Nitrogen Use Efficiency Using Controlled-release and Soluble Urea in Tomato Grown on Raised Conventional and Compact Beds on Coastal Plain Sands

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ABSTRACT. **Nitrogen (N) is an essential macronutrient for plant growth; however, intensive management of vegetable production systems may lead to inefficient N use, often as low as 30% to 50%. Among emerging solutions, the one-time preplant application of controlled-release urea (CRU) offers significant advantages over soluble urea by incorporating innovative polymer coatings that retain nutrients in the soil longer and release them in alignment with plant demand. This approach reduces the frequency of fertigation, saving time, energy, and labor. In addition, taller and narrower compact beds, compared with wider conventional beds, may lower seasonal production costs by reducing water and nutrient application rates, pesticide use, and plastic waste, while minimizing leaching. Our research study addresses the challenges of low N use efficiency (NUE) and environmental concerns using CRU and different bed sizes. A replicated field study comparing polymer-coated CRU and urea was conducted on tomato (var. HM 1823) grown in sandy soils under two plastic-mulched bed sizes (conventional and compact). Seasonal differences were found in yield, dry matter weight (DMW), N, and carbon (C) accumulation across both bed systems. CRU treatments consistently resulted in significantly higher yield, DMW, and accumulation of N and C compared with control treatments, whereas urea treatments showed variable effects. Although higher N rate (224 kg/ha) increased yield, the highest NUE was observed at lower rates, highlighting the need to balance productivity with environmental and economic considerations. Overall, applying CRU at optimal rates in conventional raised beds improves yield and NUE, offering a more sustainable approach for tomato production in the sandy soils of north Florida.**

Tomato (*Solanum lycopersicum* L.) is the fourth most produced vegetable in the United States (10.2 million tonnes) (FAOSTAT 2023). In the United States, Florida was the second highest tomato-producing state, after California, producing 37,660.6 kg/ha in 2023 (USDA-NASS 2024). Tomato rank as the second-largest agricultural crop following citrus (*Citrus* spp.) in Florida, making a substantial $426 million contribution to the state's economy. Florida has a distinct seasonality in fruit and vegetable production, flourishing in the winter when other states face low temperatures. This enables growers to command premium prices for tomato, averaging $1.06/kg, whereas California's summer yields only fetch $0.78/kg (Chanda et al. 2021).

Tomato production systems demand careful management of nutrients and water to maximize their use efficiency and reduce nutrient losses to the environment, especially N. Excess N fertilizer is commonly used in tomato cultivation as an insurance against unforeseen yield depressions. However, excessive N application can lower yield and quality and raises potential environmental concerns (Fan et al. 2014; Kuscu et al. 2014; Zhang et al. 2011). N is an essential macronutrient for plant growth that is potentially lost to the environment due to excess and ineffective application methods. In comparison with arable crops, many vegetable crop species have relatively low NUE, primarily due to the short growing season and superficial roots (Greenwood et al. 1989; Thompson et al. 2020). Due to the fibrous root system, which is primarily concentrated near the soil surface, the ability to access nutrients from deeper soil layers is often limited. These root characteristics might not directly cause low NUE but can exacerbate N losses such as leaching, runoff, volatilization and denitrification. Therefore, to overcome the challenges of low NUE and mitigate potential N losses, it is necessary to optimize nutrient applications in vegetable crops such as tomato. This is especially important for crops grown in sandy soils to ensure maximum productivity. The recovery of applied N is typically about 50% or lower depending on the management, nutrient source, and soil (Shaviv and Mikkelsen 1993). In sandy soils with low nutrient retention, nitrate leaches easily, potentially impacting groundwater (Hartz 2006; Jackson et al. 1994; Sanchez 2000). To address this, split applications of N fertilizer and the use of enhanced-efficiency fertilizers (EEFs)—a category that includes stabilized fertilizers, slow-release fertilizers, and controlled-release fertilizers (CRFs)—have been identified as best management practices to mitigate N loss. Enhanced-efficiency fertilizers improve nutrient use efficiency by reducing N losses through leaching or volatilization. Specifically, CRFs release N gradually in smaller doses over the crop growth period, better aligning nutrient availability with plant demand (Sartain et al. 2004). CRFs are soluble fertilizers coated with materials such as polymer, sulfur, or resin and are applied once at the preplant stage (Guertal 2009). The coating thickness and material type determines the release dynamics, allowing N to be delivered in alignment with the crop's growth stages. For instance, CRF formulations with thinner coatings release nutrients more rapidly, making them suitable for shorter growing seasons, while thicker coatings extend

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release periods, aligning with prolonged crop demands. To sustainably feed a projected global population of 9.8 billion (United Nations 2017) by 2050, there is a critical need to enhance the efficiency of N fertilizers, particularly to overcome suboptimal utilization. When combined with strategies such as 4R Nutrient Stewardship (right source, right rate, right time, and right place), EEFs can effectively minimize N losses from agricultural systems (Lam et al. 2022). Therefore, in this study, we used polymer-coated CRU (a type of CRF) with two different release periods and soluble urea to improve NUE in tomato.

Traditional tomato production systems, especially on sandy soils, often require high inputs of water, fertilizers, pesticides, and plastic mulch, leading to elevated production costs and environmental concerns. In an effort to reduce these inputs, researchers in south Florida have evaluated the use of a narrower bed (reduced bed width without increasing bed height) in the past, which increased the yield of various vegetables including tomato (Clark and Maynard 1992) and recently investigated the use of both narrow and tall (compact) beds as an alternative to traditional wide bed systems (Holt et al. 2017, 2019). These compact beds, typically 25–30 cm in height and 41–45 cm in width, have been shown to reduce input requirements by decreasing the bed surface area, which lowers costs associated with plasticulture, fumigation, and irrigation, while maintaining crop productivity (Holt et al. 2017). They may also improve moisture retention and reduce runoff, particularly under extreme rainfall conditions, due to their taller and narrower structure. The increased elevation and smaller surface area of compact beds enhance water infiltration and limit surface water accumulation, helping to prevent waterlogging and promote more efficient soil moisture management during heavy rainfall events (Holt et al. 2019).

Compact beds were originally developed to reduce flooding risk in south Florida, where shallow water tables and frequent heavy rainfall increase the likelihood of waterlogging. In contrast, north and central Florida typically have deeper water tables, often ≈2 m, which reduce flooding risk but may influence how compact beds affect soil moisture retention and plant growth. In addition, tomato production in north Florida occurs during both fall and spring, with greater seasonal variation in temperature, rainfall, and wind patterns compared with south Florida. To address these regional differences, our study investigated the effectiveness of compact beds under north Florida conditions. Specifically, we compared plant N uptake efficiency and yield responses between compact and conventional beds using either CRU or split-applied soluble urea. We hypothesized that CRU would improve NUE and tomato yield compared with urea, and that compact beds would reduce N input needs while maintaining or improving yield compared with conventional beds.

Materials and methods

Research site and experimental design. The 2-year study (2021 and 2022) was located at the University of Florida (UF)/Institute of Food and Agricultural Sciences (IFAS) Plant Science Research and Education Unit in Citra, FL, where the field site was distinguished by a udic moisture regime, with high precipitation and humidity occurring most of the year. The mean annual temperature ranged from 20 to 25 °C with a frost-free period of 280 to 365 d and the mean annual precipitation was ∼1200 to 1400 mm. The soil at the study site is categorized as Candler sand (99% sand, 0.5% silt, and 0.5% clay), hyperthermic, uncoated lamellic quartzipsamments with parent material of eolian deposits, and/or sandy and loamy marine deposits (Jalpa et al. 2024). The Florida Automated Weather Network (FAWN) at the UF measured the monthly minimum and maximum temperatures as well as the amount of precipitation, for spring and fall tomato (Fig. 1). For each season, the study site was rototilled, and six preliminary raised soil beds referred to as false beds were formed to incorporate CRF into the soil (Jalpa et al. 2024). These false beds were then reshaped into final planting beds. Final bed dimensions were 0.15 m in height and 0.76 m in width for conventional beds, and 0.25 m in height and 0.61 m in width for compact beds. Each row was 49.4 m long. Pic Clor 60 fumigant (TriEst Ag. Group Inc., Greenville, NC, USA) was applied at a rate of 336 kg/ha to prevent nematode infestation and control weeds. During fumigation, drip tape with 0.31-m emitter spacing was installed, and beds were mulched with black plastic. Holes were punched into the mulch at 0.61-m intervals in preparation for transplanting.

Although the control treatment did not receive any N (0 kg N/ha),

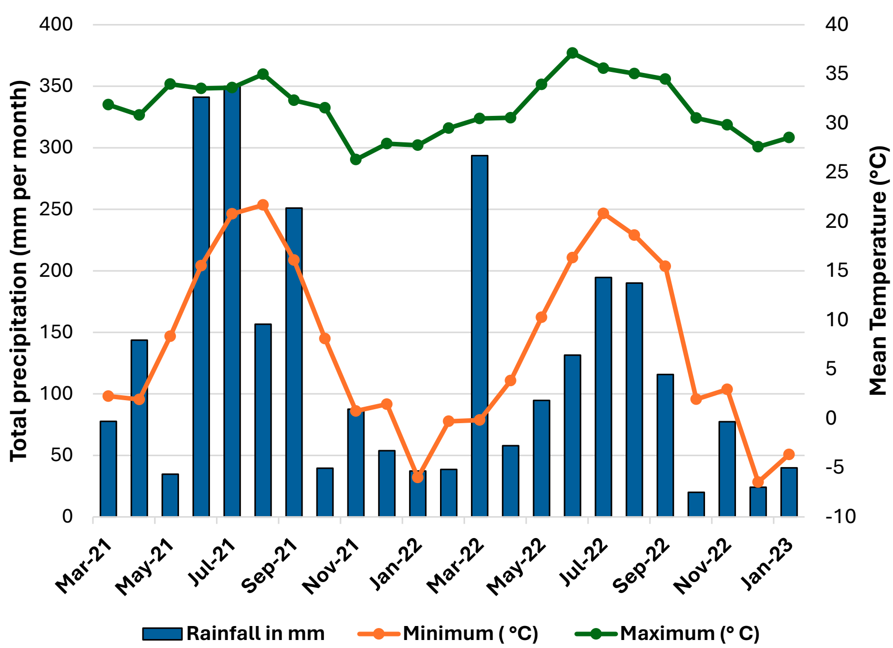

Fig. 1. Mean monthly minimum and maximum air temperatures (°C) and total precipitation (mm) per month during the experimental years of Mar 2021 to Jan 2023 in northern Florida with a humid-type climate. Tomato growing months ranged between September and January for fall and March and July for spring production. Data source: Florida Automated Weather Network (FAWN) at the University of Florida (UF) (https://fawn.ifas.ufl.edu/).

soluble urea and CRU plots received 140, 168, and 224 kg/ha, respectively. CRU formulations included two durations, a 60-d release (CRU-60) and a 75-d release (CRU-75), which align with the critical period of N uptake during tomato growth stages. Both CRU formulations were applied at all three application rates for both bed size treatments. The CRU formulation used in this study was POLYON, a polymer-coated urea product by Harrell's. CRU fertilizers were applied at the time of bed formation, whereas the urea treatments were applied 1 week after planting. Urea treatments were applied through the drip weekly in 13 equal doses throughout the growing period beginning 7 d after transplantation. CRU formulations were applied differently based on bed type. In conventional beds, CRU was incorporated into the false bed before forming the actual beds, whereas in compact beds, CRU was applied at the bed shoulders to prevent excessive burial of CRU below 30 cm due to the taller beds.

The experiment was designed in a randomized complete block design with 10 treatments and three blocks. Each block consisted of two raised beds, with five treatments randomly assigned within each bed, for a total of 10 treatments per block. Each plot is defined as the experimental unit where treatments were applied, which was 9.1 m long with 0.91 m buffer between each plot in both beds. Planting and harvest dates for tomato are summarized in Table 1. Tomato (*Solanum lycopersicum* L.; cv. HM 1823) seedlings were transplanted 3 weeks after fumigation in each season in both beds. Fifteen seedlings were planted per treatment. At harvest, three representative plants were randomly sampled from each treatment for data collection. After transplanting, irrigation was operated three times a day at 1-h intervals at 31.5 cm^3/s per 30.5 m of tape (69 kPa).

Table 1. Tomato planting and harvesting days for the years 2021 and 2022 and cultural practices for each season of tomato production in conventional and compact beds in northern Florida.

Planting and harvesting date	2021	2022
Spring	25 Mar–28 Jun	6 May–28 Jul
Fall	16 Sep–18 Jan 2022	4 Oct–12 Jan 2023
Conventional Beds		
Variety	HM 1823	
Planting spacing (m)	0.61	
Bed spacing (m)	1.83	
Sampling plot length (m)	9.14	
Bed width (m)	0.76	
Bed height (m)	0.15	
Harvested plot length (m)	1.83	
Replications	3	
Fumigant	Pic Clor 60 (336 kg/ha)	
Drip irrigation	31.5 cm^3/s per 30.5 m of tape (69 kPa) for three 1-h intervals per day	
	0.5 gal/min per 100 ft drip tape at 10 psi for three 1-h intervals per day	
Mulch	Black VIF (Spring and Fall 2021 and Fall 2022)	
	White VIF (Spring 2022)	
Compact Beds		
Variety	HM 1823	
Planting spacing (m)	0.61	
Bed spacing (m)	1.83	
Sampling plot length (m)	9.14	
Bed width (m)	0.61	
Bed height (m)	0.25	
Harvested plot length (m)	1.83	
Replications	3	
Fumigant	Pic Clor 60 (336 kg/ha)	
Drip irrigation	31.5 cm^3/s per 30.5 m of tape (69 kPa) for three 1-h intervals per day	
	0.5 gal/min per 100 ft drip tape at 10 psi for three 1-h intervals per day	
Mulch	Black VIF (Spring and Fall 2021 and Fall 2022)	
	White VIF (Spring 2022)	

VIF = virtually impermeable film.

Crop sampling, yield, and C:N ratio. For each tomato season, there were two to three harvests conducted in both bed size plots. Following the final harvest, three plant samples per treatment were collected. Tomato fruit were taken to a grading machine after a harvest and divided into four sizes: small, medium, large, and extralarge (USDA 1991). The minimum designated diameters for grading were 5.4 cm, 5.7 cm, 6.4 cm, and 7.0 cm, respectively. We combined large and extralarge grade into marketable class. Overall yield and yield count by tomato grade were determined. The three plants were separated into components of leaf, stem, and root. Samples of fruit and plant components were dried at 65 °C for at least a week. After recording the dry weights, the tomato fruit and plant components were ground and analyzed for total nitrogen (TN) and total carbon (TC) at the UF/IFAS Analytical Research Laboratories (ANSERV Laboratories) in Gainesville according to standard procedures (Mylavarapu et al. 2024). The C:N ratio of the tissue was calculated using TC and TN values. The total C and N accumulations (kg/ha) of the entire plant were estimated by multiplying the TC and TN values by the DMW. For calculating whole plant dry matter, tomato dry matter (kg/ha) was estimated for each plant component and then added together.

TN accumulation. Total N accumulation is the amount of N in the plant, calculated as the product of the N content (in percentage) and the total DMW (kg/ha) of the plant, which is critical for assessing NUE and understanding how effectively the plant has used available N from the soil.

$$\text{TN accumulation} = \frac{TN\ content}{100} * Total\ dry\ matter\ weight \quad [1]$$

Total DMW = Fruit, leaves, stem and roots combined

TC accumulation. Total C accumulation is the amount of C in the plant, calculated as the product of the C content (in percentage) and the total DMW (kg/ha) of the plant, which is important for evaluating plant C storage and understanding its growth and metabolic processes.

$$TC\ accumulation = \frac{TC\ content}{100} * Total\ dry\ matter\ weight \quad [2]$$

Nitrogen use efficiency. The ratio of the plant's intake of N to the total N fertilizer input is known as nitrogen use efficiency. The NUE was calculated by the following:

$$NUE(\%) = \frac{N\ uptake\ in\ plant}{Amount\ of\ N\ fertilizer\ applied(kgNha^{-1})} \quad [3]$$

Apparent N recovery. Apparent N recovery (APR) is calculated as the difference in N uptake (kg/ha) between fertilized and unfertilized plots (controlled plots), relative to the amount of N fertilizer applied.

$$APR\ (\%) = \frac{N\ uptake\ from\ fertilized\ plots - N\ uptake\ from\ unfertilized\ plots}{Total\ amount\ of\ N\ fetilizer\ applied} \quad [4]$$

Statistical analysis. Response data were analyzed using generalized linear mixed models procedures as implemented in SAS® PROC GLIMMIX (SAS/STAT 15.2; SAS Institute, Cary, NC, USA) using appropriate data distribution functions and their canonical links (e.g., normal for yield, N content, C content, APR, NUE, etc.) and beta for continuous fruit size proportions. The fixed effects portion of the model was Response = Bed|Trt|YS, where the vertical indicates the presence of all possible two-way and higher order interactions. Random effects included Block(Bed), Trt*Block(Bed), and YS * Block(Bed), where YS = Year × Season combination. This model is known as an RCB-Split Block in Time, which assumes uncorrelated residuals, which is the simplest case. However, because the same plots were used repeatedly across seasons, we modeled the residuals using an unstructured covariance matrix to account for potential correlations over time and ensure appropriate estimation of treatment effects. This assumption is likely not warranted in a repeated measures situation, where plots received the same treatment year after year and season after season. In the second step of the analysis the YS * Block (Bed) effect was omitted from the models and residuals were modeled using an unstructured (UN) covariance matrix, which makes no assumptions about the correlation structure by allowing each YS to have its own variance and each pair of YS to have its own covariance. In some cases, a Cholesky (Chol) model resulted in model conversion, when the UN structure would not. The Chol structure is simply a UN structure parameter through its Cholesky root, which ensures a positive semidefinite variance-covariance matrix. The covariance matrix was depicted in tabular form as a decision-making tool in conjunction with the AkaiKe's Information Criterion corrected for sample size (AICc); a smaller value indicates a better model. In many cases, the covariance among YS-pairs was very small and a UN(1) model was fitted; this model allows YS to have unequal variance and sets the covariances to zero. Once a model was chosen, it was saved using the STORE option of PROC GLIMMIX. This model was then used in the SAS® PLM = Post Linear Modeling procedure (SAS/STAT 15.2; SAS Institute), to calculate least squares means and linear and deviation from linearity contrast, then transferring the estimates to EXCEL for the construction of tables or used by the SAS® PROC SGPLOT or SGPANEL to generate graphs.

Contrast analysis was used in this experiment because there was only a single zero control treatment, and including this treatment in a regression analysis would require the same zero control to be recycled for every N source, thus underestimating the true variability. In addition, the differences between the N rates are unbalanced at 140, 28, and 56, leading to unreliable estimates. Of the three rates 140, 168, and 224 used in the study, two are available for polynomial contrasts. The first contrast establishes the linear response, and the second assesses the deviations from linearity. It cannot be considered quadratic because the next higher level is missing for N rate.

Results and discussion

Tables 2 through 8 present statistical contrasts for each N source across three application rates (140, 168, and 224 kg/ha), with the unfertilized control included as a reference. The control serves as the baseline for comparison, and the first contrast tests whether the fertilized treatments, as a group, differ significantly from the control. The second contrast evaluates whether a linear trend exists across increasing N rates, and the third identifies any deviation from linearity, indicating whether the response plateaus or declines at higher rates. These contrasts help determine whether higher N inputs continue to improve outcomes such as yield, nutrient accumulation, or efficiency, and whether those benefits diminish at higher rates.

Yield

Variations in tomato yield were observed in response to the significant interaction between treatments (N source and N rate) and year-season (YS). CRU treatments consistently yielded higher than the control across almost all seasonal comparisons in 2021 and 2022. For CRU-60 d, average yield across combined rates were 45,156, 39,873, 25,666, and 20,395 kg/ha in Spring 2021, Fall 2021, Spring 2022, and Fall 2022, respectively, compared with control yield of 23,112, 28,748, 18,600, and 4708 kg/ha, respectively (Table 2). For CRU-60 d, the 224 N rate often produced the highest yield, where yield was 46.2% and 27.4% higher than the lowest applied N rate (140 kg/ha) in Spring and Fall 2021. However, in 2022, yield differences between N rates were less pronounced due to unfavorable weather conditions (e.g., high heat in spring and frost events in fall), which suppressed yield.

Similarly, CRU-75 d maintained higher yield across seasons, with averages of 48,037, 44,148, 26,062, and 21,652 kg/ha in Spring 2021, Fall 2021, Spring 2022, and Fall 2022, respectively (Table 2). In Spring 2021, Fall 2021, and Spring 2022, there were no significant differences in tomato yield among the N rates for CRU-75 d. However, in Fall 2022, the 224 N rate had a significantly higher yield than the 168 and 140 N rates, yielding 75% more than the 140 N rate and 68% more than the 168 N rate.

Yield differences between CRU-60 d and CRU-75 d could be linked to variations in their coating thicknesses.

Table 2. Contrast analysis for nitrogen (N) sources and their rate on tomato yield (kg/ha) in Spring and Fall 2021 and 2022.

	Spring 2021		Fall 2021		Spring 2022		Fall 2022	
N source/Rate	Estimate	*SE*	Estimate	*SE*	Estimate	*SE*	Estimate	*SE*
Control	23,112	5,731	28,748	4,370	18,600	2,680	4,704	3,371
60-d controlled-release polymer-coated urea								
140	37,113	5,731	37,947	4,370	26,960	2,680	20,139	3,371
168	44,103	5,731	33,325	4,370	26,240	2,680	24,361	3,371
224	54,252	5,731	48,346	4,370	23,797	2,680	16,684	3,371
Contrast *P* values								
Control vs. all rates	0.0012*		0.0269*		0.0169*		0.0001*	
Linear	0.0350*		0.0441*		0.3547		0.3078	
Deviation from linear	0.8567		0.1326		0.9148		0.1865	
75-d controlled-release polymer-coated urea								
140	42,275	5,731	45,112	4,370	24,956	2,680	17,155	3,371
168	48,487	5,731	42,858	4,370	26,945	2,680	17,778	3,371
224	53,348	5,731	44,473	4,370	26,284	2,680	30,024	3,371
Contrast *P* values								
Control vs. all rates	0.0003*		0.0025*		0.0118*		0.0000*	
Linear	0.1837		0.9730		0.7749		0.0033*	
Deviation from linear	0.7215		0.7022		0.6214		0.3659	
Urea								
140	31,589	5,731	38,243	4,370	23,220	2,680	11,580	3,371
168	48,645	5,731	30,324	4,370	29,857	2,680	10,894	3,371
224	36,546	5,731	27,005	4,370	29,605	2,680	12,042	3,371
Contrast *P* values								
Control vs. all rates	0.0179*		0.5295		0.0027*		0.0724	
Linear	0.8334		0.0849		0.1230		0.8866	
Deviation from linear	0.0321*		0.4351		0.1526		0.8353	

CRU-60 d, with a 43% N formulation, features a thinner 3% coating, which accelerates N release and leads to higher yields at elevated application rates, but may reduce efficacy at lower rates. In contrast, CRU-75 d, containing 42% N and a thicker 4% coating releases N more gradually, providing consistent performance across a broader range of application rates. This characteristic enables lower rates of CRU-75 d to achieve yields comparable to higher rates of CRU-60 d. Additionally, environmental factors such as temperature can impact N release rates in CRU. For example, in Fall 2022, the lower temperature might have slowed the N release from CRU-75, requiring higher N application rates to maintain higher yield. This highlights the importance of adjusting N management practices and application rates in response to environmental conditions, especially considering the temperature sensitivity of CRU fertilizers, to optimize crop yield.

Urea treatments also yielded higher than the control, particularly in Spring 2021 and Spring 2022. The average yield for combined rates of urea were 38,926, 31,857, 27,561, and 11,505 kg/ha compared with the control yield of 23,112, 28,748, 18,600, and 4708 kg/ha in Spring 2021, Fall 2021, Spring 2022, and Fall 2022, respectively (Table 2). Seasonal yield variability was significant, with the observed deviation from linearity in Spring 2021 suggesting a possible nonlinear yield response to increasing N rates.

Seasonal conditions had a marked influence on yield outcomes. In 2021, yield for CRU-60 d, CRU-75 d, and urea (Spring 2021) exceeded the Florida fresh market tomato yield standard of 37,660.6 kg/ha (USDA-NASS 2024). Although urea treatments yielded higher than the control in spring seasons, this effect was not consistent across all seasons. In contrast, CRU treatments consistently produced higher tomato yield than the control in all seasons in line with the finding of Mao et al. (2024), who found that use of CRU significantly increased the tomato yield by 60.25% compared with unfertilized plots. The high yield potential affirms CRU effectiveness in surpassing market yield expectations, supporting findings by Qu et al. (2020), who reported an 11.7% yield increase for CRU-treated plots over those treated with regular urea.

However, in 2022, yield across treatments were generally lower. The late Spring 2022 planting exposed tomato plants to higher temperatures, leading to smaller fruit production compared with the more favorable conditions in other seasons (Jalpa 2022). These results indicated the importance of adjusting planting schedules to mitigate potential yield limitations. Despite these challenges, CRU-treated plots continued to show resilience, maintaining yield advantages over both control and urea treatments, suggesting CRU potential for year-round tomato production. This advantage of CRU could be related to their controlled-release mechanism, which mitigates leaching losses, a common issue with soluble urea. Ayankojo and Morgan (2020) noted that fall planting in southern regions can increase frost risk, thus limiting production windows and reducing yield potential. In our study, yield was higher in the plots with CRU application compared with the control and urea, despite being affected by frost in Fall 2022. The ability of CRU to sustain yield under adverse conditions highlights its value as an effective N source that supports climate adaptability.

Although the highest N rate of 224 kg/ha generally corresponded to increased yield, similar benefits were sometimes achieved at lower rates, particularly within the CRU-75 treatment. This outcome is consistent with Zotarelli et al. (2009b), who found that higher N rates do not always produce corresponding yield gains. Instead, optimal N rates appeared to shift depending on seasonal conditions and environmental factors, which may allow for moderate N rates to achieve desirable yield. It was also reported that N rates above 224 kg/ha had no response to tomato yield for drip-irrigated tomato in Florida (Hochmuth and Cordasco 2008). Thus, it may be possible to use lower N rates without compromising yield, leading to more efficient and sustainable N management practices.

Significant differences in tomato yield were observed between compact and conventional beds in 2021 but not in 2022 (Fig. 2). Compact beds produced higher yield in Spring 2021, with an average of 46,217 kg/ha compared with 37,677 kg/ha for conventional beds, possibly due to enhanced root zone water and nutrient access during warm season production. Conversely, in Fall 2021, conventional beds yielded higher at 46,642 kg/ha compared with 28,634 kg/ha for compact beds, potentially due to their greater resilience to cold weather effects. These results align with Holt et al. (2017), who found that although bed size can influence yield outcomes, the effect may vary seasonally.

FRUIT SIZE. The harvested tomato fruits were categorized into three size classes such as small, medium, and marketable (combining the large and extralarge fruit) size where the significant interactions were observed between bed type, YS, treatment, and fruit size class. There is a lot of variability in result and no clear and consistent advantage of any specific N rate or N source over others in terms of marketable yield. Both compact and conventional beds exhibit similar proportions of marketable yield across all N rates and N sources during each season, suggesting that the choice of bed type and fertilizer rate may not impact the marketable yield. When comparing the treatments CRU60, CRU75, and urea, no significant differences in marketable yield proportions are observed across the different fertilizer rates (Figs. 3–5). For instance, in the CRU-60 d treatment, a higher proportion of medium-sized fruits was observed across most rates and bed size in Spring 2021, while the marketable class was higher in Fall 2021 for all rates. In Spring 2022, the proportions of medium and marketable classes were similar across most rates and bed size. Conversely, in Fall 2022, there were no significant differences among the small, medium, and marketable fruit classes across most rates and bed size (Fig. 3). All three treatments perform similarly across all rates, indicating that any of these fertilizers can be effectively used without expecting large differences in marketable yield based on the rate applied. Therefore, the decision on which fertilizer rate to use may depend more on considerations such as cost, environmental impact, and specific crop

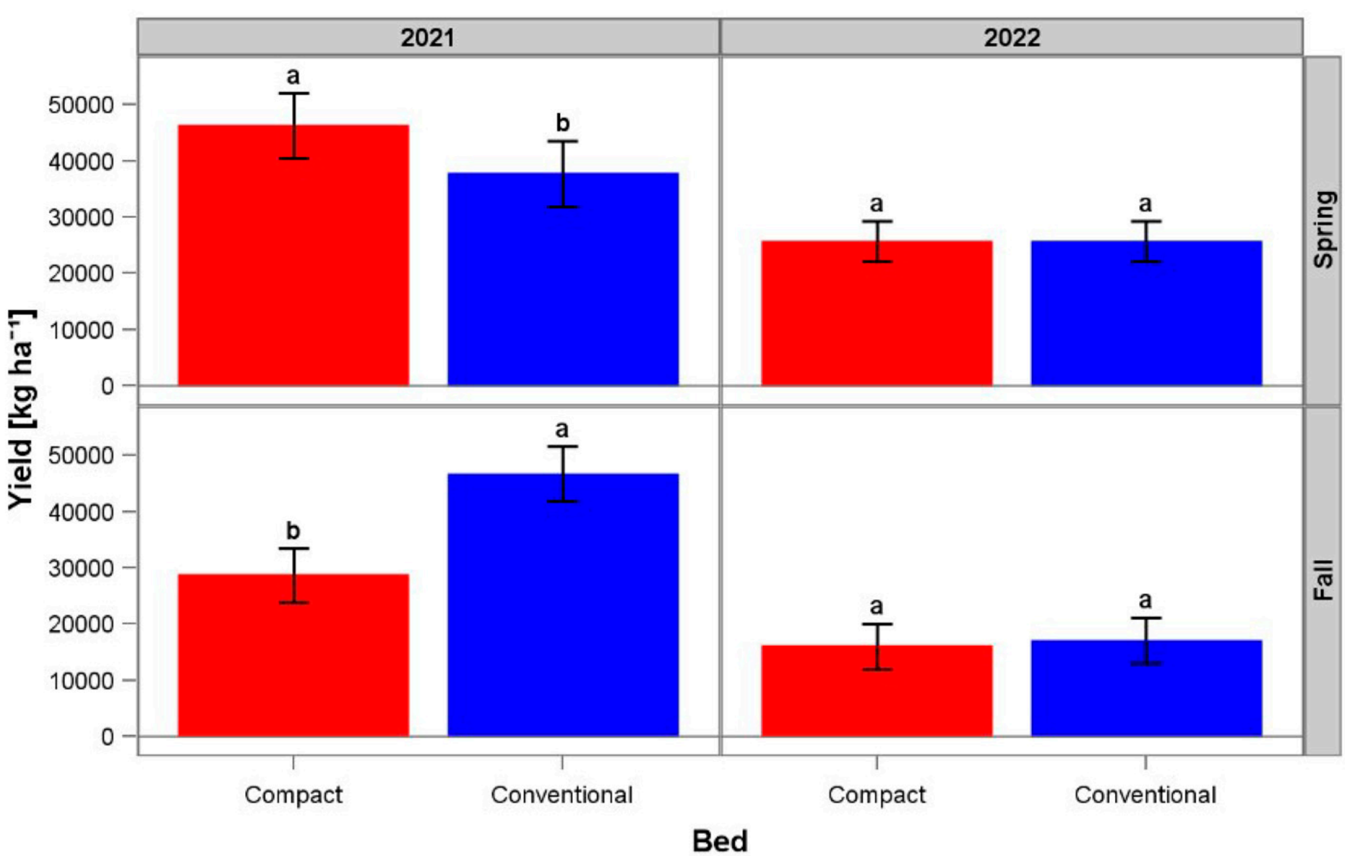

Fig. 2. Tomato yield in different bed sizes in Spring and Fall 2021 and 2022. Error bars indicate the 95% confidence interval for the population mean.

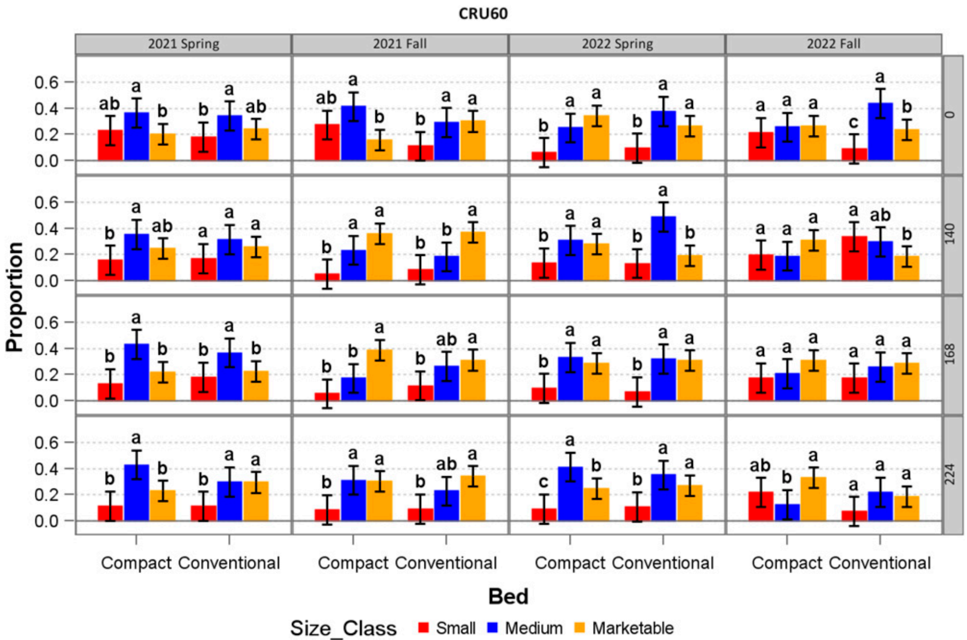

Fig. 3. Fruit size class proportions for different nitrogen rates of controlled-release urea (CRU)-60 in compact and conventional beds in Fall and Spring of 2021 and 2022. Error bars indicate the 95% confidence interval for the population mean.

requirements rather than on differences in fruit class proportions.

Dry matter weight

There were significant interactions between bed type and YS, indicating that DMW varied depending on season and bed type, as well as between YS and treatment, showing that DMW also varied with season and treatments. The average DMW in CRU-60 d was 2970, 2375, 2059, and 2100 kg/ha; CRU-75 d was 3135, 2808, 2073, and 1901 kg/ha; and urea was 2150, 2294, 2209, and 1249 kg/ha DMW compared with 1760, 2427, 1552, and 537 kg/ha in control in Spring and Fall of 2021 and 2022, respectively (Table 3). The DMW of CRU-applied plots were significantly higher than control treatment except in Fall 2021, whereas urea was found to have significantly higher DMW than control treatment in 2022 only. Regarding rate, increasing the N application rates for CRU-60 d increased DMW in 2021 but only in Fall 2022 CRU-75 d. Urea had a linear increase in DMW in Spring 2021 but a linear decrease in Fall 2021. In case of CRU-60 d, the 224 N rate had 22.2% and 37.5% higher DMW than the 140 N rate in Spring and Fall 2021, respectively. In

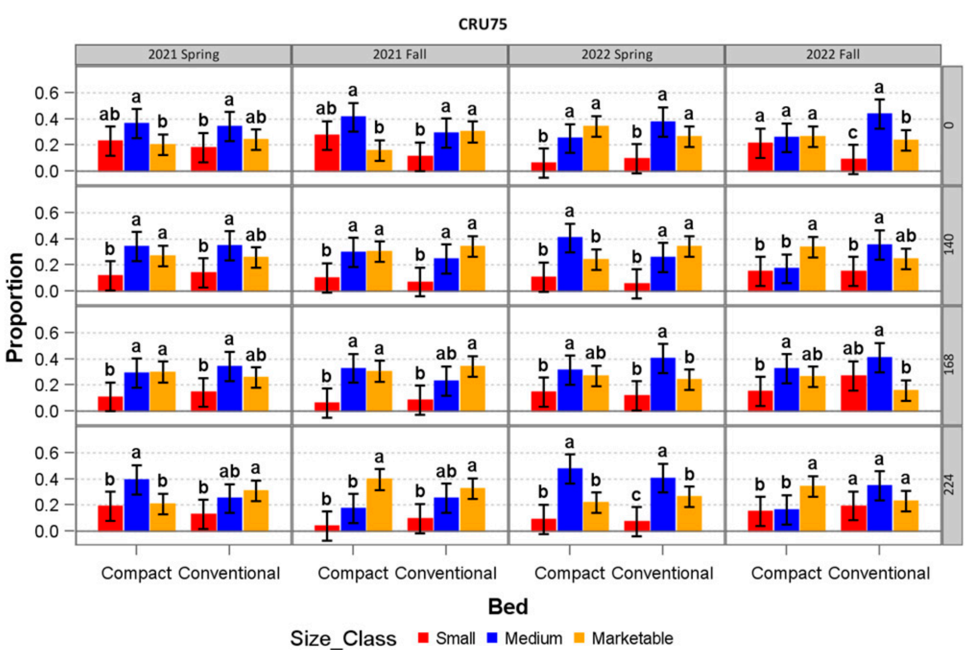

Fig. 4. Fruit size class proportions for different nitrogen rates of controlled-release urea (CRU)-75 in compact and conventional beds in Fall and Spring of 2021 and 2022. Error bars indicate the 95% confidence interval for the population mean.

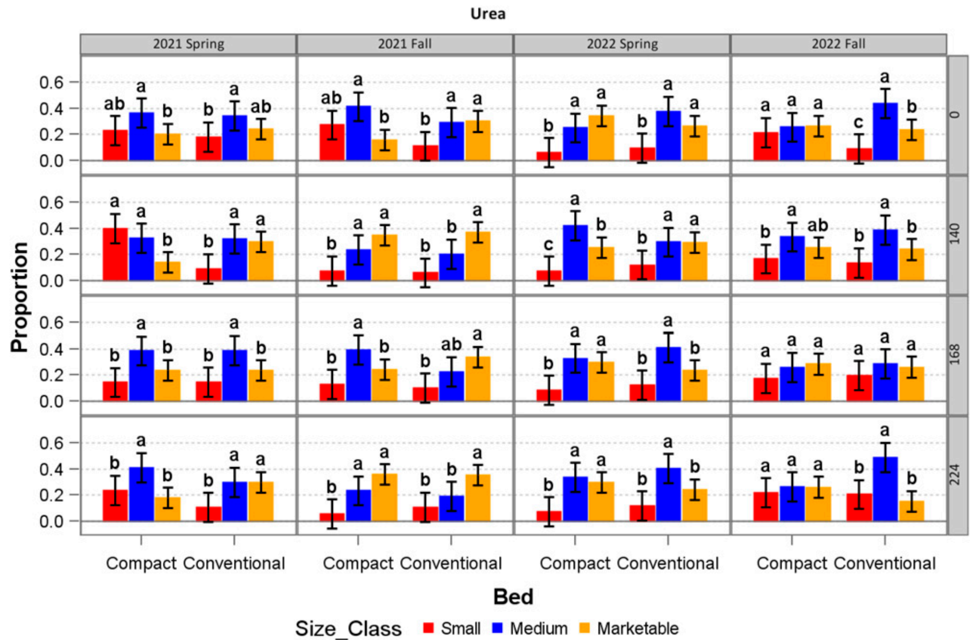

Fig. 5. Fruit size class proportions for different nitrogen rates of controlled-release urea (CRU)-75 in compact and conventional beds in Fall and Spring of 2021 and 2022. Error bars indicate the 95% confidence interval for the population mean.

Fall 2022, the 224 N rate of CRU-75 d had 51.9% higher DMW than the 140 N rate. In a similar previous study by Jalpa (2022) DMW was lower in the spring season compared with the fall season. However, in the current study, we did not observe any seasonal fluctuations of DMW among different rates of N sources.

There was a significant difference in DMW between compact bed and conventional bed in Spring 2021 and Fall 2021, whereas no difference among the beds in 2022 (Fig. 6). In Spring 2021, compact bed had 2944.77 kg/ha DMW, which was higher than 2359.44 kg/ha DMW in conventional bed. In contrast in Fall 2021, conventional bed

Table 3. Contrast analysis for nitrogen (N) sources and their rate on whole plant (leaves, stem, root, and fruit) dry matter weight (kg/ha) in Spring and Fall 2021 and 2022.

	Spring 2021		Fall 2021		Spring 2022			Fall 2022
N source/Rate	Estimate	*SE*	Estimate	*SE*	Estimate	*SE*	Estimate	*SE*
Control	1,760	238.4	2,427	263.3	1,552	238.4	537	238.4
60-d controlled-release polymer-coated urea								
140	2,746	238.4	2,136	238.4	2,144	238.4	2,001	238.4
168	2,805	238.4	2,053	263.0	2,112	262.7	2,231	238.4
224	3,358	238.4	2,936	263.3	1,921	238.4	2,068	262.7
Contrast *P* values								
Control vs. all rates	0.0000*		0.8467		0.0398*		0.0000*	
Linear	0.0286*		0.0064*		0.4263		0.9427	
Deviation from linear	0.5768		0.2239		0.8821		0.4312	
75-d controlled-release polymer-coated urea								
140	2,854	238.4	3,024	262.9	2,048	238.4	1,523	238.4
168	3,293	238.4	2,639	263.0	2,132	238.4	1,867	238.4
224	3,256	238.4	2,762	263.0	2,039	238.4	2,313	238.4
Contrast *P* values								
Control vs. all rates	0.0000*		0.1664		0.0329*		0.0000*	
Linear	0.2472		0.5495		0.9251		0.0088*	
Deviation from linear	0.2435		0.3131		0.7384		0.7549	
Urea								
140	1,808	238.4	2,756	263.3	2,011	238.4	1,265	238.4
168	2,189	238.4	2,287	263.0	2,281	238.4	1,226	238.4
224	2,452	238.4	1,838	238.4	2,334	238.4	1,257	238.4
Contrast *P* values								
Control vs. all rates	0.1083		0.6210		0.0075*		0.0038*	
Linear	0.0381*		0.0048*		0.3221		0.9983	
Deviation from linear	0.5230		0.5770		0.5346		0.8878	

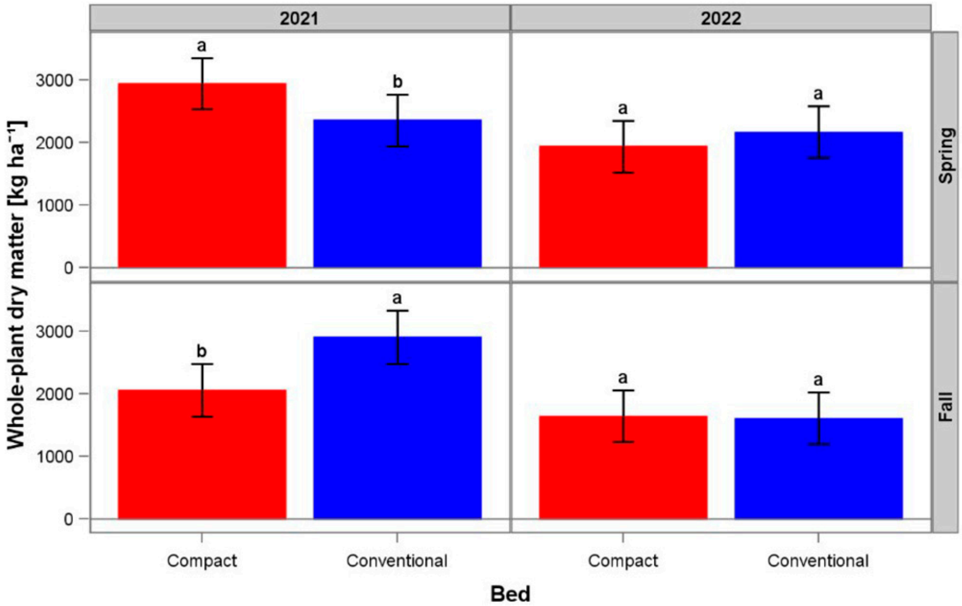

Fig. 6. Dry matter weight in different bed sizes in Spring and Fall 2021 and 2022. Error bars indicate the 95% confidence interval for the population mean.

had 2906.47 kg/ha DMW, which was higher than 2065.25 kg/ha DMW in compact bed. The higher DMW observed in the compact beds during spring may be attributed to warm season production, as well as the increased volume of compact beds, which could enhance water and nutrient contact with the root system, thereby benefiting DMW. Conversely, the lower DMW in the compact beds during fall could be due to the taller beds being less suitable in cooler temperatures, likely due to increased exposure to ambient weather conditions. The result of tomato yield in different bed size correlates with DMW, as both yield and DMW were higher in compact beds than in conventional beds in Spring 2021. Conversely, conventional beds had higher yield and DMW than compact beds in Fall 2021; however, no significant differences were observed in either yield or DMW across both bed types in the 2022 seasons. The total fruit yield in tomato was strongly correlated with the total dry biomass produced, indicating that the crop adjusts its fruit biomass in proportion to the overall accumulated biomass (Patanè et al. 2011). Zotarelli et al. (2009b) also found a similar trend in which higher tomato aboveground biomass was associated with higher fruit yield. In a study by Andersen et al. (1999), the DMW of two tomato varieties in 1996 and 1997 ranged from 2700 kg/ha to 3200 kg/ha under N rates of 67 to 269 kg/ha. In our study, N rates of 140 to 224 kg/ha produced similar DMW in the compact beds during Spring 2021 and the conventional beds during Fall 2021. In Fall 2022, the field experienced a frost event before harvest, while in Spring 2022 there was delayed planting due to technical issues, which likely contributed to low DMW and yield in 2022.

N accumulation

There were significant interactions between treatment and YS, suggesting that N accumulation varied depending on the season and treatments as well as between the bed and YS, which suggest N accumulation might also vary by the different bed size over time. The average N accumulation of combined rates of CRU-60 d was 95.5, 64.7, and 67.5 kg/ha and CRU-75 d was 99.5, 66.9, and 57.1 kg/ha compared with 54.0, 42.5, and 9.6 kg/ha of control treatment in the Spring season of 2021 and 2022 and Fall 2022, respectively, but was not significant in Fall 2021 (Table 4). However, for CRU-60 d, 224 N rate had 59.8% higher N accumulation than 140 N rate and 47.9% higher N accumulation than 168 N rate in Fall 2021 only. Similarly, for CRU-75 d, 224 N rate had 66.3% higher N accumulation than 140 N rate and 35.6% higher N accumulation than 168 N rate in Fall 2022 only.

The average N accumulation of combined rates of urea was 61.1, 30.0 compared with 42.5 and 9.6 kg/ha of control treatment in Spring 2022 and Fall 2022 but was not significant in Spring and Fall 2021 (Table 4). Furthermore, there were no significant differences in N accumulation among the N rates for urea in both years.

Overall, in our study, the mean N accumulation for CRU-60 d ranged from 46.52 to 109.64 kg/ha, whereas CRU-75 d ranged between 44.03 and 104.39 kg/ha across various seasons. In comparison, N accumulation from urea varied between 28.89 and 69.64 kg/ha. In a study conducted from 2005 to 2007 under a different growing season in Florida, total N accumulation in tomato grown using different N rates (176 to 330 kg/ha) ranged from 66.7 to 166 kg/ha (Zotarelli et al. 2009a). Significant effects of N source and N rate were observed in Spring seasons of 2021 and 2022, and Fall 2022, for both the CRUs treatment showed significantly higher N accumulation compared with the control. Tian et al. (2022) also found higher N accumulation in CRU treatments compared with untreated control in rice. This result aligns with the expectation that CRU enhances N uptake efficiency by providing a sustained release of N, thereby reducing potential losses due to leaching or denitrification. The higher accumulation during these seasons also suggests that tomato

Table 4. Contrast analysis for nitrogen (N) sources and their rate on N accumulation (kg/ha) in Spring and Fall 2021 and 2022.

	Spring 2021		Fall 2021		Spring 2022		Fall 2022	
N source/Rate	Estimate	*SE*	Estimate	*SE*	Estimate	*SE*	Estimate	*SE*
Control	53.98	9.04	55.70	9.82	42.46	6.80	9.56	6.92
60-d controlled-release polymer-coated urea								
140	90.37	9.04	46.52	8.94	66.18	6.80	64.33	6.92
168	86.46	9.04	50.27	9.82	70.49	7.91	71.18	6.92
224	109.64	8.99	74.38	8.53	57.42	7.06	66.87	8.16
Contrast *P* values								
Control vs. all rates	0.0001*		0.9015		0.0052*		0.0000*	
Linear	0.0840		0.0167*		0.2763		0.9044	
Deviation from linear	0.3532		0.6353		0.4329		0.4816	
75-d controlled-release polymer-coated urea								
140	92.30	9.32	78.22	9.87	65.27	5.84	44.03	7.22
168	101.90	9.04	62.53	9.82	72.40	6.80	54.00	6.92
224	104.39	9.32	56.86	9.88	62.89	5.84	73.26	7.22
Contrast *P* values								
Control vs. all rates	0.0000*		0.3654		0.0015*		0.0000*	
Linear	0.3938		0.1533		0.6030		0.0036*	
Deviation from linear	0.6203		0.4798		0.3114		0.9786	
Urea								
140	43.27	5.61	55.15	5.97	55.46	6.80	30.33	6.92
168	59.85	6.16	44.85	5.61	58.12	5.84	28.89	7.22
224	47.90	5.61	61.51	5.61	69.64	6.80	30.87	6.92
Contrast *P* values								
Control vs. all rates	0.1761		0.5614		0.0152*		0.0101*	
Linear	0.1230		0.2772		0.1119		0.9240	
Deviation from linear	0.3930		0.9490		0.7814		0.8515	

plants had greater N demand during periods of active growth, which the CRU was able to meet effectively. In contrast, in Fall 2021, there were no significant differences between the control and N treatments, which could possibly be due to environmental factors, such as the higher rainfall event near the transplanting period in Fall 2021, compared with Fall 2022, which may have reduced N accumulation in Fall 2021. This observation aligns with a study by Rowlings et al. (2022), which found that early-season rainfall, occurring before small plants were able to absorb significant amounts of N, could result in substantial N losses. Linear trends for N accumulation were not significant across most treatments, indicating that increasing N rates did not result in proportional increases in N percentage or accumulation. This suggested that the tomato plant reached a point of adequacy beyond which N accumulation was not seen, likely due to physiological limitations or environmental constraints.

There was significant difference in N accumulation between compact bed and conventional bed in Spring 2021 and Fall 2021, whereas no difference was observed among the beds in both seasons of 2022 (Fig. 7). In Spring 2021, compact bed had 92.3 kg/ha N accumulation compared with 76.25 kg/ha N accumulation in the conventional bed. In contrast, in Fall 2021, conventional bed had 68.56 kg/ha N accumulation compared with 45.87 kg/ha N accumulation in compact bed.

C accumulation

There was a significant difference in treatment and YS interaction suggesting that C accumulation varied depending on the season and treatments. In addition, the bed and YS interaction was also significantly different. This indicates that C accumulation might not have been solely driven by the treatment, but also by the differences in growing conditions (e.g., soil depth, temperature, moisture) between the different-size beds, which could have varied over time.

The average C accumulation of combined rates of CRU-60 d was 1170.2, 831.2, and 816.1 kg/ha and CRU-75 d was 1218.5, 834.4, and 739.5 kg/ha compared with 679.7, 615.5, and 205.9 kg/ha of control treatment in Spring 2021 and 2022 and the fall season of 2022, respectively, but was not significant in Fall 2021 (Table 5). However, for CRU-60 d, 224 N rate had 33.8% higher C accumulation than the 140 N rate and 38.8% higher C accumulation than the 168 N rate in Fall 2021 only. Similarly, for CRU-75 d, 224 N rate had 50.2% higher C accumulation than 140 N rate and 27.0% higher C accumulation than 168 N rate in Fall 2022 only.

The average C accumulation of combined rates of urea was 864.4 and 482.9 compared with 615.5 and 205.9 kg/ha of control treatment in Spring 2022 and Fall 2022, respectively, but was not significant in Spring and Fall 2021 (Table 5). In Fall 2021, 140 N rate had 46.42% higher C accumulation than 244 N rate and 168 N rate had 25.17% higher C accumulation than 244 N rate. In case of urea, as the N rate increases the C accumulation decreases in Fall 2021. However, in Spring 2021 and 2022 and Fall 2022 there were no significant differences in C accumulation among the N rates for urea.

Overall, the mean C accumulation for CRU-60 d ranged from 778.61 to

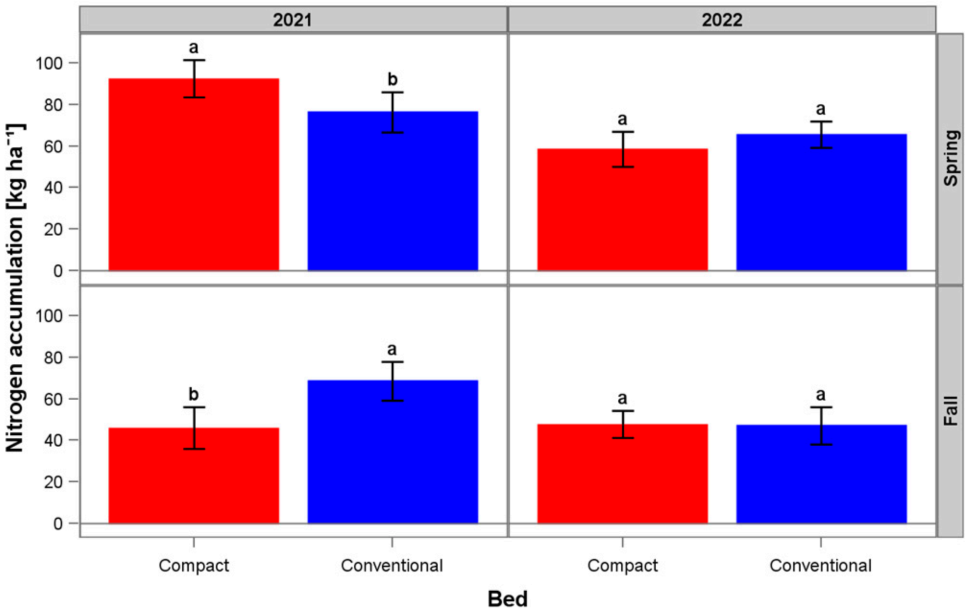

Fig. 7. Nitrogen accumulation in different bed sizes in Fall and Spring 2021 and 2022. Error bars indicate the 95% confidence interval for the population mean.

1321.4 kg/ha, whereas CRU-75 d ranged between 602.15 and 1285.7 kg/ha across various seasons. In comparison, C accumulation from urea varied between 481.67 and 1016.35 kg/ha. Significant effects of N source and N rate were observed in Spring 2021 and 2022, and Fall 2022, for both the CRU-60 d and CRU-75 d treatments and showed significantly higher C accumulation compared with the control. In a previous study by Jalpa (2022), the average C accumulation at tomato harvest ranged from 1230 to 1783 kg/ha for similar rates and sources of fertilizers during the 2019 to 2021 seasons. These data are higher than the data observed in our study.

Table 5. Contrast analysis for nitrogen (N) sources and their rate on C accumulation (kg/ha) in Spring and Fall 2021 and 2022.

	Spring 2021		Fall 2021		Spring 2022		Fall 2022	
N source/Rate	Estimate	*SE*	Estimate	*SE*	Estimate	*SE*	Estimate	*SE*
Control	679.72	100.23	928.25	115.12	615.51	83.58	205.93	81.56
60-d controlled-release polymer-coated urea								
140	1084.09	100.23	807.60	101.88	866.88	83.58	780.01	81.56
168	1105.02	100.23	778.61	115.11	855.82	99.29	864.71	81.56
224	1321.40	100.45	1081.31	98.43	770.92	86.84	803.70	95.68
Contrast *P* values								
Control vs. all rates	0.0000*		0.7604		0.0262*		0.0000*	
Linear	0.0701		0.0303*		0.3870		0.9527	
Deviation from linear	0.6350		0.3754		0.8552		0.4423	
75-d controlled-release polymer-coated urea								
140	1115.71	102.68	1138.70	114.49	835.42	73.43	602.15	85.23
168	1253.99	100.23	1024.52	115.12	858.99	83.58	711.94	81.56
224	1285.70	102.68	1033.97	114.50	808.73	73.44	904.42	85.24
Contrast *P* values								
Control vs. all rates	0.0000*		0.2952		0.0188*		0.0000*	
Linear	0.2768		0.5762		0.7322		0.0103*	
Deviation from linear	0.5095		0.5747		0.7365		0.9281	
Urea								
140	699.30	100.23	1016.35	115.12	799.21	83.58	481.67	81.56
168	853.79	102.68	868.84	114.50	858.81	73.44	493.59	85.24
224	944.67	100.23	694.12	101.88	935.20	83.58	473.46	81.56
Contrast *P* values								
Control vs. all rates	0.1808		0.5972		0.0085*		0.0032*	
Linear	0.0949		0.0348*		0.2378		0.9176	
Deviation from linear	0.5596		0.7743		0.8777		0.8852	

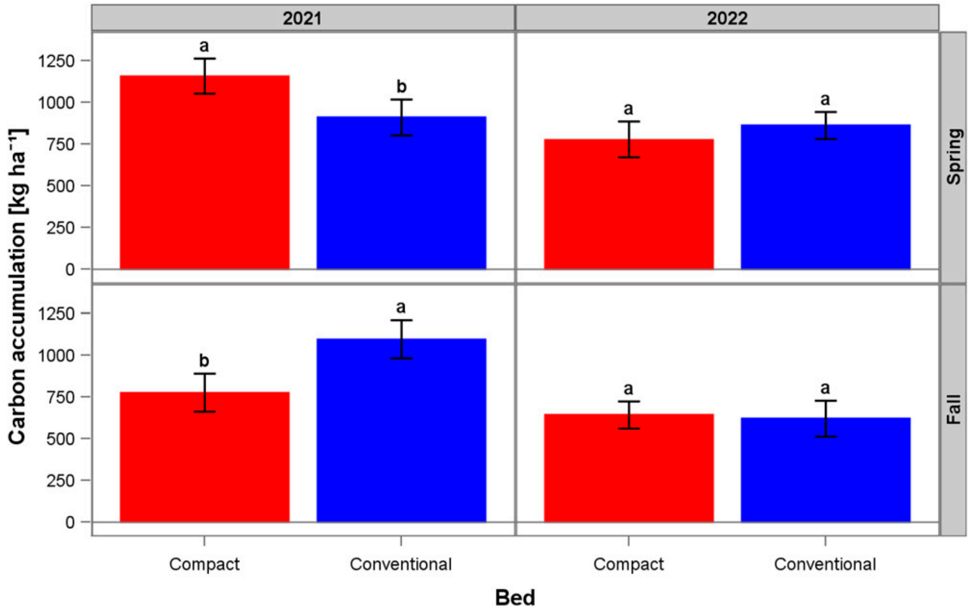

Fig. 8. Carbon accumulation in different bed sizes in Fall and Spring 2021 and 2022. Error bars indicate the 95% confidence interval for the population mean.

There was a significant difference in C accumulation between compact bed and conventional bed in Spring 2021 and Fall 2021, whereas no difference was observed among the beds in both seasons of 2022 (Fig. 8). In Spring 2021, compact bed had 1157.85 kg/ha C accumulation compared with 910.83 kg/ha C accumulation in conventional bed. In contrast, in Fall 2021, conventional bed had 1097.38 kg/ha C accumulation compared with 777.07 kg/ha C accumulation in compact bed. Our result suggested that N sources and bed size did not influence the plant C% except once with CRU-60 d but the difference was minimal. Previous findings suggested that N fertilization helps to improve C storage in plants by enhancing the enzyme activities related to C assimilation (Lin et al. 2013). In our study, despite having no difference among treatments for C%, we found higher C accumulation in CRU-applied plots compared with control, which suggests improved enzyme activities because of N application. Because there were no consistent results regarding bed size in our study, we expect season-specific effects of bed size for C accumulation in tomato.

C:N ratio

There was a significant difference in treatment and YS interaction, suggesting that C:N ratio varied depending on the season and treatments. The average C:N ratio of combined rates of CRU-60 d was 12.19, CRU-75 d was 13.50, and urea was 16.72 compared with 23.42 of control treatment in Fall 2022 but was not significant in Spring 2021 and 2022 and Fall 2021 (Table 6). There were no significant differences in C:N ratio among the N rates for both CRUs and urea for all seasons of both years.

The difference in C:N ratio observed between N source and control at the Fall 2022 season for all treatments may indicate a cumulative effect of multiple years of fertilizer application at the experiment location. Our observations in Fall 2022 align with the findings of Andersen et al. (1999), in which the C:N ratio decreased with fertilizer application compared with control treatments because of the strong positive influence of fertilization on N accumulation in tomato plants. A previous study conducted on the same experimental site also had a higher C:N ratio in the unfertilized treatment compared with the fertilized plots (Jalpa and Mylavarapu 2023). The decrease in the C:N ratio with fertilizer application corresponds with enhanced N uptake, which improves plant growth and productivity by ensuring a more balanced supply of essential nutrients. However, the observation that different rates of N application did not significantly change the C:N ratio implies that even lower levels of fertilizer application can effectively influence this balance, thereby potentially reducing the need for high doses of fertilizers.

Impact of N treatments on plant use efficiency

Nitrogen use efficiency. There was a significant difference in treatment and YS interaction suggesting that NUE varied depending on the season and treatments. However, in case of bed size, no difference was found in NUE between compact and conventional beds.

Significant differences in NUE were observed among the different N rates of CRU-60 d fertilizer across the Spring seasons of 2021 and 2022, and Fall 2022, but not in Fall 2021 (Table 7). In Spring 2021, the 140 N rate resulted in 29.5% higher NUE compared with the 224 N rate and 25.4% higher NUE compared with the 168 N rate. The trend continued in Spring 2022, with the 140 N rate exhibiting 82.9% higher NUE compared with the 224 N rate and 14.5% higher NUE compared with the 168 N rate. Similarly, in Fall 2022, the 140 N rate showed 48.6% higher NUE compared with the 224 N rate and 8.4% higher NUE compared with the 168 N rate.

Significant differences in NUE were observed among the different N rates of CRU-75 d fertilizer across the Spring seasons of 2021 and 2022 and Fall 2021, but not in Fall 2022 (Table 7). In Spring 2021, the 140 N rate resulted in 39.9% higher NUE than

Table 6. Contrast analysis for nitrogen (N) sources and their rate on C:N ratio in Spring and Fall 2021 and 2022.

	Spring 2021		Fall 2021		Spring 2022		Fall 2022	
N source/Rate	Estimate	*SE*	Estimate	*SE*	Estimate	*SE*	Estimate	*SE*
Control	12.70	1.30	16.62	1.76	14.53	1.50	23.42	0.93
60-d controlled-release polymer-coated urea								
140	12.11	1.30	19.02	1.76	13.29	1.50	12.15	0.93
168	12.86	1.30	19.69	1.76	12.29	1.79	12.24	0.93
224	11.88	1.30	16.61	1.48	13.63	1.51	12.17	1.04
Contrast *P* values								
Control vs. all rates	0.7833		0.3656		0.4098		0.0000*	
Linear	0.8194		0.2222		0.7840		0.9962	
Deviation from linear	0.6121		0.4974		0.5998		0.9482	
75-d controlled-release polymer-coated urea								
140	12.27	1.30	13.93	1.76	13.14	1.50	14.40	0.93
168	12.29	1.30	18.14	1.76	11.92	1.50	13.58	0.93
224	12.41	1.30	19.22	1.76	12.65	1.50	12.50	0.93
Contrast *P* values								
Control vs. all rates	0.8059		0.8126		0.2611		0.0000*	
Linear	0.9362		0.0536		0.8991		0.1507	
Deviation from linear	0.9862		0.2670		0.5767		0.8722	
Urea								
140	12.66	1.30	17.66	1.76	14.49	1.50	15.84	0.93
168	12.31	1.35	21.73	1.93	14.35	1.17	17.97	0.94
224	12.61	1.30	16.91	1.76	13.57	1.50	16.36	0.93
Contrast *P* values								
Control vs. all rates	0.9091		0.2967		0.8187		0.0000*	
Linear	0.9890		0.4944		0.6464		0.9339	
Deviation from linear	0.8415		0.0672		0.9213		0.0961	

the 224 N rate and 7.0% higher NUE than the 168 N rate. Similarly, in Fall 2021, the 140 N rate showed 125% higher NUE compared with the 224 N rate and 62.3% higher NUE compared with the 168 N rate. In Spring 2022, the 140 N rate resulted in 60.9% higher NUE than the 224 N rate and 7.3% higher NUE than 168 N rate.

Table 7. Contrast analysis for nitrogen (N) sources and their rate on NUE (%) in Spring and Fall 2021 and 2022.

	Spring 2021		Fall 2021		Spring 2022		Fall 2022	
	Estimate	*SE*	Estimate	*SE*	Estimate	*SE*	Estimate	*SE*
N source/ Rate				%				
60-d controlled-release polymer-coated urea								
140	64.55	4.75	33.23	4.94	47.27	4.58	45.95	4.38
168	51.46	4.75	27.50	5.52	41.28	5.19	42.37	4.38
224	49.82	4.75	33.92	4.91	25.84	4.71	30.92	4.92
Contrast *P* values								
Linear	0.0234*		0.7396		0.0002*		0.0071*	
Deviation from linear	0.1089		0.3115		0.8317		0.7544	
75-d controlled-release polymer-coated urea								
140	64.92	4.75	56.94	5.36	46.28	4.23	30.77	4.51
168	60.65	4.75	35.07	5.52	43.09	4.58	32.14	4.38
224	46.38	4.75	25.20	5.36	28.76	4.23	32.63	4.51
Contrast *P* values								
Linear	0.0012*		0.0000*		0.0003*		0.7456	
Deviation from linear	0.7051		0.0659		0.5667		0.8697	
Urea								
140	39.51	4.75	39.00	5.52	39.61	4.58	21.66	4.38
168	41.75	4.75	29.87	5.36	35.66	4.23	16.63	4.51
224	34.20	4.75	18.61	4.94	31.09	4.58	13.78	4.38
Contrast *P* values								
Linear	0.2754		0.0023*		0.1240		0.1451	
Deviation from linear	0.4283		0.6958		0.8032		0.6036	

In terms of urea, significant differences in NUE were observed among the different N rates only in Fall 2021 (Table 7). The 140 N rate resulted in 109.5% higher NUE than 224 N rate and 30.5% higher NUE than 168 N rate.

The average NUE for the 140 N rate across most of the seasons and N sources was consistently higher compared with the 168 and 224 N rates. This suggested that lower rates of N fertilizer led to higher NUE, particularly when using CRU formulations. This might be due to the reduced risk of leaching from lower N rates of CRU and split doses of urea, which helped synchronize N release with plant growth and N demand, promoting efficient N use. Using optimum N rates might encourage proper root development, leading to more efficient nutrient utilization. This higher NUE is also economically beneficial for farmers in terms of saving production costs and fertilizer input while simultaneously achieving comparable or even improved crop yields. The observed trend, with a lower rate showing consistently higher NUE across multiple seasons for CRUs, highlights the importance of carefully considering fertilizer rates and application timing to optimize NUE, minimize environmental impacts, and maximize profitability. This trend is supported by the article by Zotarelli et al. (2009a), in which NUE was significantly higher when lower N rates were applied. As the N rate application increased, the N availability may have gone beyond the saturation point, where additional N did not contribute to enhanced growth or yield.

Apparent N recovery. APR indicates the proportion of applied N that is recovered by plants from the soil. Higher APR indicates a greater portion of the applied N is absorbed by the plant rather than being lost to the environment through leaching, volatilization, and denitrification. There was a significant difference in treatment and YS interaction, suggesting that APR varied depending on the season and treatments. However, in the case of bed size, no difference was found in APR between compact and conventional beds.

Significant differences in APR were observed among the N rates of CRU 60-d fertilizer across Fall 2021 and 2022, but not in Spring 2021 and 2022 (Table 8). In Fall 2021, the APR was −11.39%, −0.63%, and 9.06% for the 140, 168, and 224 N rates, respectively. A zero APR value means that N accumulation in unfertilized (control) plots is not different from that in fertilized plots, suggesting that the available soil N was sufficient, and the N fertilizer inputs were excessive and unnecessary to meet the crop's N requirement (Craswell and Godwin 1984; Mengel et al. 2006). In our study, we observed negative APR values at higher N rates during some seasons, indicating that N fertilizer inputs exceeded crop uptake needs. Importantly, crop yield and N accumulation were not negatively affected, suggesting that sufficient N was available to meet plant demand. Thus, the low APR values likely reflect excess N fertilizer rather than environmental limitations on uptake. This unused N remains under the plastic mulch and is susceptible to in-season losses, such as leaching via drip irrigation. In addition, after the tomato season ends, the plastic is removed, and fields are typically left fallow for several months. During this period, rainfall may mobilize residual soil N, increasing the risk of post-season losses to the environment.

In Fall 2022, the 140 N rate for CRU-60 d showed higher APR (39.12%) compared with the higher rates of 168 (36.68%) and 224 N (26.91%), suggesting better N utilization at lower application doses. This indicates the higher recovery at lower rates in this season. In a similar study by Jalpa et al. (2020) and Jalpa and Mylavarapu (2021), a higher APR was observed for lower N rate applied in

Table 8. Contrast analysis for nitrogen (N) sources and their rate on APR (%) in Spring and Fall 2021 and 2022.

	Spring 2021		Fall 2021		Spring 2022		Fall 2022	
	Estimate	*SE*	Estimate	*SE*	Estimate	*SE*	Estimate	*SE*
N source/Rate				%				
60-d controlled-release polymer-coated urea								
140	25.99	5.72	−11.39	6.57	16.94	5.46	39.12	5.36
168	19.33	5.72	−0.63	7.79	15.73	5.96	36.68	5.36
224	25.72	5.72	9.06	6.08	6.68	5.56	26.91	5.82
Contrast *P* values								
Linear	0.8441		0.0024*		0.0502		0.0279*	
Deviation from linear	0.2080		0.5891		0.6767		0.7231	
75-d controlled-release polymer-coated urea								
140	26.47	5.73	16.08	6.90	15.51	5.17	23.97	5.46
168	28.52	5.72	3.25	7.79	17.82	5.46	26.46	5.36
224	22.31	5.73	−0.40	6.91	9.93	5.17	28.34	5.46
Contrast *P* values								
Linear	0.3977		0.0489*		0.1696		0.4310	
Deviation from linear	0.5086		0.3319		0.3575		0.8220	
Urea								
140	0.95	5.72	−1.54	6.57	9.28	5.46	14.83	5.36
168	9.67	5.73	1.62	6.91	10.79	5.17	10.92	5.46
224	10.10	5.72	−8.81	6.57	12.13	5.46	9.51	5.36
Contrast *P* values								
Linear	0.1720		0.2137		0.6017		0.3366	
Deviation from linear	0.2764		0.3861		0.8989		0.6457	

spring tomato and APR was similar in fall tomato for all N rates, indicating that application rates above the lowest rate were more than sufficient for crop growth.

Significant differences in APR were observed among the different N rates of CRU-75 d fertilizer across Fall 2021, but not in Spring 2021 and 2022 and Fall 2022 (Table 8). In Fall 2021, the 224 N rate resulted in the lowest APR of −0.4%, followed by 3.25% in the 168 N rate, and 16.08% in the 40 N rate. No significant differences in APR were observed among the different N rates of urea across all seasons of both years (Table 8).

The data show that both CRU-60 d and CRU-75 d treatments generally exhibited higher APR compared with conventional urea across different seasons. The lack of significant APR differences among urea rates across seasons is likely due to the crop's N demand not aligning with the timing or quantity of N provided, even when urea was applied in 13 split doses. These concentrated doses may have still exceeded crop needs at specific times, leading to limited uptake and potential loss. In contrast, the one-time preplant application of CRU provided a gradual and sustained N release that more closely matched the tomato crop's N uptake pattern. This improved synchronization likely contributed to the more distinct APR differences observed among CRU rates across seasons.

In the case of bed size (compact vs. conventional), there was no significant difference observed in all seasons. This suggested that the size of the bed was not a significant factor that affects spring and fall tomato APR. Although bed size did not significantly affect APR in this study, future research could investigate whether compact beds offer agronomic or environmental benefits under different soil types, irrigation strategies, or extreme weather conditions. Long-term studies that evaluate soil nutrient dynamics, residual nitrogen losses, or economic trade-offs between bed systems may help clarify whether compact beds provide advantages beyond nitrogen productivity, particularly in climates or production systems with higher risk of waterlogging or nutrient leaching.

Conclusion

Polymer-coated CRU has an advantage over soluble urea for sustainable and efficient tomato production. Our study demonstrated that CRU treatments consistently produced higher tomato yields compared with control and urea treatments across four seasons, even during adverse weather events such as delayed planting and frost that reduced overall yields in 2022. This suggested CRU could be used in tomato production to achieve marketable yields under challenging production conditions. In addition, CRU treatment resulted in higher C and N accumulation and improved NUE in tomato plants, indicating its effectiveness in enhancing N use. Moreover, CRU fertilizer offers potential economic benefits by reducing time, energy, and labor costs, as it requires only a single preplant application compared with the multiple applications needed for soluble urea. In addition to improving operational efficiency, CRUs could help address environmental concerns by minimizing N losses through leaching, especially in sandy soils. If state agencies provided financial incentives to offset the higher upfront cost, broader adoption of CRUs could support more sustainable and environmentally responsible tomato production in north Florida.

Despite higher yields associated with higher N application rates of CRU in some seasons, N and C accumulation did not consistently increase linearly with increasing application rates. This indicates a potential saturation point in tomato plant nutrient uptake, possibly due to environmental or physiological constraints. Moreover, lower application rates resulted in higher NUE across multiple seasons for CRUs. Thus, applying lower N rates promotes efficient nutrient use, reduces environmental losses, and enhances economic benefits.

Compact beds may not be beneficial compared with conventional beds in north Florida, due to their inconsistent effect on tomato yield, N and C accumulation, and no significant impact on NUE and APR. The tall and narrow compact beds with larger volume may be exposed to winter frost risk and higher air circulation, making them unsuitable for north Florida. They might also require extra costs for re-tooling machinery, increasing production costs and decreasing profitability. Overall, adoption of CRUs for tomato production in conventional beds, with consideration of environmental conditions and optimal N rates, would help maximize production efficiency and profitability. Future research should be focused on the long-term environmental impacts of CRUs, the degradation rate of their polymer coatings, and effect on soil health and N leaching to ensure sustainability in agricultural practices.

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