable outcome data

2.3. Study Selection Process

The selection methodology employed in this research project was conducted utilizing a PRISMA systematic review protocol for data extraction that yielded an initial search of an estimated 960 unique articles. Duplicates from this initial search (n = 170) were subsequently eliminated and resulted in approximately 790 articles remaining for the screening of title/abstract. An overwhelming majority (560) were deemed irrelevant with respect to the topic of sugarcane deficit irrigation water-use efficiency (WUE). After the title/abstract screening, 230 articles were reviewed in full text form and 196 were subsequently excluded from the qualitative synthesis because they did not contain extractable quantitative data, had not been peer-reviewed or were dataset duplicates. Ultimately, 34 studies constituted the final qualitative synthesis. Refer to Figure 1 for the selection process outlined herein.

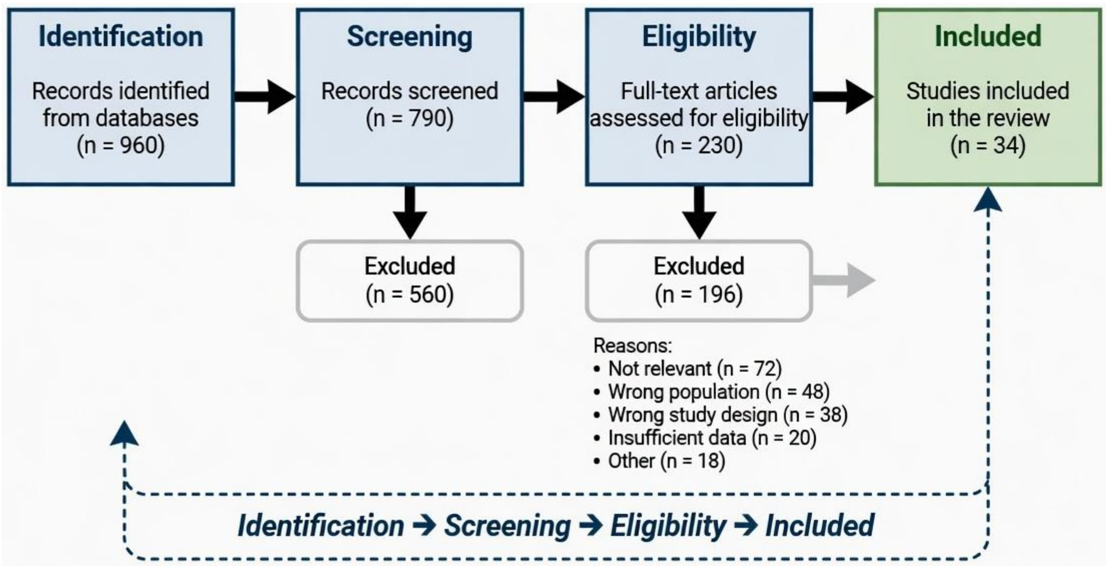

Fig 1: PRISMA flow diagram illustrating identification, screening, eligibility assessment, and final inclusion of studies (records identified n=960; duplicates removed n=170; screened n=790; excluded n=560; full-text assessed n=230; excluded n=196; included n=34).

3. Literature Review and Thematic Analysis

The following five areas are the basis for the organized literature: (1) how deficit levels affect WUE and yield; (2) sensitivity at different growth stages to water deficits; (3) strategies for deficit irrigation (RDI and partial root-zone drying); (4) interaction of irrigation methods and deficit (drip vs. surface); and (5) how different genotypes have varying levels of water productivity when under deficit. Each area will be discussed below, including a critical analysis of the available literature in regard to each area.

3.1. Deficit Level, WUE, and Yield Trade-Offs

All studies show that the use of deficit irrigation will decrease cane yield but usually will increase WUE and water productivity (Fereres & Soriano, 2007) [6] (Geerts & Raes, 2009) [10] (Tayade *et al*., 2020) [5] (Coelho *et al*., 2018) [13] (Dingre *et al*., 2021) [15]. This occurs because in deficit irrigation the relative reduction in water input is greater than the relative reduction in cane yield when deficit irrigation has been appropriately managed (Fereres & Soriano, 2007) [6] (Geerts & Raes, 2009) [10]. Additionally, a study conducted in a semi-arid region of western India demonstrated that using DI reduced the yield of cane significantly showing that the quantity of water used directly controls cane production, and cane production is directly proportional to water transpiration rates (Dingre *et al*., 2021) [15]. The direct relationship between yield and transpiration represents the fundamental tradeoff with regard to sugarcane DI; since sugarcane produces a high quantity of biomass via high levels of transpiration, irrigating sugarcane crops at reduced levels will result in a loss of yield; thus the objective of cane agronomy should be to minimize the yield loss resulting from irrigation reduction per unit of irrigation water saved (Coelho *et al*., 2018) [13].

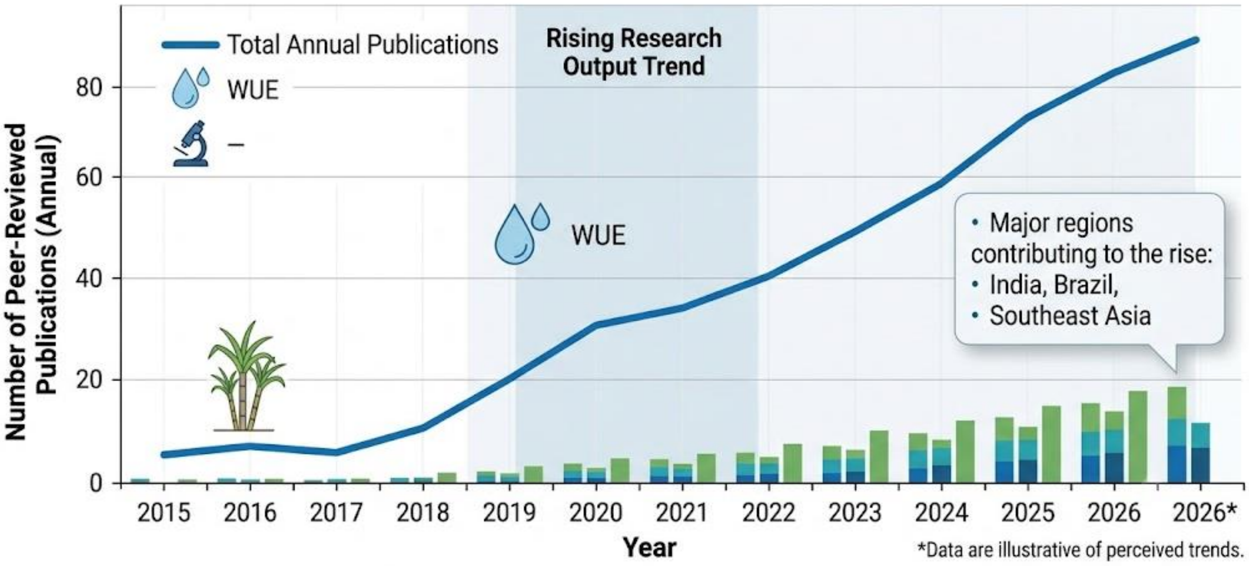

Fig 2: Publication trend (2015–2026) showing the annual number of peer-reviewed sugarcane deficit-irrigation/WUE studies, indicating rising research output since 2018 across India, Brazil, and Southeast Asia.

There is sufficient modelling & site evidence to support the presence of a yield loss threshold defining the level below which yield loss becomes disproportionately high. AquaCrop-based modelling in Guyana was used to model irrigating with 50%-100% of total available water (TAW). The results showed no significant difference in yield among these varied irrigation scenarios; therefore, the authors recommend maintaining a TAW threshold of 50% in dry periods to protect against significant yield loss (Misra & Singh, 2023) [12]. This is an important finding in that it suggests that in certain environments you may be able to withhold approximately half of a full irrigation supply during non-critical periods without causing statistically significant yield penalties, therefore providing considerable water savings and improving WUE. However, the authors cautioned that this simulation generated threshold needs to be validated by field studies; there appears to be an ongoing tension within the body of literature that models-based optimisation and empirical verification are two distinct processes.

Researchers have conducted research on Brazilian regulated deficit irrigation (RDI) to determine the effect of moisture deficiency on five cultivars, applying 50% replacement of ETc (with 15 mm per each 30 mm of accumulated deficit). Water productivity values recorded from the RDI study ranged between 11.45 - 18.45 kg m^-3, including a subset of these cultivars being at their maximum production level with full irrigation (T100) and the same cultivars exhibiting respectable water productivity levels under 70% moisture deficiency (T70) (da Silva *et al*., 2013) [4]. These findings have indicated that the cultivar response to moisture deficiency greatly influences WUE, with some genotypes maintaining good water productivity even when subjected to extremely high levels of moisture deficiency (Coelho *et al*., 2018) [13].

3.2. Growth-Stage Sensitivity to Water Deficit

The main reason that deficit irrigation systems work for crops is that different crop stages have varying levels of vulnerability to drought (Fereres & Soriano, 2007) [6] (Geerts & Raes, 2009) [10]. The literature specifies that the greatest amount of susceptibility to water deficit is during formative, tillering, and elongating stem periods of growth (Robertson *et al*., 1999) [29] (Dingre *et al*., 2021) [15]. A study conducted in the Philippines examined 10 varieties of high-yield sugar cane (genotype) that were subjected to drought conditions at both the tillering stage and the elongation stage. In this study, it was noted that water stress during both of the above periods greatly reduced the total chlorophyll content and stomatal conductance of the plants while producing higher antioxidant activity and electrolyte leakage. Essentially, drought stress adds stress to the plant, resulting in lower productivity (Ferreira *et al*., 2020) [14]. Since forming through tillering through stem elongation represent periods of critical development, these periods should not experience any deficit irrigation, but rather irrigation should occur outside of critical growth periods (late-season development or early establishment when water stress has the least amount of impact on crop yields) (Robertson *et al*., 1999) [29] (Dingre *et al*., 2021) [15].

The agricultural community in India, via analysis of the sugarcane DI completed on different growth stages in semi-arid conditions, supports the existence of this stage-specific framework. The research completed so far, using soil-water-replenishment-based deficit treatment trials established on four growth-stage levels, indicates that the timing of a deficit has a direct impact on the amount of sugarcane yield reduction, due to sugarcane's growing water requirement greatly varying during the germination, tillering, growing (grand growth) and mature (ready for harvest) phases, including the maximum evapotranspirative demand and water-use efficiency (WUE) being required during the vegetative grand-growth phase of growing (Dingre & Gorantiwar, 2021) [8] (Dingre *et al*., 2021) [15] (Dingre *et al*., 2022) [16]. Another important finding of research conducted in semi-arid conditions related to validated irrigation practices developing from water-deficit studies was that extended delays (e.g., 70 days) in applying deficit treatment just prior to and after the rainy season lead to substantially reduced WUE by sugarcane, due to the sensitive demand periods of sugarcane (Elbasheir *et al*., 2024) [11]. Conversely, providing treatment during lower demand periods will provide for higher WUE than other stages of sugarcane growth (Elbasheir *et al*., 2024) [11]. This principle regarding stage-targeting is arguably the most actionable principle available from the sugarcane DI literature.

Table 3: Summary of Selected Studies on Deficit Irrigation and Sugarcane WUE

Author(s) & Year	Location	DI Strategy	Key WUE/Yield Outcome
Elbasheir *et al*., 2024 [11]	Sudan/semi-arid	Water deficit before/after rainfall	DI reduced cane/sugar yield; high WP when deficit before rainfall
Misra & Singh (Guyana), 2023 [12]	Guyana	AquaCrop, 50–100% TAW scenarios	No significant yield loss to 50% TAW; 50% TAW threshold advised
Coelho *et al*., 2018 [13]	São Paulo, Brazil	RDI at 50% ETc, 5 cultivars	Water productivity 11.45–18.45 kg m^{-3}; cultivar-dependent
Ferreira *et al*. (Philippines), 2020 [14]	Philippines	Drought at tillering & stalk elongation	Both formative stages drought-sensitive; reduced Chl and Gs
Dingre & Gorantiwar, 2021 [15]	Maharashtra, India	Soil-moisture-based DI by growth stage	Stage-specific deficit governs yield; grand-growth most sensitive
Wu *et al*. (PRD), 2014 [17]	Greenhouse	Partial root-zone drying (PRD)	Water use −17.6%; biomass −11.3%; agronomic WUE 2.9→4.1 g L^{-1}
Singh *et al*. (Nature), 2023 [18]	Tropical India	Drip vs. conventional, deficit scheduling	Drip raised WUE 60–200%; 20–60% water saving; +7–25% yield
Ramasamy *et al*., 2023 [19]	India (multi-genotype)	Deficit irrigation across hybrids	High-WP genotypes (e.g., Co 86249) suited to DI strategies

3.3. Regulated Deficit Irrigation and Partial Root-Zone Drying

Two more refined methods than conventional and simple uniform deficit irrigation to enhance WUE while minimizing yield reduction, which have received particular attention, are regulated deficit irrigation (RDI) and partial root-zone drying (PRD) (Fereres & Soriano, 2007) [6] (Geerts & Raes, 2009) [10]. Their common method exploits root-to-shoot chemical signaling, primarily abscisic acid (ABA), to reduce water loss via stomata without a proportional photosynthetic reduction (Dry & Loveys, 1998) [9] (Wu *et al*., 2014) [17]. A controlled experiment measuring PRD in young sugarcane demonstrated a 17.6% reduction in water use with only an 11.3% reduction in biomass, while also demonstrating significantly increased WUE (4.1 g L^{-1}) as compared to the WUE of sugarcane grown at full irrigation (3.6 g L^{-1}) or without irrigation (2.9 g L^{-1}) (Wu *et al*., 2014) [17]. The relatively low biomass penalty to PRD-based water savings, along with the large gain in WUE, illustrates the principal benefit of PRD; it moves the yield–water relationship in a favorable direction compared to uniform deficit irrigation (Wu *et al*., 2014) [17].

RDI is a more practical alternative to PRD because it allows for delivering a consistent amount of ETc over time (or during specific times), making it easier to implement at large commercial fields (Fereres & Soriano, 2007) [6] (Geerts & Raes, 2009) [10]. The Brazilian RDI study mentioned previously demonstrated that the provision of 50% of the crop's *et al*lowed for excellent water footprint per unit of crop yield with well-matched cultivars (da Silva *et al*., 2013) [4]. RDI has been proven to be a suitable field-scale tactic when used with proper genotype choices (Coelho *et al*., 2018) [13]. A consistent limitation on both strategies will be when providing a deficit is most effective based solely on growth stage sensitivity (Robertson *et al*., 1999) [29] (Dingre *et al*., 2021) [15]. For instance, if RDI was widely used, supplying a deficit during the sensitive early-mature stages will likely result in a greater loss in yield than would occur from having the same average deficit applied strictly at the tolerant late-mature stages; thus, it supports the necessity of combining Sections 3.2 and 3.3.

3.4. Irrigation Method and Deficit Interaction

The interaction of the irrigation method used and the method used to manage deficits is one of the most significant variables that determine the possible achievable WUE or water use efficiency (Geerts & Raes, 2009) [10] (Fereres & Soriano, 2007) [6]. Under deficit scenarios, micro (drip) irrigation has consistently outperformed conventional surface irrigation methods (Surendran *et al*., 2016) [26] (Kambale *et al*., 2018) [27] (Singh *et al*., 2023) [18]. A review of the water footprint literature synthesised findings demonstrated that drip systems achieved anywhere from 60 to 200% higher WUE than conventional surface irrigation systems, they saved between approximately 20% and 60% of the water required, they reduced fertiliser needs by 20-33%, they increased the yield of sugarcane by 7-25% (Singh *et al*., 2023) [18]. In India alone, subsurface and surface drip systems saved approximately 31% and 23% of the water used, respectively, as compared to conventional surface systems (Surendran *et al*., 2016) [26]. The data indicates that the water delivery method can be considered just as important as the amount of deficit, since drip systems provide greater application uniformity and less non-productive losses due to evaporation, deep percolation and runoff; as a result the improvement in WUE realised from any given deficit will be greater (Singh *et al*., 2023) [18].

One of the greatest limitations on expanding drip technology for deficit irrigation for sugarcane is an economic barrier rather than an agronomic barrier. Micro-irrigation systems can represent more than 25% of the total costs associated with producing sugarcane and is thus a major barrier to the expansion of these irrigation systems, and especially for smallholder growers in India and other similar situations (Singh *et al*., 2023) [18]. The cost barrier represents a significant practical limitation. However, the predominant agronomic literature has only minimally addressed this limitation and will be discussed as a gap in research in Section 5.

3.5 Genotypic Variation in Water Productivity Under Deficit

There is a significant level of genotype variation in terms of both water productivity and the ability of a particular plant to withstand periods of low irrigation (Ferreira *et al*., 2020) [14] (Ramasamy *et al*., 2023) [19] (Singh *et al*., 2023) [18]. This means we can use the existing genotypes to identify specific cultivars that produce well using deficit-irrigation strategies (fixed percentage increase in crop yield caused by deficit irrigation). The Indian evaluation of multiple genotypes identified a group of hybrids (Co 86249 and several related hybrids) that were able to produce above their respective mean yields under deficit-irrigation conditions, making them good candidates for use in production systems where water is limited (Ramasamy *et al*., 2023) [19] (Singh *et al*., 2023) [18]. Similarly, the Brazilian experiment on RDI also determined that particular hybrids (CTC6 and CTC14) were able to maintain good levels of water productivity when subjected to 70% deficit irrigation but did not exhibit similar levels of productivity under full irrigation (da Silva *et al*., 2013) [4] (Coelho *et al*., 2018) [13]. These collective findings demonstrate that the water use efficiency (WUE) of a genotype varies based on the level/type of irrigation available. Therefore, the utilization of high-water productivity and deficit tolerant genotypes are complementary tools that could assist with irrigation scheduling – growing an appropriate DI-suited genotype in combination with stage-specific irrigation and drip irrigation represents the strongest combination suggested by current literature (Coelho *et al*., 2018) [13] (Geerts & Raes, 2009) [10].

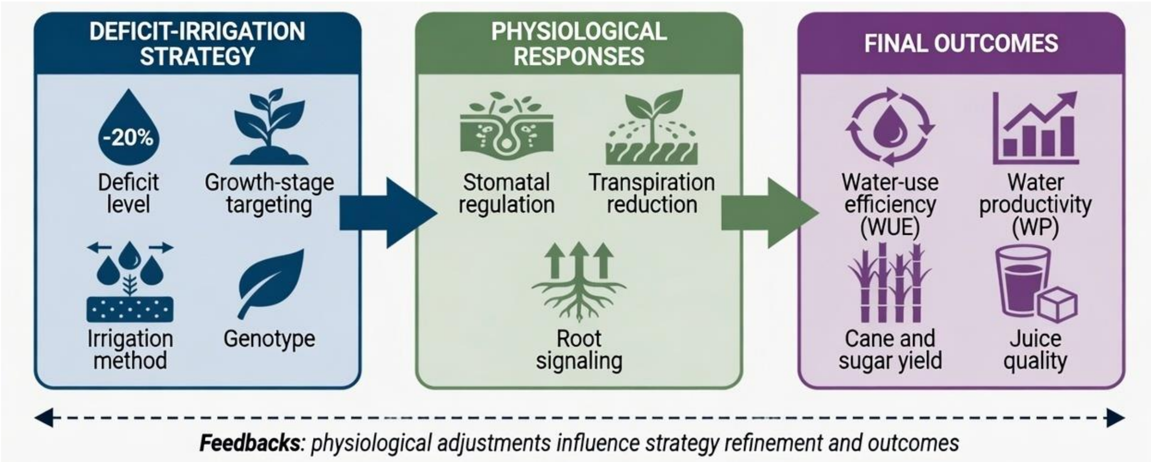

Figure 3: Conceptual framework linking deficit-irrigation strategy (deficit level, growth-stage targeting, RDI/PRD, irrigation method, genotype) to physiological responses (stomatal regulation, transpiration reduction, root signalling) and final outcomes (water-use efficiency, water productivity, cane and sugar yield, juice quality).

4. Comparative Analysis of Previous Studies

Table 4 presents a structured comparison of methodologically diverse studies, highlighting differences in location, design, and reported limitations that constrain direct cross-study comparison.

Across all of the research presented in Table 4 there are many variations in methodology from field trials, greenhouse experiments and crop-simulation modelling which all provide valuable information but because WUE is reported and measured differently across studies (agronomic WUE=grams /litre, water productivity=kilograms /metre3) makes it impossible to directly compare WUE experimentally as this varies between studies. The fact that WUE is not consistently reported also presents a methodological limitation to comparing results (discussed in Section 5).

5. Research Gaps and Emerging Trends

5.1. Unresolved Issues and Knowledge Gaps

There are many inconsistencies among WUE measurements. Some studies report agronomically measured WUE; others report productivity measured using WP, IWP, or percentage water savings. The discrepancies impede meta-analysis and synthesis across studies, hence the need for standardized reporting protocols (Coelho *et al*., 2018) [13] (Wu *et al*., 2014) [17] (Singh *et al*., 2023) [18]. Secondly, the strongest evidence available for WUE comes largely from studies involving a plant crop grown in one season or from short-term studies done in greenhouses. However, sugarcane is typically a multi-ratoon crop, so much remains unknown about the effects of long-term multi-ratoon deficit irrigation on soil health and root architecture and the cumulative effect of water-use efficiency (WUE) (Ferreira *et al*., 2020) [14] (Wu *et al*., 2014) [17]. Thirdly, the economic feasibility of the most effective methods, including drip and subsurface irrigation systems, is rarely included with the agronomic outcomes; drip systems typically comprise >25% of total production costs. So, the question concerning affordability for smallholder farmers remains largely unanswered (Singh *et al*., 2023) [18]. Fourthly, the complementary effects of deficit irrigation together with other practices such as trash mulching, fertigation, silicon supplementation, and selection for water-efficient genotypes are only being studied as individual components, not as integrated packages (de Camargo *et al*., 2021) [20] (Singh *et al*., 2023) [18]. Finally, model-derived deficit irrigation thresholds (e.g., 50% TAW) require external field validation through multiple testing sites before any general recommendations can be made (Misra & Singh, 2023) [12].

5.2. Emerging Technologies and Future Developments

Several new trends include using sensor-based soil moisture monitoring in conjunction with crop-simulation models like AquaCrop (Misra & Singh, 2023) [12] (FAO, 2021) [32]. By integrating the two, users can determine the best amount of water to use during each stage of plant growth by using machine-learning and physics-informed neural network-based frameworks instead of relying on fixed prescriptions (Hatfield & Dold, 2019) [3]. With the use of optimized subsurface and pulse-drip irrigation technologies in addition to traditional drip irrigation, water-use efficiency can be increased by reducing evaporative losses and decreasing percolation losses (Surendran *et al*., 2016) [26] (Kambale *et al*., 2018) [27] (Singh *et al*., 2023) [18]. Breeding and deploying genetically water-efficient sugarcane can also reduce water usage through multi-genotype deficit screening (Ramasamy *et al*., 2023) [19] (Singh *et al*., 2023) [18]. Additionally, the combination of deficit irrigation with amendments (such as silicon supplementation, which has been proven to reduce the impact of water deficits) may provide agronomic and physiological solutions to support crop production when moistures are limited (de Camargo *et al*., 2021) [20].

6. Discussion

Evidence shows that deficit irrigation is a successful method to increase sugarcane water-use effectiveness, with decreased absolute yield yet increased WUE and productivity in the range of diverse seasonality across a wide variety of locations because the amount of water supplied has been decreased proportionately to the number of tonnages of biomass produced when correctly managing deficits with regards to seasonal changes through the use of proper irrigation methods (Elbasheir *et al*., 2024) [11] (Coelho *et al*., 2018) [13] (Wu *et al*., 2014) [17]. A significant amount of deficit irrigation can be obtained through partial root zone drying (increasing agricultural water use effectiveness from 2.9 to 4.1 per litre of water applied) while providing a water savings of 17.6% and an 11.3%; this means that for every billion dollars saved by getting more than 11 million dollars more than the cost of producing the same amount of waste output from drip irrigation versus surface irrigation will produce approximately the same amount of waste from conventional irrigation using between 20–60% of the available water (Wu *et al*., 2014) [17] (Singh *et al*., 2023) [18].

An overarching theme that emerges from the research on the effects of deficit irrigation on WUE is that the potential WUE benefit arises from the ability of producers to utilize four management factors (deficit amount, timing of the deficit relative to growth stage, irrigation method and genotype). The strongest and most reliable area of the literature in this regard relates to the appropriate time to target a growth stage for imposing deficit irrigation. For example, studies have clearly documented that drought-sensitive growth stages such as formative tillering and stalk elongation, are not suitable growth stages to apply a deficit during, whereas avoidance of water use during low demand periods increases the potential for WUE (Ferreira *et al*., 2020) [14] (Dingre *et al*., 2021) [15] (Dingre *et al*., 2022) [16]. The confounding results from studies administered to drought-sensitive growth stages vs. studies targeting drought-tolerant windows or modeling an average drought during the entire crop cycle (where a drought-tolerant window would have been the 50% TAW threshold) is most likely the result of timing of the deficit, not because the crop was not managed consistently by the producer (Misra & Singh, 2023) [12] (Ferreira *et al*., 2020) [14].

The second theme reflects the dominant and consistent influence of each crop's genotype on WUE. The fact that certain cultivars can maintain high levels of WUE when imposed with a 70% deficit while other cultivars can achieve similar levels of WUE only under full irrigation demonstrates that these cultivars express different levels of tolerance for deficits and provides an opportunity for breeders to select and utilize genotypes with improved WUE potential (da Silva *et al*., 2013) [4] (Ramasamy *et al*., 2023) [19]. Taken together, the literature indicates that there exists an integrated optimum: combining a high-WUE, drought-tolerant genotype with drip irrigation and a stage-targeted deficit irrigation strategy. While few studies assess these three variables as a unified strategy, there is a considerable knowledge gap regarding trialing all three components together and thus a considerable opportunity for future integrated trials (Coelho *et al*., 2018) [13] (Geerts & Raes, 2009) [10].

There is limited literature documenting economic and practical implications of agronomic findings. The most efficient forms of drip irrigation (subsurface and surface) represent a capital cost greater than one-quarter of the total production costs and whereas the mostly agronomic literature identifies this cost, it does not consistently include these costs into the recommendations (Singh *et al*., 2023) [18]. As a result, the gap between agronomically optimal and economically viable production systems still has not been adequately addressed for resource constrained sugarcane growers. Additionally, the limited research to date has mainly focused on either single-season or greenhouse/controlled environment studies thus the long-term impacts of sustained deficit irrigation on soil structure, root development, and cumulative WUE have yet to be effectively evaluated, even though sugarcane is produced in a multi-ratoon production system (Ferreira *et al*., 2020) [14] (Wu *et al*., 2014) [17].

The concept of sugarcane WUE is reinforced by reviewing recent studies on the interaction between the physiological development of the crop and the water supply; therefore, it is emergent from the combination of these two factors because the crop's physiology changes throughout development, and the crop's physiology is influenced by the regulation of stomata and root signals. These interactions are influenced by the way in which water is applied to sugarcane, which has been affected by the introduction of PRD. In practical terms, a number of recommendations can be made from the data: (1) Target Deficits away from formative stages. (2) Deliver Water Through Efficient Drip Systems, where Economically Viable. (3) Select Deficit Tolerant High-WP Genotypes. (4) These combinations provide the greatest opportunities for increasing and sustaining Sugarcane Productivity in periods of limited water.

7. Conclusion

This review combines 34 published studies and modelling analyses to examine peer-reviewed studies, which have been published mainly between 2015 and 2025, to evaluate the impact of deficit irrigation on the water-use efficiency (WUE) of sugarcane (*Saccharum officinarum* L.). The consistency in studies showed that WUE and water productivity would improve with deficit irrigation versus full irrigation and usually had smaller proportional yield reductions to this practice. The degree of benefits will depend on the interaction between deficit level, growth-stage timing, irrigation method, and genotype. The ability to improve the yield-water trade-off favourably by the use of partial root-zone drying and regulated deficit irrigation, quickly produce a large positive gain in WUE when used in conjunction with drip irrigation, which resulted in 60-200% WUE improvement with 20-60% water savings for this irrigation method. The growth stages of formative tillering and stalk elongation were both found to be the most sensitive to drought and, therefore, poor candidates for the imposition of deficit irrigation. Considerable genotypic variability in water productivity can facilitate the choice of cultivars adaptable to systems involving deficit irrigation.

Recommendations for researchers to measure and report WUE and water productivity more consistently, so that cross-study comparisons are more meaningful, conduct long-term multi-ratoon field-studies to measure cumulative benefit from WUE and water productivity increases, co-ordinate studies of deficit irrigation with complementary practices (such as mulching, fertigation, using silicon, and selecting water-efficient genotypes) in one overall design, and conduct field validation studies to determine model-simulated deficit thresholds among a wide range of environmental conditions.

The implications for policymakers and practitioners are encouraging the implementation of growth-stage specific deficit irrigation strategies that rely on achieving water savings outside of sensitive formative periods using efficient drip irrigation systems, where feasible from an economic standpoint, and growing deficit-tolerant, high-water-productivity crop cultivars. Policies that will lessen smallholder access to capital for micro irrigation systems will greatly increase adoption rates among smallholder sugarcane producers.

Research that develops integrated, economically based deficit irrigation systems, precision irrigation schedules through machine-learning or computational models, as well as multi-site replication and validation, should be the priority for sustaining sugarcane productivity and sugar yield numbers while continuing to significantly reduce water use as water resources become scarcer, and climate change becomes an increasing factor.

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