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Research Article

Foliar nitrogen dynamics and yield responses of sugarcane (CP69-1062) to urea and urea–ammonium nitrate under delayed fertigation in northern Khuzestan, Iran

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ABSTRACT- Delayed planting and variable spring rainfall frequently complicate nitrogen (N) management in sugarcane production systems in Iran. Despite the large scale of production, information on foliar N dynamics and crop performance under delayed fertigation with different N sources remains limited. This study evaluated the response of sugarcane cultivar CP69-1062 to nitrogen source (urea vs. urea–ammonium nitrate (UAN)) and fertigation timing (early June, 1-week delay, and 3-week delay). Furrow fertigation was applied either as urea (184 kg N ha^{-1}) or UAN (97 kg N ha^{-1}), with both treatments delivered in three monthly split applications. Statistical analysis using a Linear Mixed Model (LMM) showed that foliar N concentration decreased significantly as fertigation was delayed ($P \leq 0.05$). However, UAN resulted in a significantly faster recovery of foliar N status compared with urea. Despite these differences in early-season foliar N dynamics, end-of-season quantitative and qualitative traits did not differ significantly between fertilizer sources ($P > 0.05$). In contrast, fertigation timing significantly affected yield-related traits. Delayed application reduced stalk density and final biomass, indicating that the timing of N availability is more critical than the fertilizer source itself. Overall, these findings provide practical guidance for optimizing N management under delayed planting conditions and are particularly relevant for improving productivity in semi-arid sugarcane production systems similar to those evaluated in this study.

INTRODUCTION

Nitrogen plays a crucial role as a nutritional source in agricultural products, supporting various metabolic processes essential for crop growth, such as tillering and cane height (Koochekzadeh et al., 2013). Nitrogen deficiency reduces light absorption and photosynthetic capacity, primarily due to the decreased leaf size, reduced chlorophyll synthesis, and a consequent decline in biomass production. Intensive agricultural systems such as sugarcane, which accumulate large amounts of biomass, therefore require substantial nitrogen inputs to sustain optimal growth and productivity (Thorburn et al., 2005; Van Heerden et al., 2010). Nitrogen recommendations should minimize environmental effects while maintaining agricultural productivity. Nitrogen fertilizer requirements for sugarcane vary considerably across major production regions. In Brazil, they range from 40–80 kg N ha^{-1} and 100–150 kg N ha^{-1} for ratoon crops (Otto et al., 2014). In India, 150–180 kg N ha^{-1} in the north to 250–350 kg N ha^{-1} in the south (Shukla et al., 2017). In China, annual recommendations can reach up to 500–700 kg N ha^{-1} (Li et al., 2013). Numerous studies indicate that the optimal nitrogen application rate is influenced by a variety of factors such as soil type, crop age, plant and soil attributes, climate conditions, and duration of the growing period (Kühling et al., 2025; Lu et al., 2024; Wang et al., 2020; Wiedenfeld, 1995; Wood et al., 1996).

Current nitrogen recommendations for sugarcane cultivation in Iran range from 161 to 184 kg ha^{-1}, depending on the age and variety (Alimohammadi et al., 2020). Sugarcane cultivation in Iran faces several distinct challenges, including a shortened growing season caused by delayed harvesting, as well as variability in spring rainfall and soil moisture conditions. These factors need adjustments to nitrogen fertigation compared with other sugarcane-growing regions. Urea is typically the primary nitrogen fertilizer used in Iranian sugarcane production. After application to the soil, urea undergoes hydrolysis, producing ammonia and carbon dioxide. The ammonia is subsequently oxidized to nitrate through nitrification, allowing the nitrogen to be absorbed by the plant (Britto & Kronzucker, 2005). Urea is widely used in the formulation of multi-component solid fertilizers and, due to its high solubility in water, it is also well suited for use in fertilizer solutions, often in combination with ammonium nitrate. One common liquid formulation is urea–ammonium nitrate (UAN), which typically contains about 30% nitrogen. A distinguishing feature of UAN is that nitrogen is present in

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three forms: urea ($CO(NH_2)_2$), nitrate (NO_3^-), and ammonium (NH_4^+). In addition to the total amount of nitrogen applied, effective nitrogen management also depends on optimizing the timing of fertilizer application. In sugarcane production systems, frost damage to the aerial parts of the crop followed by regrowth, along with spring rainfall, can delay the initiation of fertigation. Therefore, this study aimed to evaluate the effects of nitrogen fertilizer timing and source on sugarcane growth dynamics, foliar nitrogen concentration throughout the growth cycle, and final quantitative and qualitative yield.

MATERIALS AND METHODS

This study was conducted on farms in southwestern Iran at the Karun Agro Industrial, Inc., (48°37′E, 32°01′N). The main physical and chemical characteristics of the soils at the study site are summarized in Table 1. The study area, located in northern Khuzestan, has a hot and arid climate, with an average annual temperature of approximately 25 °C and average annual precipitation of about 250 mm, reflecting semi-arid conditions that require irrigation for crop production (Ghorbani et al., 2021). In this region, sugarcane is typically planted in late August. Due to lower temperatures, plant growth during autumn and winter is minimal (Ramesh et al., 2022; Souza et al., 2019). As late winter transitions into early spring, rising temperatures promote renewed sugarcane growth (Ramesh et al., 2022; Souza et al., 2019). Accordingly, weekly evaluations of sugarcane growth begin on May 1, and harvesting occurs in autumn or winter depending on the variety. The initiation of furrow fertigation is generally determined by crop growth status, plant age, variety, precipitation, and soil moisture conditions (Singh et al., 2019). However, the large volume of water required per hectare, particularly during the first irrigation, combined with fixed water allocations for each farm and the inherently slow irrigation rate, often extends the fertigation cycle beyond its planned schedule. Thus, these operational constraints frequently make unavoidable delays in irrigation scheduling for some adjacent fields within the Karun Agro-Industrial plantation.

In 2021, fertilization was delayed by approximately one month and began in early June due to the spring rainfall. This delay coincided with a period of high evapotranspiration and increased nitrogen demand by the crop. Under normal management conditions, sugarcane receives 184 kg N ha^{-1} supplied as urea, applied in three split doses equivalent to 100, 150, and 150 kg ha^{-1} of urea fertilizer. Experiments were conducted under commercial on-farm conditions in three adjacent fields, each covering 12 ha, and followed an on-farm, split-plot arrangement within a randomized framework. The main-plot factor was timing of nitrogen (N) fertilizer application, implemented at three levels: early June (T1), a 1-week delay (T2), and a 3-week delay (T3). Due to the logistical constraints associated with large-scale field operations, each timing treatment was assigned at the field scale, with one timing level applied per field. The sub-plot factor consisted of nitrogen fertilizer source with two levels: urea (control) and urea–ammonium nitrate (UAN). Within each field, fertilizer source treatments were randomly allocated to a total area of 6 ha per fertilizer source, subdivided into three replicate plots of 2 ha each. Urea–ammonium nitrate was applied at a total rate equivalent to 97 kg N ha^{-1} through three split fertigation events at application volumes of 60, 95, and 95 L ha^{-1}. Weekly measurements of stem growth were collected over a 19-week period, while foliar nitrogen concentration was monitored weekly for 17 weeks during the vegetative growth stage. Since the fertigation timing factor was assigned at the field level, all repeated-measures data were analyzed using a linear mixed model (LMM) implemented in PROC MIXED (SAS version 9.4, SAS Institute Inc., Cary, NC). Fertigation timing, fertilizer source, week of measurement, and their interactions were treated as fixed effects for the purpose of weekly response analysis. To account for the experimental design, the field, serving as the main-plot unit for the timing factor, was included as a random effect. Replicates nested within each field and fertilizer source combination were also treated as random effects to capture spatial variability and account for repeated measures over time. We utilized the Kenward–Roger (KR) approximation to adjust the denominator degrees of freedom, ensuring reliable statistical inference for the timing factor within this field-scale layout. Differences between fertilizer sources were evaluated using the LSMEANS statement, with a Tukey–Kramer adjustment applied to control the experiment-wise error rate. This unified LMM framework was then applied to all quantitative traits, including millable cane height, stalk diameter, stalk density, and millable cane yield, as well as qualitative traits, such as juice proportion, °Brix, polarity, extractable sugar, and sugar yield. This approach allowed for the simultaneous evaluation of main effects and interactions while rigorously addressing the hierarchical, on-farm structure of the experiment.

Table 1. Physical and chemical characteristics of the soils of the study area

Parameter	Unit	Amount
Soil texture	-	Silty clay loam
Soil classification (USDA Soil Taxonomy)	-	Typic Haplocalcids
Soil available K	mg kg^{-1}	110 ± 16
Soil available P	mg kg^{-1}	9.0 ± 0.6
Soil total N	%	0.055 ± 0.003
SOM	%	1.10 ± 0.06
$CaCO_3$	%	39.0 ± 5.8
pH	-	7.80 ± 0.07
Ec_e	dS m^{-1}	1.10 ± 0.11
CEC	Cmol (+) kg^{-1}	14.80 ± 0.96

SOM: Soil organic matter; Ec_e: Saturated soil electrical conductivity; CEC: Cation exchange capacity.

RESULTS AND DISCUSSION

Growth period factors

The analysis of variance indicated that sugarcane growth and foliar nitrogen content were significantly influenced by fertilizer type and growth period (Table 2). Differences associated with fertilizer application timing were primarily reflected in temporal growth dynamics throughout the measurement period. According to the LMM results, fertigation timing was highly significant ($P \leq 0.001$), and its effects were therefore interpreted based on robust statistical inference. In addition to statistical significance, consistent and biologically meaningful trends related to fertigation timing were evident across the growth cycle. Across all fertilizer treatments, sugarcane had a similar overall developmental trajectory. However, the plots that received nitrogen without delay consistently demonstrated significantly greater stem elongation than those subjected to 1-week or 3-week delays (Fig. 1A-C). As illustrated in Fig. 1C, the divergence in growth curves suggests that early nitrogen stress restricted internode expansion (Inman-Bamber, 2004). These differences were most pronounced during the early vegetative stage and persisted through the end of the observation period. Statistical comparisons indicated that fertigation delay imposed early-season nitrogen limitation, constraining initial growth that was not fully compensated during later developmental stages. Patterns of foliar nitrogen concentration further supported this interpretation. Following the initial fertilization event, delayed fertigation resulted in significantly lower foliar nitrogen than the non-delayed treatment, particularly during the first weeks of growth (Fig. 1A). As shown in Fig. 1A, the T1 treatment-maintained nitrogen concentrations above the critical threshold more effectively than the delayed treatments (Muchow & Robertson, 1994). This trend was consistent across fertilizer types (Fig. 1A), indicating that the timing of nitrogen availability played a central role in determining early plant nitrogen status. As the growth period advanced and nitrogen demand increased, the ability of fertilizer application to correct this early deficiency progressively declined. Although nitrate assimilation requires greater metabolic energy than ammonium assimilation (Britto & Kronzucker, 2005), nitrate is the predominant nitrogen form available to crops in most agricultural soils because of its higher concentration in the soil solution (Owen & Jones, 2001). Consequently, urea continues to be the most widely used nitrogen source because of its high solubility and ready accessibility to the plant roots (Miller & Cramer, 2005; Zayed et al., 2023). Previous research has further shown that ammonium nitrate and urea ammonium nitrate fertilizers can improve nitrogen use efficiency and crop productivity relative to urea (da Silva et al., 2020; Ren et al., 2021).

In the present study, UAN application produced a more rapid increase in foliar nitrogen concentration following fertigation, with peak values occurring at least one week earlier than those observed with urea (Fig. 1B). This response is consistent with previous reports indicating that complete urea hydrolysis under field conditions may require 3 to 14 days (Singh & Bajwa, 1986). The faster response associated with UAN can be attributed to the presence of both nitrate (NO_3^-) and ammonium (NH_4^+) in UAN solutions, which provide readily available nitrogen forms that are more rapidly absorbed by plants (da Silva et al., 2020; Ren et al., 2021). The steeper nitrogen accumulation slope observed for UAN in Fig. 1B during the grand growth phase further highlights its efficiency in supplying nitrogen rapidly. Consequently, differences between fertilizer sources were most evident during the early weeks following fertigation, a period when nitrogen availability is particularly critical for sustaining rapid vegetative growth. This early advantage associated with UAN application appears to be agronomically relevant under delayed fertigation conditions, where immediate nitrogen availability may partially offset the negative effects of postponed fertilizer delivery. These findings support the view that nitrate-containing fertilizers can play an important role in alleviating nitrogen deficiency, particularly during the initial fertilization stage, thereby enhancing early plant growth and supporting canopy development (Abhiram et al., 2025).

Although nitrate-based fertilizers are susceptible to leaching and potential nitrogen losses, their immediate availability appears to play an important role in alleviating early nitrogen deficiency and supporting initial sugarcane growth (Abhiram et al., 2025). However, during the later stages of the growth period, urea application maintained higher foliar nitrogen concentrations than UAN (Fig. 1B), suggesting a more sustained nitrogen supply over time. This shift in foliar nitrogen dynamics toward the end of the growth cycle likely reflects the slower but more prolonged release of nitrogen from urea, which may reduce differences between fertilizer sources as crop nitrogen demand stabilizes. Boschiero et al. (2018) similarly reported that although NH_4^+ uptake can occur more rapidly than NO_3^- uptake, a presumed preference for NH_4^+ does not necessarily result in greater nitrogen recovery. These findings underscore the importance of considering both fertilizer form and application timing when interpreting nitrogen uptake dynamics and their implications for crop growth.

Table 2. Linear mixed model (LMM) of fertilizer type and growth period on nitrogen concentration and stem elongation of sugarcane

	Source	Timing (T)	Fertilizer (F)	T × F	Week (W)	T × W	F × W	T × F × W
Nitrogen content	Num DF	2	1	2	16	32	16	32
	Den DF	12	12	12	192	192	192	192
	F Value	117.35***	67.25***	6.91*	165.4***	26.14***	11.79***	11.88***
Cane growth	Num DF	2	1	2	18	36	18	36
	Den DF	12	12	12	216	216	216	216
	F Value	34.14***	7.02*	0.22ns	6794***	2.24***	1.82*	0.63ns

ns: non-significant ($P > 0.05$); *: $P \leq 0.05$; **: $P \leq 0.01$; ***: $P \leq 0.001$. Degrees of freedom for F-tests were adjusted using the Kenward–Roger method (Num DF = numerator degrees of freedom associated with fixed effects; Den DF = denominator degrees of freedom corresponding to the error term).

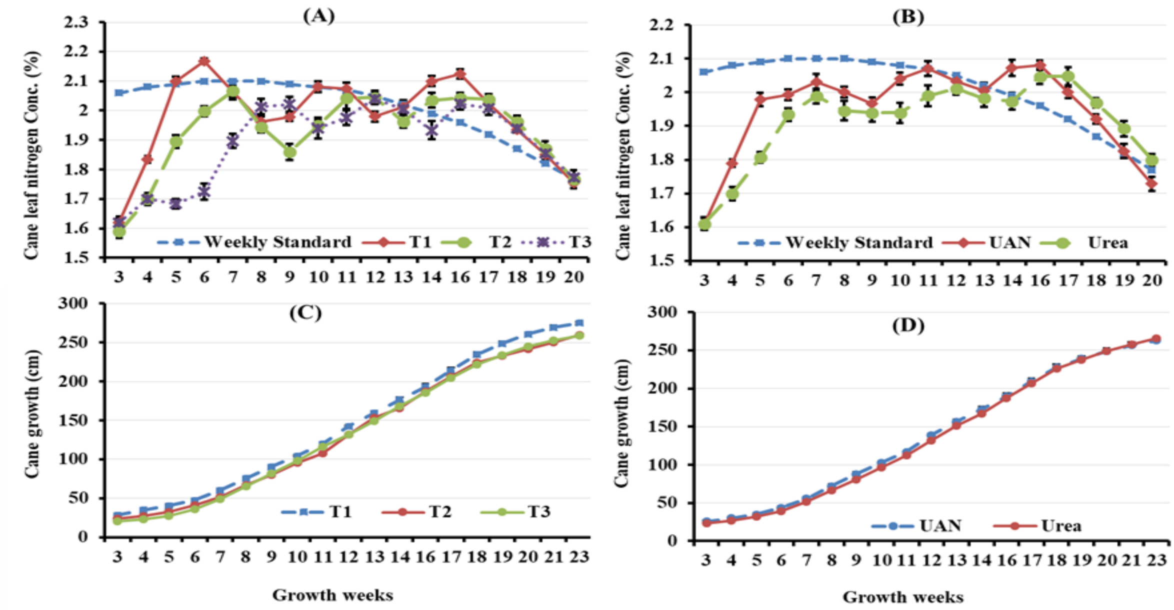

Fig. 1. Temporal changes in sugarcane foliar nitrogen concentration and growth traits. (A) Foliar nitrogen concentration under different fertilizer application timings (T1 = no delay, T2 = 1-week delay, and T3 = 3-week delay). (B) Foliar nitrogen concentration comparing fertilizer types (urea vs. UAN). (C) Sugarcane growth (cane height) under different fertilizer application timings (T1, T2, and T3). (D) Sugarcane growth comparing fertilizer types (urea vs. UAN). Error bars represent least-square means ± SE (*n* = 3).

Quantitative and qualitative yield

The nitrogen fertilizer type affected several quantitative and qualitative traits of sugarcane, including millable cane height, stalk density, millable cane yield, and sugar yield, although these effects were not statistically significant in most cases (Table 3). Millable cane diameter, individual stalk weight, °Brix, and sugar recovery percentage were likewise unaffected by fertilizer type ($P > 0.05$). In contrast, the LMM indicated that fertigation timing had a significant impact on final crop performance ($P < 0.05$). Millable cane height, cane density, millable cane yield, and sugar yield were significantly greater when fertigation was applied without delay compared with delays of 1 or 3 weeks (Fig. 2). As illustrated in Fig. 2B and Fig. 2C, the reduction in stalk density was the primary factor driving yield decline in delayed treatments (Bell & Garside, 2005). These results suggest that delayed fertigation reduces final crop performance, likely through its influence on early-season growth and tiller establishment. Similar interactions between nitrogen application timing and soil physical properties have been reported in sugarcane systems (Garrett, 2018). Notably, the timing-related patterns observed in this study were consistent across multiple yield components, indicating a cumulative effect of early nitrogen availability on canopy development, stalk population, and final biomass accumulation. Overall, the type of fertilizer source did not produce statistically significant differences in either quantitative or qualitative yield parameters (Table 3), whereas variation associated with fertigation timing appeared to play a more influential role in shaping yield-related traits under the conditions of this study. As illustrated in Fig. 2D, sugar yield closely mirrored the pattern observed for cane yield, indicating that sugar production was largely biomass-limited. However, the prolonged presence of high foliar nitrogen concentrations after urea application during the third fertilization event appeared to reduce observable differences between fertilizer sources, particularly for millable cane yield and sugar yield (Fig. 2B and Fig. 2D). This response suggests that the slower but more sustained nitrogen release from urea may partially compensate for its delayed initial availability. Such compensatory effects may explain the convergence in yield responses between fertilizer sources toward the end of the growing season, despite differences in early nitrogen dynamics. Zeng et al. (2020) evaluated some variations of nitrogen application rates in sugarcane and reported that increased nitrogen supplies enhanced cane yield, stalk density, and syrup content. Consistent with these findings, the present results suggest that nitrogen availability during early growth stages, rather than fertilizer form alone, plays a crucial role in determining final yield components. This observation aligns with the work of Lofton and Tubaña (2015), who demonstrated that delaying nitrogen application beyond the optimal window can result in yield losses regardless of the nitrogen source used. Moreover, earlier fertigation appeared to promote the survival of early-formed tillers and increased stalk density, ultimately contributing to greater cane and sugar yields (Fig. 2). Thus, these observations are consistent with previous studies that highlighted the essence of timely nitrogen availability for optimizing sugarcane productivity (Vuyyuru et al., 2019; Zeng et al., 2020).

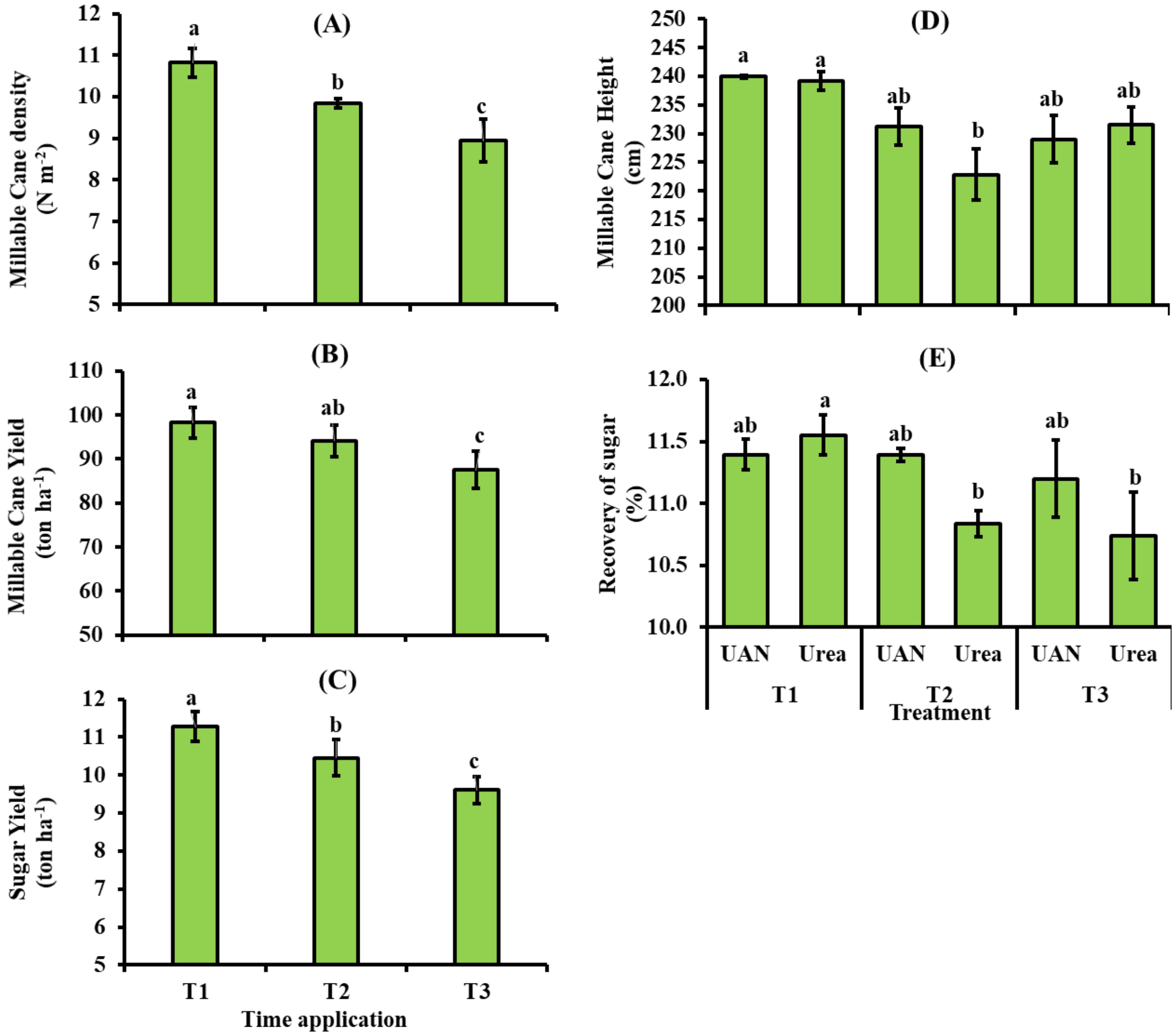

Fig. 2. Comparison of the single effect of fertilizer application timing (T1, T2, and T3) on millable cane density (A), millable cane yield (B), and sugar yield (C) and interaction effects of fertilizer application timing and fertilizer source (T × F) on cane height (D) and sugar recovery (E) in CP69-1062. Error bars represent least-square means ± SE (n = 3).

Table 3. Linear mixed model (LMM) analysis of the effects of fertigation timing (T), fertilizer source (F), and their interaction (T × F) on quantitative and qualitative traits of sugarcane

Parameter		**Timing (T)**	**Fertilizer (F)**	**T × F**
DF	Num DF	2	1	2
	Den DF	6	6	6
Cane height	F Value	4.87^{ns}	2.53^{ns}	5.31*
Cane diameter	F Value	0.70^{ns}	2.64^{ns}	0.04^{ns}
Cane weight	F Value	1.34^{ns}	0.06^{ns}	0.292^{ns}
Cane density	F Value	21.43**	0.97^{ns}	2.55^{ns}
Millable cane yield	F Value	7.90*	0.50^{ns}	0.01^{ns}
Brix	F Value	1.22^{ns}	2.26^{ns}	2.99^{ns}
Polarity	F Value	0.26^{ns}	4.39^{ns}	2.46^{ns}
Recovery of sugar	F Value	1.63^{ns}	14.62**	8.71*
Sugar yield	F Value	20.56**	3.41^{ns}	1.22^{ns}

ns: non-significant (P > 0.05); *: $P \leq 0.05$; **: $P \leq 0.01$; ***: $P \leq 0.001$. Degrees of freedom for F-tests were adjusted using the Kenward–Roger method (Num DF = numerator degrees of freedom associated with fixed effects; Den DF = denominator degrees of freedom corresponding to the error term).

CONCLUSION

Delayed or poorly timed nitrogen application is a common challenge in sugarcane production, particularly under variable spring rainfall and large-scale field conditions. This study demonstrated that the timing of fertilizer application had a stronger influence on sugarcane growth, foliar nitrogen concentration, and yield-related traits than the fertilizer source itself. Delayed fertigation significantly reduced foliar nitrogen concentrations during the early growth stages, thereby constraining initial growth and tiller establishment. Compared with urea, UAN fertilizer promoted a more rapid recovery of foliar nitrogen concentrations, suggesting that it may be a more suitable option under delayed fertigation conditions. These findings may help emphasize the subtle importance of timely nitrogen availability, and indicate that scheduling fertigation as early as possible can support early crop development and optimize overall crop performance.

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT AUTHORSHIP CONTRIBUTION STATEMENT

Conceptualization: Ali Motamedi Amin; Methodology: Ali Motamedi Amin; Software: Ali Motamedi Amin; Validation: Ali Motamedi Amin; Formal analysis: Ali Motamedi Amin; Investigation: Ali Motamedi Amin; Resources: Ali Motamedi Amin; Data curation: Ali Motamedi Amin; Writing—original draft preparation: Ali Motamedi Amin; Writing—review and editing: Ali Motamedi Amin; Visualization: Ali Motamedi Amin; Supervision: Ali Motamedi Amin; Project administration: Ali Motamedi Amin; Funding acquisition: Ali Motamedi Amin.

DECLARATION OF COMPETING INTEREST

The authors declare no conflicts of interest.

ETHICAL STATEMENT

Author have approved the manuscript and agree with the submission to “Iran Agricultural Research” journal. Manuscript was prepared in compliance with Ethics in Publishing Policy and we used Guide for Authors in preparing submitted manuscript.

DATA AVAILABILITY

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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