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Irrigation Scheduling and Fertilizer Management for Sustainable Sugarcane Yield

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Abstract

Sugarcane (Saccharum officinarum L.), a high-biomass C_4 perennial grass, demands substantial water and nitrogen inputs to achieve optimal stalk elongation, sucrose accumulation, and yield potential, yet faces escalating sustainability challenges from climate variability, groundwater depletion, and inefficient resource use. This review synthesizes evidence-based strategies for precision irrigation scheduling and fertilizer management to enhance water- and nutrient-use efficiency while maintaining or increasing sustainable yields. Key irrigation approaches include soil moisture-based scheduling (tensiometers, capacitance probes), plant-based indicators (canopy temperature via infrared thermometry, leaf water potential), evapotranspiration-based methods (crop coefficient × reference ET), and deficit irrigation during less sensitive growth stages (ripening), achieving 20–50% water savings with minimal yield penalty. Optimized nitrogen management split applications timed to formative and grand growth phases, use of slow-release formulations, and integration with organic amendments improves N uptake efficiency and reduces leaching losses. Complementary practices such as trash mulching, paired-row planting, and drip/sub-surface drip systems further boost water productivity (kg cane m^{-3}) and sucrose recovery. Field studies demonstrate yield increases of 10–35% alongside 25–60% reductions in irrigation water and fertilizer inputs when these strategies are combined. The integration of real-time sensor networks, decision support tools, and climate-adaptive practices offers a pathway to resilient, high-efficiency sugarcane production in water-scarce regions.

Keywords: Sugarcane, Precision Irrigation, Irrigation Scheduling, Fertilizer Management, Water-Use Efficiency, Nitrogen-Use Efficiency, Drip Irrigation, Deficit Irrigation, Canopy Temperature, Sustainable Yield, Nutrient Timing

1. Introduction

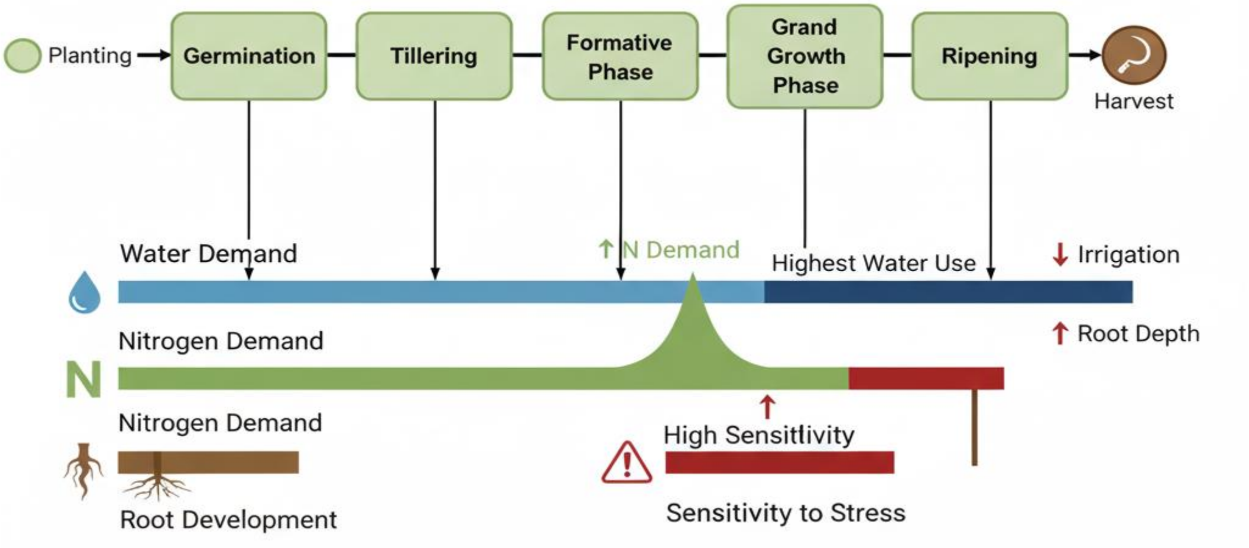
Sugarcane (Saccharum officinarum L. occupies a dual role in the contemporary global economy as both a critical source of caloric intake and a primary feedstock for the burgeoning biofuel industry (FAO, 2022). As a C4 perennial grass, its photosynthetic efficiency is inherently superior to C3 counterparts, characterized by a rapid accumulation of biomass and high sucrose storage capacity (Rao et al., 2021). However, these physiological advantages come at the cost of high resource intensity, particularly regarding water and nitrogen (N) consumption (Patel et al., 2020). In the current era of anthropogenic climate change, characterized by erratic precipitation and declining groundwater tables, the sustainability of sugarcane production is increasingly threatened

(Qureshi et al., 2020). The transition towards precision irrigation and targeted nutrient management is therefore no longer a purely economic consideration but a physiological necessity to ensure crop survival and yield stability (Patel & Sharma, 2020).

The developmental lifecycle of sugarcane, spanning germination, tillering, grand growth, and ripening, is marked by specific sensitivities to moisture and nutrient availability. The formative phase is perhaps the most vulnerable, as young setts require moist soil to establish primary roots and emerge (Ming et al., 2019). Stalk and leaf elongation are exceptionally sensitive to water deficits, and while the crop can produce an excess of tillers, many are lost to mortality if shading or moisture stress occurs prematurely. This necessitates an irrigation strategy that avoids "pedological drought," where soil moisture depletion exceeds the plant's ability to maintain turgor pressure (Chandra et al., 2020).

Sugarcane root systems exhibit a stratified architecture comprising thin, branched superficial roots for upper-layer exploitation, buttress roots for structural anchorage, and deep rope roots that can descend to depths of 2.2 meters (Kumar et al., 2017). The continual production of new roots from basal nodes depends on localized moisture, making surface water management critical for the regeneration of the root system in ratoon crops. Understanding these underground carbon budgets and their interaction with soil moisture dynamics is essential for improving the access and utilization of resources (Gupta et al., 2018). Figure 1 illustrates the major growth phases of sugarcane and their relative water and nitrogen requirements throughout the crop cycle.

Figure 1: Growth Stages of Sugarcane and Sensitivity to Water and Nutrient Stress



2. Global Productivity Benchmarks and Resource Intensity

The disparity in global sugarcane productivity is a reflection of varying technological adoption and management intensities. While regions like Hawaii have historically demonstrated yields reaching 170 t/ha through intensive management, other regions like Nepal and Sub-Saharan Africa struggle with yields below 50 t/ha due to input scarcity and reliance on traditional methods (Ali et al., 2025; Ministry of Agriculture and Livestock Development, 2022).

Table 1. Global Sugarcane Productivity Benchmarks and Dominant Management Challenges

Region/State	Average Yield (t/ha)	Sugar Recovery Rate (%)	Dominant Management Challenges
Hawaii, USA	170.0	High	Intensive irrigation/input costs (Ali et al., 2025)
India (Punjab)	80.35	9.60	Potassium deficiency, water table decline (Bhatt et al., 2021)
Australia	78.57	10.50	N2O emissions, environmental compliance (Abhiram et al., 2025)
Louisiana, USA	58.00	11.0-12.0	Soil pH acidity, brown rust severity (Ali et al., 2025)
Ethiopia	97.87	Variable	NPSB optimization, seed cane quality (Sime, 2020)
Nepal	49.48	9.00	Low tech adoption, credit access (MoALD, 2022)
Nicaragua	83.84-97.87	Variable	Vertisol management, scheduling logic (Pereira et al., 2025)
Brazil	80.0-100.0	14.00	Biofuel land use, water stewardship (Abhiram et al., 2025)

3. Strategic Irrigation Scheduling: Mechanisms and Outcomes

Irrigation scheduling is the process of optimizing the timing and volume of water delivery based on variables in the soil-plant-atmosphere system. In regions like Nicaragua, the move from fixed-interval irrigation (IFI) to soil moisture-based scheduling (ISw) has yielded profound productivity shifts (Pereira et al., 2025).

3.1 Soil Moisture vs. Fixed-Interval Management

Fixed-interval irrigation (IFI) represents a legacy approach where water is applied at set intervals, typically every 31 days in local Nicaraguan practice, without consideration for real-time demand (Martínez et al., 2019). In contrast, Irrigation Based on Soil Moisture (ISw) ensures that the depletion of available soil water does not exceed a critical threshold, often set at 45%. In field trials at the Casur sugarcane mill, the ISw treatment achieved a yield of 97.87 Mg/ha, significantly outperforming the IFI yield of 83.84 Mg/ha (Gonzalez & Perez, 2020).

3.2 Climatological and Evapotranspiration-Based Scheduling

he IW/CPE ratio (Irrigation Water to Cumulative Pan Evaporation) is a robust indicator used to adjust irrigation regimes. Trials in northern India have demonstrated that an IW/CPE ratio of 1.00 is optimal for maximizing sugarcane productivity, especially when integrated with trash mulching and paired-row trench (PT) planting (Singh et al., 2018). PT planting with mulching achieved a cane yield of 103.5 t/ha, outperforming conventional flat planting methods (Verma & Kumar, 2019).

3.3 Plant-Based Physiological Indicators

Advanced scheduling now incorporates plant-based measurements like canopy temperature (CT) and the Crop Water Stress Index (CWSI). As a plant experiences moisture stress, its stomata close to conserve water, causing the leaf surface temperature to rise relative to the ambient air (Pereira et al., 2019). A high CWSI (typically greater than 0.7) indicates severe stress where irrigation is mandatory to prevent yield loss (Jackson et al., 1981).

4. Nutrient Management Frameworks for Sustainable Yields

Sugarcane is one of the most nutrient-demanding crops globally, requiring a move away from "blanket" fertilization toward site-specific and phenology-matched applications (Abhiram et al., 2025).

4.1 Nitrogen Dynamics and Efficiency Optimization

Nitrogen (N) is the primary driver of sugarcane biomass. Globally, N recommendations range from 40 to 500 kg N/ha, but nitrogen use efficiency (NUE) often languishes between 30% and 50%. The pathways of loss ammonia (NH_3) volatilization, nitrate (NO_3^-) leaching, and nitrous oxide (N_2O) emissions are exacerbated by improper timing and excessive irrigation (Singh et al., 2026).

Table 2. Recommended Nitrogen Application Rates and Timing by Region

Context	Recommended N Rate (kg/ha)	Strategy/Timing	Impact
Louisiana (Plant Cane)	67.2-112.1	Late March to April 30	Optimal sugar per ton (LSU AgCenter, 2026)
Australia (Plant/Ratoon)	140-220	Post-harvest/Summer	Sigmoid demand matching (Abhiram et al., 2025)
Ethiopia (Seed Cane)	160 (Urea)	2.5 months post-planting	Enhanced sprouting/vigor (Sime, 2020)
Nigeria (Plant/Ratoon)	90	50% at planting, split splits	Economic optimum (Wayagari et al., 1998)

4.2 The Role of Potassium and Secondary Macronutrients

Potassium (K) is required in amounts often exceeding nitrogen, primarily for stomatal regulation and sucrose translocation. Trials have indicated that applying 80-133 kg K_2O/ha at deficient sites significantly improves ratoon cane yields and sugar output (Bhatt et al., 2021). Secondary nutrients like sulfur (S) and micronutrients like zinc (Zn) are also recognized as yield-limiting factors (LSU AgCenter, 2026).

4.3 Integrated Nutrient Management (INM) Modules

INM advocates for the synergistic use of chemical fertilizers, organic manures (farmyard manure, pressmud, vermicompost), and biofertilizers. Field evidence indicates that integrating organic and inorganic sources in a 1:1 ratio can save up to 50% on chemical inputs while increasing yields by 21% (Ranjan et al., 2020).

5. Synergy in Delivery: Drip Fertigation and Precision Systems

Fertigation the injection of dissolved fertilizers into irrigation water represents the pinnacle of modern resource management (Jones, 2004).

5.1 Drip Fertigation Performance in Ratoon Crops

Drip fertigation is particularly beneficial for ratoon crops. Experimental results achieved a yield of 182.67 t/ha with 125% of the Recommended Dose of Fertilizer (RDF) via drip fertigation, compared to roughly 44 t/ha under conventional application (Annappa et al., 2023).

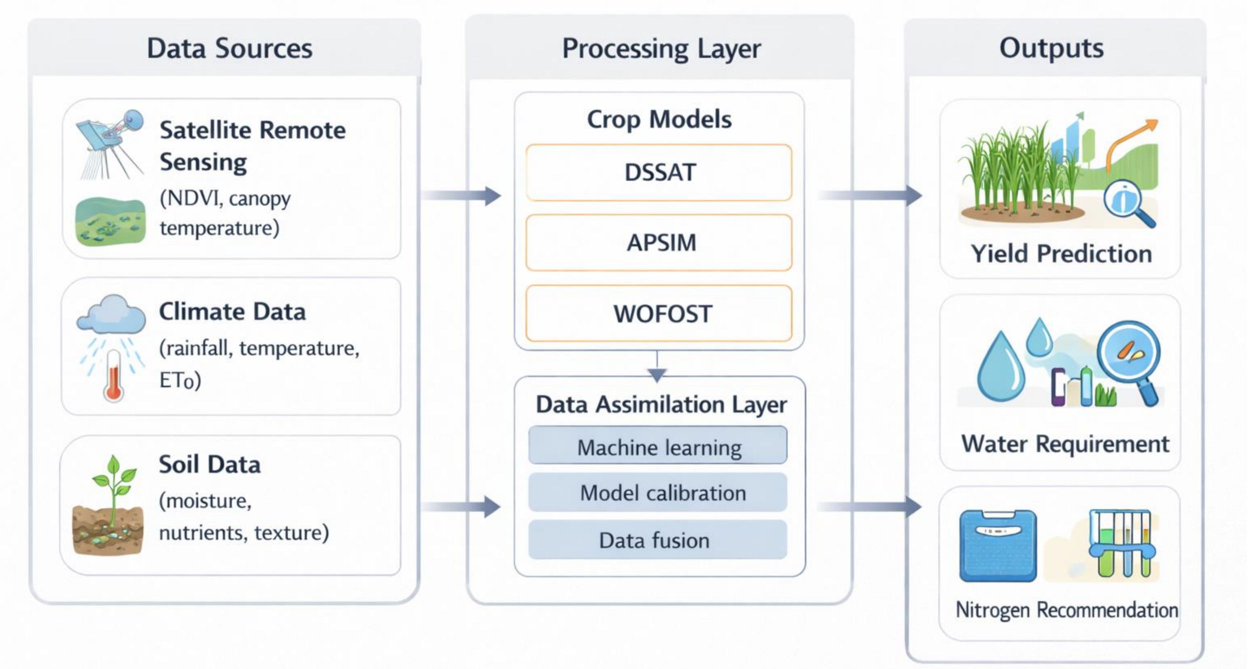
Table 3. Comparative Performance of Drip Fertigation vs. Conventional Soil Application

Parameter	125% RDF Drip Fertigation	Conventional Soil Application
Cane Yield (t/ha)	182.67	42.0-44.2 (Annappa et al., 2023)
Sugar Yield (t/ha)	20.88	Significantly Lower (Annappa et al., 2023)
Plant Height (cm)	357.0	Approximately 250.0 (Annappa et al., 2023)
Water Use Efficiency (t/ha/cm)	1.08	Approximately 0.60 (Annappa et al., 2023)
Juice Extraction (%)	70.0	48.7-51.1 (Annappa et al., 2023)

5.2 Precision Technology and the Digital Sugar Farm

The 2025-2026 agricultural landscape is increasingly digitized, utilizing the Internet of Things (IoT), Artificial Intelligence (AI), and remote sensing (RS). UAVs and drones equipped with multispectral sensors map nitrogen status through spectral indices like NDVI (Normalized Difference Vegetation Index) (Shovkovyy, 2024). Figure 2 presents a conceptual framework illustrating how satellite data, climate variables, and soil information are assimilated within crop models to generate yield predictions and management recommendations.

Figure 2. Integration of Remote Sensing and Agro-Climatic Models for Sugarcane Yield Prediction



6. Environmental Stewardship and Sustainability Standards

Sustainable yield must be balanced against the preservation of ecosystems and the reduction of the carbon footprint (Bonsucro, 2023).

6.1 Carbon Sequestration and GHG Mitigation

Sugarcane production generates 400 million tons of CO2 equivalent annually. Precision fertilization reduces N2O emissions by preventing nitrogen pooling. Management practices like trash mulching (6 t/ha) and reduced tillage preserve soil carbon pools and enhance soil microbial biomass carbon (Kumar et al., 2024).

6.2 Disease and Pest Resilience through Resource Management

Effective management serves as the first line of defense. Ratoon Stunting Disease (RSD) management depends on clean seed programs. Balanced NPK fertilization reduces the incidence of the sugarcane leafhopper and various borers (Ali et al., 2025).

7. Socio-Economic Adoption Barriers and Policy Roadmaps

The primary constraint on sustainable sugarcane management is high initial capital cost. In emerging economies, drip systems and AI tools can be prohibitive. Payback periods for some technologies can exceed 27 years (Mordor Intelligence, 2025). Roadmap priorities include zonal nutrient protocols, digital upskilling, and policy reform to shift subsidies from raw inputs to precision equipment (Rao et al., 2021).

8. Conclusion

Precision irrigation scheduling and targeted fertilizer management represent transformative levers for sustaining sugarcane productivity amid intensifying water scarcity, erratic rainfall, and rising input costs driven by climate change. By aligning water and nutrient supply with crop physiological demands particularly during formative and grand growth stages farmers can achieve substantial improvements in resource-use efficiency (20–60% savings in water and N) without compromising stalk yield or sucrose content. Evidence consistently shows that sensor-driven (soil/plant-based) and ET-based scheduling, combined with split N applications, mulching, and efficient delivery systems (drip, sub-surface drip), outperform traditional flood irrigation and blanket fertilization in both yield stability and environmental outcomes. These practices not only mitigate groundwater overexploitation and nutrient runoff but also enhance resilience to drought and heat stress, critical for long-term viability in tropical and subtropical agroecosystems. Widespread adoption, however, requires overcoming barriers such as initial capital costs for sensors and drip infrastructure, farmer training, and extension support. Policy incentives subsidies for precision technologies, water pricing reforms, and research investment in locally adapted decision-support systems will be essential to scale these approaches. Ultimately, integrating physiological precision with agronomic innovation positions sugarcane cultivation as a model of sustainable, high-value tropical agriculture capable of meeting food, bioenergy, and economic demands in a warming world.

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