HortScience 59(4):442–452. 2024. https://doi.org/10.21273/HORTSCI17679-23

Nitrogen Use Efficiency and Yield Levels Using Soluble and Controlled-release Urea Formulations in Tomato Production

Laura Jalpa, Rao S. Mylavarapu, and George Hochmuth
Soil, Water, and Ecosystem Sciences Department, University of Florida, Gainesville, FL 32611, USA

Yuncong Li
Soil, Water, and Ecosystem Sciences Department, Tropical Research and Education Center, IFAS, University of Florida, Homestead, FL 33031, USA

Bala Rathinasabapathi
Horticultural Sciences Department, University of Florida, Gainesville, FL 32611, USA

Edzard van Santen
Department of Agronomy and IFAS Statistical Consulting Unit, University of Florida, Gainesville, FL 32611, USA

Keywords. CRF, N management, N sources, nitrogen use efficiency, *Solanum lycopersicum*, sustainable vegetable production, urea

Abstract. **This research study evaluated the suitability of controlled-release urea (CRU) as an alternate nitrogen (N) fertilizer source to conventional soluble urea (U) for tomato production under a humid, warm climate in coastal plain soils. Tomatoes are typically produced on raised plastic-mulched beds, where U is fertigated through multiple applications. On the other hand, CRU is applied once at planting, incorporated into soil before the raised beds are covered with plastic mulch. N source and management will likely impact tomato yield, N use efficiency (NUE), and apparent recovery of N fertilizer (APR). A 2-year field study was conducted on fall and spring tomato crops in north Florida to determine the crop N requirement and NUE in tomatoes (var. HM 1823) grown in sandy soils under a plastic-mulched bed system. In addition to a no N fertilizer treatment, three urea N sources [one soluble source and two polymer-coated CRU sources with different N release durations of 60 (CRU-60) and 75 (CRU-75) days] were applied at three N rates (140, 168, and 224 kg·ha^{-1}). Across all N sources and N rates, fall yields were at least 20% higher than spring seasons. At the 140 kg·ha^{-1} N rate, APR and NUE were improved, especially when U was applied in fall tomato, whereas preplant CRUs improved N efficiency in spring tomato. Based on the lower APR values found in spring production seasons (0% to 16%) when compared with fall (57.1% to 72.6%), it can be concluded that residual soil N was an important source for tomatoes. In addition, the mean whole-plant N accumulation of tomato was 102.5 kg·ha^{-1}, further indicating that reducing the N rate closer to crop N demand would greatly improve conventional vegetable production systems on sandy soils in north Florida. In conclusion, polymer-coated CRU and fertigation U applications were able to supply the N requirement of spring and fall tomato at a 38% reduction of the recommended N rate for tomato in Florida (224 kg·ha^{-1}). Preliminary results show that adoption of CRU fertilizers can be considered a low-risk alternative N source for tomato production and the ease of applying CRU once during the bed preparation period for tomato may be an additional incentive.**

Global vegetable production grew 65% between 2000 and 2019, producing up to 1128 million tonnes in 2019 (FAO 2021). The increase in worldwide production is due more to increased use of inputs (e.g., fertilizers, irrigation, pesticides), high-yield crops, implementation of best management practices (BMPs), and less to the expansion of the cultivated area. In the United States, Florida is the second largest producer of vegetables, which are grown under intensive management of nutrients and water on typically sandy textured soils of the state. About 12,140 ha are used for tomato production in Florida (USDA-NASS 2022), where round fresh-market tomato makes up ∼70% of Florida's total tomato production (Florida Tomatoes 2022). Optimization of nutrient and water applications and their use efficiency is, therefore, important for minimizing potential losses of nutrients to the environment, particularly nitrogen (N), in sandy soils. Use of predictive and diagnostic scientific tools such as soil and plant tissue testing are critical for determining the crop nutrient requirements and recommendations for supplemental nutrient applications for sustainable crop production. Several agricultural BMPs have been identified, developed, and implemented for enhancing plant use efficiency of nutrients such as N in conjunction with the 4Rs principles, where soil testing is inherently the first step (Mikkelsen 2011). For tomato production on sandy soils in Florida, BMPs include drip irrigation, splitting of the N fertilizer application into 13 weekly doses (Jalpa et al. 2020), and plastic-mulched raised beds, all of which help improve fertilizer NUE.

N is a common limiting factor in the growth of plants and an essential nutrient with respect to increasing yield (in most agricultural settings), making the use of N fertilizer extensive worldwide. To increase NUE in vegetable production systems, it is critical to understand how to provide the crop N requirement (CNR) without negatively impacting yield by reduced application of fertilizer. High N rate applications (Ramos et al. 2002) are common in conventional tomato production, where loss of N, more specifically NO_3^-, from the root zone can decrease groundwater quality (Sainju et al. 2002). Horticultural crops such as tomato have a short season growth (4–5 months), high N uptake rates (up to 4.3 kg·ha^{-1}·d^{-1}), and are considered to have low fertilizer NUE between 30% to 50% (Mosier et al. 2004). The high uptake of N by tomato combined with a low fertilizer NUE indicates that residual soil N is a considerable N source for this crop (Broadbent et al. 1980; Hills et al. 1983; Jalpa et al. 2021) and that perhaps mismanagement of water and N fertilizer is resulting in a discrepancy between application and crop demand.

Tomato CNR is predominantly determined by physiological need (Mengel 1983) and will vary depending on the cultivar and physiographic region. In Florida, the recommended N rate for tomato production is 224 kg·ha^{-1} N (Mylavarapu et al. 2022). However, FL vegetable growers may apply N fertilizer rates higher than the recommended to potentially limit negative yield impacts from leaching rainfall (Hochmuth and Hanlon 2014). Commercial tomato grower N fertilization often exceeds 470 kg·ha^{-1} per production season (Cantliffe et al. 2009); the variability of applied N among growers within Florida may be due to the differences in duration of seasonal production. For instance, the average tomato production season in north Florida is ∼13 weeks and there are typically two seasons per year (fall and spring), whereas in south Florida, production can last up to 18 weeks and there may be three production seasons per year (fall, winter, and spring) (Ozores-Hampton et al. 2015). Therefore, a longer production season may result in additional N fertilizer input.

High N rate application could be justified if similar crop N accumulation occurred; however, vegetable NUE less than 50% indicates there is an asynchrony between N fertilizer application practices and tomato N uptake.

Extensive research on the impacts of N fertilizer rate for various cultivars of round fresh-market tomato have been conducted, in which whole-plant N accumulation in fertilized tomato ranged between 61.4 kg·ha^{-1} to 176 kg·ha^{-1} (Ayankojo et al. 2020; Jalpa et al. 2021). These N accumulation rates resulted in the successful production of tomatoes that met or exceeded typical yields in Florida, which are currently ~33.6 Mg·ha^{-1} (USDA-NASS 2022). In an early south Florida tomato N rate study conducted on a fine sand, tomato yield in fall and spring averaged 50.9 Mg·ha^{-1} and 48.4 Mg·ha^{-1}, respectively, with N fertilizer application rates ranging between 60 kg·ha^{-1} and 837 kg·ha^{-1} (Everett 1976). Yields did not vary considerably among these applied N rates and the non-N-fertilized control yielded reasonably well in the spring season (30.0 Mg·ha^{-1}) when compared with fall (15.8 Mg·ha^{-1}) (Everett 1976). Appreciable yield in unfertilized tomato has been observed in other studies including in north Florida (Andersen et al. 1999; Jalpa et al. 2021) and may be due to favorable production conditions (e.g., warm temperature and aeration from course/fine sandy soil) that enhances organic matter mineralization rates and increased the availability of soil N for crop use. A ^{15}N study on drip-irrigated spring tomatoes determined that the soil N contribution was ~38% of the total N uptake, indicating that at least one-third of the N requirement for round fresh-market tomato could potentially be met in predominately sandy soils protected by plastic mulch (Jalpa et al. 2021). Therefore, N fertilizer management practices based on typical tomato N requirements or potential N recovery of N sources (native and applied) for a certain physiographic region needs to be focused on to increase N efficiency of the production system. Such information could better guide future N fertilizer BMPs, especially when alternative N sources are assessed for the purpose of increasing nutrient sustainability in conventional vegetable production systems.

Fertigation (application of soluble fertilizer via drip irrigation) is a common practice for vegetable production that is intended to reduce N and water use by splitting its application during the growing season (Hartz and Hochmuth 1996). If managed correctly, conventional soluble N fertilizer sources can be kept within the root zone, therefore increasing crop NUE and reducing N loss (Kennedy et al. 2013). Because of the use of plastic mulch, the impact of leaching rain events during the production season can be considered negligible (Zotarelli et al. 2008). Thus, movement of N fertilizer beyond the root zone can be attributed to the mismanagement of water applied through the drip system. So far, the intensive nature of vegetable production (frequent water and nutrient applications) combined with BMPs (e.g., drip irrigation, raised beds, plastic mulch) have resulted in NUEs smaller than 50%, which suggests the need to assess alternative methods to supply N to the crop that do not need water to be applied. Use of controlled-release fertilizer (CRF) with a polymer coating is a BMP tool that can gradually provide N to the crop throughout the season, reduce N pollution to the environment, and reduce the costs of labor due to one-application at preplant when compared with multiple fertigation applications of N (Sempeho et al. 2014). The mechanism of release from polymer-coated CRFs is affected by temperature (Lawrencia et al. 2021); manufacturers generally report N release durations that are determined typically at 25 °C (Sempeho et al. 2014). Field conditions, however, experience temperature fluctuations, which may result in N release durations that are different from reported manufacturer durations. It is therefore critical to determine the risks (ineffective at maintaining economical yield) or benefits (sustain yield and CNR of tomatoes) to the crop when CRF is applied under seasonal variability in the field. This study assessed two CRU fertilizers with different release durations of 60 d (CRU-60) and 75 d (CRU-75) to determine the optimum N release rate that can best fulfill the CNR of tomatoes grown in north Florida.

Evaluation on the use of CRFs for drip-irrigated tomato could aid in providing information for how an alternative N fertilizer BMP can be adopted convincingly for tomatoes produced on sandy soils. These BMPs relate to timing, rate, source, and placement of fertilizer application, where the differences between CRF and soluble N sources could result in differences to the NUE of the production system. Therefore, a field study assessing the efficiency of applied CRUs and soluble urea (U) as the conventional N source was conducted for commercially produced tomato. Our objectives were to determine the effect of N rate and N source on the responses of tomato (yield, fruit size, and whole-plant N accumulation) and NUE and APR were used as indices of evaluating efficiency. In addition, to determine whether the polymer-coated CRUs successfully released N during the entirety of the active growing periods under fall and spring tomato production, a field mesh bag experiment was conducted.

Materials and Methods

Field site and experimental design. A 2-year field experiment was conducted at the University of Florida, Plant Science Research and Education Unit in Citra, FL, USA (29.4054° N, −82.1400° W) during Fall 2019 and 2020 and Spring 2020 and 2021 tomato growing seasons. The field site, which was previously left fallow, is characterized as having a udic moisture regime, with high precipitation and humidity occurring most of the year. Mean annual precipitation is ~1200–1400 mm and mean annual temperatures range from 20 to 25 °C with a frost-free period of 280 to 365 d. Soil at the field site is classified as a Candler sand (99% sand, 0.5% silt, 0.5% clay; hydrometer method), hyperthermic, uncoated lamellic quartzipsamments with a parent material of eolian deposits and/or sandy and loamy marine deposits. Hydraulic conductivity is high to very high (0.15 to

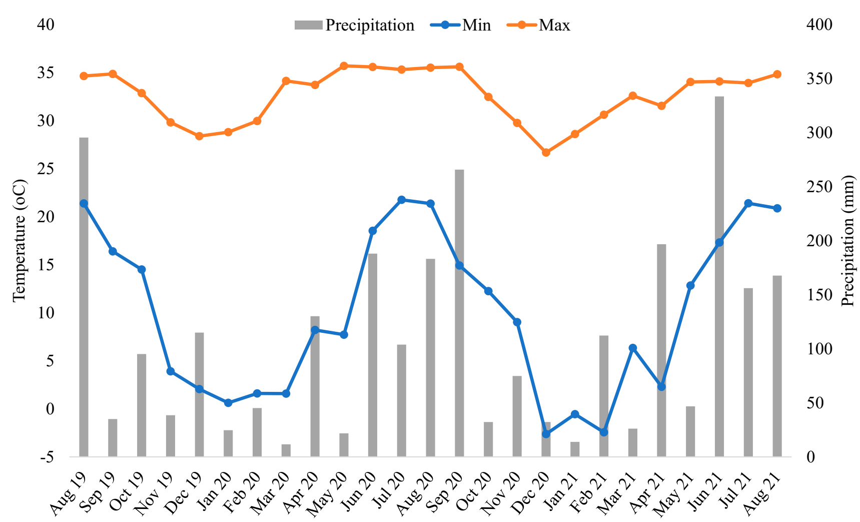

Fig. 1. Mean monthly minimum and maximum air temperatures (°C) and total precipitation (mm) per month during the experimental years of Aug 2019 to Aug 2021 in northern Florida with a humid-type climate. Growing months ranged between September and December for fall tomato and March and July for spring tomato production. Data source: Florida Automated Weather Network (https://fawn.ifas.ufl.edu/).

Received for publication 26 Dec 2023. Accepted for publication 4 Jan 2024.
Published online 26 Feb 2024.
This research was partially funded by the Florida Department of Agriculture and Consumer Services-Office of Agricultural Water Policy Award #27163.
L.J. is a Post-doc.
G.H. is a Professor Emeritus.
Y.L. is a Professor.
B.R. is a Professor.
E.v.S. is a Professor.
R.S.M. is the corresponding author. E-mail: raom@ufl.edu.

Table 1. Summary of color mulch, transplant, and final harvest dates for each season of tomato production in northern Florida.

Cultural practices	Fall 2019	Spring 2020	Fall 2020	Spring 2021
Mulch	White VIF	Black VIF	White VIF	Black VIF
Transplant date	5 Sep	1 May	10 Sep	25 Mar
Final harvest date	2 Dec	15 Jul	2 Dec	28 Jun

VIF = virtually impermeable film.

$0.5\ m\cdot h^{-1}$) and soil is excessively drained with a very low available water storage capacity of 0.06 m in a 2-m profile (USDA-NRCS 2022). Monthly air and soil temperature and precipitation were measured by the Florida Automated Weather Network at the University of Florida, Plant Science Research and Education Unit in Citra for the duration of the experimental years, which were from Aug 2019 to Aug 2021 (Fig. 1).

Cultural practices, planting dates, final harvest dates, and fertilizers applied are summarized in Tables 1 and 2. In preparation for each season, the study area was rototilled, and six false beds were made. False beds were formed for the purpose of broadcasting polymer-coated CRU accurately in the field area where the final bed was made for planting. After application, CRU was incorporated into the soil using a rototiller. Rototilling is an efficient method for turning up soil and putting it back in place and is also effective at distributing fertilizers uniformly within 15 cm of the soil profile. The beds with incorporated CRU were reshaped and raised to be 0.15 m high on 1.8-m centers. The length of each row was ∼49.4 m. Fumigant, drip tape (0.31-m emitter spacing), and plastic mulch were put down simultaneously. Fumigant Pic-Clor 60 (1,3-Dichloropropene + Chloropicrin); TriEst Ag. Group Inc, Greenville, NC) was injected at $336\ kg\cdot ha^{-1}$ to prevent nematode infestation and suppress weeds. Pest control practices followed the recommendations for Florida commercial field tomato production (Olson et al. 2010). Three weeks after fumigation, holes were punched into the plastic ∼0.61 m apart in preparation for transplanting.

A randomized complete block design (r = 3) was established, where 10-N treatments were randomly assigned to plots that were 9.1 m long and 0.76 m wide with 0.91-m buffers between each plot. The augmented factorial treatment design consisted of a complete factorial combination of three N sources [soluble U and two CRU fertilizers with a 60-day (CRU-60) and 75-day (CRU-75) release duration], three N rates (140, 168, and 224 $kg\cdot ha^{-1}$), and an untreated N control (0 $kg\cdot ha^{-1}$) as augmentation (Table 2). An additional drip line was put in to bypass the CRU and control treatments and apply only the U treatments to the appropriate plots. CRU fertilizers were applied 100% of each N rate at the time of bed formation, whereas U fertigation treatments (split into 13 equal doses) began 1 week after transplanting. Extractable Mehlich-3 (M-3) phosphorous (P) and calcium (Ca) tested high and soil pH ranged between 6.5 and 7.8 at preplant in each season of tomato production (Table 3). Therefore, application of P, Ca, and lime was not done in each season. Extractable M-3 potassium (K) tested low in the first year and medium in the second year. Therefore, potassium sulfate was applied through the drip weekly in 13 equal doses at $252\ kg\cdot ha^{-1}$ in the first year and $112\ kg\cdot ha^{-1}$ in the second year. Extractable M-3 magnesium (Mg) tested medium in all four tomato seasons and therefore, magnesium sulfate was applied at $38\ kg\cdot ha^{-1}$ in three split doses in each production season through the drip (Table 3).

Three weeks after fumigation, tomato (*Solanum lycopersicum* L.; cv. HM 1823) seedlings were transplanted in each season (Table 1). Fifteen seedlings were planted per treatment. Irrigation was started after transplanting and was run three times a day for 1 h at a flow rate of $31.5\ cm^3/s$ per 30.5 m of tape (69 kPa). Seven days after transplanting (DAT), U was applied through the drip tape weekly into 13 equal doses during the scheduled irrigation period. Roughly 30 DAT, wooden stakes were placed into the beds and string was used to hold up the plants. Depending on the season, two to three harvests were conducted, where the dates for the final harvest conducted in each season are presented in Table 1. Measurements were taken to place the beds in the same location after each tomato production season. This makes the experiment design a repeated measures.

Tissue analysis. Sampling periods varied in both experimental years because of the impacts of the COVID-19 shutdown, where Spring 2020 was the only season that did not have in-season sampling. Tissue and soil sampling were done on the same day and sampling periods for each season are summarized in Table 3. One random tomato plant was collected at each period of in-season measurement and three plants were collected at harvest for yield determination. In addition, shovels were used to dig ∼0.22 m deep and 0.15 m wide around the plant, which is the depth at which the roots concentrated. The distance between each plant (0.61 m) provided sufficient space to collect the roots without disturbing the rest of the plot. After a harvest was completed, tomatoes were taken to a grading machine that separated them into four sizes: small, medium, large, and extra large (USDA 1991). Grader minimum designated diameters were 5.4 cm, 5.7 cm, 6.4 cm, and 7.0 cm, respectively. Total fruit yield and the proportion of fruit weight by tomato size was calculated. Tomato tissues were analyzed using standard procedures (Mylavarapu et al. 2024) at the University of Florida Institute of Food and Agricultural Sciences (UF/IFAS) Analytical Laboratories (ANSERV Laboratories) in Gainesville and were dried at 65 °C for about a week. Whole-plant tomato samples were separated into components of fruit, leaf (leaf blade and petiole), stem, and root. The dry weights of each tomato component were recorded and then samples were ground and analyzed for total N. Tomato dry matter was calculated for each plant component and summed to calculate the whole-plant dry matter. The planting density of 9075 plants per hectare was used to convert to $kg\cdot ha^{-1}$. Whole-plant N accumulation ($kg\cdot ha^{-1}$) was calculated by multiplying total N (TN) values by the dry matter.

Soil analysis. In each tomato season, in-season (except Spring 2020) and at-harvest soil samples were collected at a 15-cm depth in untreated (no N fertilizer) soil to understand soil mineral N availability during the growing season (Table 3). Preplant bulk soil samples from the field were used to determine M-3 P, K, Ca, and Mg and lime recommendations. All soil samples were oven dried at 105 °C for 24 h and passed through a 2-mm sieve. Soils were analyzed for pH, electrical conductivity (EC), total carbon (TC), TN, NO_3-N, and NH_4-N. Soil C:N ratios were calculated from TC and TN.

Efficiency evaluation. NUE is defined as N uptake by the plant divided by the total amount of N fertilizer applied. Apparent N recovery (N) is defined as the difference in N uptake ($kg\cdot ha^{-1}$) between fertilized and unfertilized plots and is in proportion to the amount of N fertilizer applied. The NUE and APR were calculated using the following equations as described by Jalpa et al. (2020, 2021):

$$NUE\ (\%) = \left(\frac{N\ uptake\ in\ plant}{N_a}\right) \times 100,$$

where N_a is the amount of N fertilizer applied ($kg\cdot ha^{-1}$ N).

$$APR\ (\%) = \left(\frac{N_f - N_{uf}}{N_a}\right) \times 100$$

where N_f and N_{uf} were total N uptake in fertilized and unfertilized plots ($kg\cdot ha^{-1}$ N) and N_a is the amount of N fertilizer applied ($kg\cdot ha^{-1}$ N).

Table 2. Nitrogen (N) source, rate, and application method for fall and spring tomato production in 2019–21 in north Florida.

Control	N source	N rate[i] ($kg\cdot ha^{-1}$)	Application
0 N	CRF-60[ii] (43–0-0)	140, 168, 224	Full rate was applied during bed preparation
	CRF-75 (42–0-0)		Full rate was applied during bed preparation
	Urea (46–0-0)		Fertigation: Mixed with water and split applied 13 times during the growing season

[i] 224 $kg\cdot ha^{-1}$ is the recommended N rate for tomato production in Florida.

[ii] CRF = controlled-release fertilizer with a 60- and 75-day duration of N release; urea as the main N source.

Table 3. Soil chemical properties for the surface (15 cm) profile at the experimental site measured at various periods in each tomato season.

Yr 1							
	Fall 2019				Spring 2020		
Soil parameter	Preplant	42 DAT[i]	56 DAT	Harvest	Preplant	Harvest	Method of analysis
Total C ($kg·ha^{-1}$)	8526	7140	8078	8588	9600	8775	Combustion
Total N ($kg·ha^{-1}$)	450	1163	2220	855	570	825	Combustion
Soil Mineral N ($kg·ha^{-1}$)[ii]	8.6	10.0	6.2	10.1	10.1	5.5	KCl extraction
C:N ratio	16.6	6.5	6.1	10.1	16.8	10.7	Combustion
pH (2:1 in water)	6.5	7.0	7.7	7.5	7.8	7.9	EPA Method 120.1
EC ($mS·cm^{-1}$)[iii]	0.0	0.0	0.0	0.1	0.1	0.0	EPA Method 150.1
Extractable phosphorous ($mg·kg^{-1}$)	205.4				222.0		Mehlich-3 Soil Extraction
Extractable potassium ($mg·kg^{-1}$)	22.3				12.0		Mehlich-3 Soil Extraction
Extractable magnesium ($mg·kg^{-1}$)	27.5				25.0		Mehlich-3 Soil Extraction
Extractable calcium ($mg·kg^{-1}$)	408.3				570.0		Mehlich-3 Soil Extraction
Yr 2							
	Fall 2020			Spring 2021			
	Preplant	42 DAT	Harvest	Preplant	56 DAT	Harvest	
Total C ($kg·ha^{-1}$)	9555	8880	9098	7808	8798	6713	Combustion
Total N ($kg·ha^{-1}$)	960	953	593	893	1013	863	Combustion
Soil mineral N ($kg·ha^{-1}$)	11.5	4.6	4.1	5.2	34.8	7.8	KCl extraction
C:N ratio	12.9	9.5	15.5	8.6	8.7	6.8	Combustion
pH (2:1 in water)	7.0	8.0	6.6	6.4	6.6	7.6	EPA Method 120.1
EC ($mS·cm^{-1}$)	0.0	0.0	0.0	0.1	0.1	0.1	EPA Method 150.1
Extractable phosphorous ($mg·kg^{-1}$)	185.7			202.0			Mehlich-3 Soil Extraction
Extractable potassium ($mg·kg^{-1}$)	34.9			47.8			Mehlich-3 Soil Extraction
Extractable magnesium ($mg·kg^{-1}$)	24.8			27.0			Mehlich-3 Soil Extraction
Extractable calcium ($mg·kg^{-1}$)	501.5			348.8			Mehlich-3 Soil Extraction

[i] DAT = days after transplanting.
[ii] Soil mineral N ($kg·ha^{-1}$) = NH_4-N + NO_3-N
[iii] EC = electrical conductivity.

Field N release characteristics of CRU. To gain insight into field CRU N release patterns during the growing season, an additional plot was set aside to bury mesh bags. The mesh bags (0.2 mm; Phifer Bettervue, Tuscaloosa, AL) were 10 cm long and 10 cm wide, and 15 g of the CRU granules were weighed to the nearest 0.01 g and were recorded. The mesh bags were buried horizontally 10 cm deep on the same day that beds were prepared and were exposed to field conditions (e.g., ambient temperatures, fumigation, drip irrigation, buried in raised beds and covered in plastic mulch). In each sampling event, three bags per fertilizer (CRU-60 and CRU-75) were collected. Mesh bags were first collected 2 weeks after fumigation (period where it is safe to handle fumigated soil). The second collection was done at planting and the rest were collected biweekly until harvest. A total of eight sample events occurred in each season. After sampling, CRU granules were removed from the bags and carefully washed with deionized water. The washed CRU granules were transferred to beakers and placed in the oven for 48 h at 75 °C after which the weight of the remaining CRU was recorded. The percent N cumulative release rate by weight was calculated as

$$\text{Percent cumulative N release from CRU} = \%NR_w = (1 - a/b)$$

where $\%NR_w$ is the percent of N released as determined by the weight method, a is the end weight of the dried granules, and b is the beginning weight of the granules, which was 15 g.

Statistical analysis. Data were analyzed jointly across all seasons using generalized linear mixed model methodology as implemented in SAS® PROC GLIMMIX (SAS/STAT 15.1; SAS Institute, Cary, NC, USA) using appropriate data distributions, viz. binomial for fruit size class analysis and normal for continuous quantitative responses such as yield, NUE, etc. Nitrogen treatment (N-source × N-rate) Season, and their interaction were considered fixed effects, whereas Block and Block × treatment were treated as random effects. Because plot identity was preserved across all seasons, this experiment is of a repeated measures nature requiring that the residuals be modeled accordingly. Under the basic assumption of independence and homogeneity of variance, the residual variance is described as I σ^2, where I equals an identity matrix with all off-diagonal elements equal to zero, meaning all seasons share the same residual variance σ^2. The best-fitting covariance model (based on AICc) was a banded main diagonal model, with each season having its own variance but without a covariance between seasons. Thus, the best-fitting model still has zeroes in the off-diagonals but the common σ^2 is replaced by $\sigma^2{}_1$, $\sigma^2{}_2$, $\sigma^2{}_3$, and $\sigma^2{}_4$ for the four seasons in the study. This lack of covariance among seasons is not all that surprising given the differences among the seasons and the time lag and cover crop treatment between seasons. Fruit weight classes were compared within each season × N treatment (N-source × N-rate) using simple *t* tests [least significant difference $(LSD)_{0.05}$] based on the recommendations by Milliken and Johnson (2009) and Saville (2015). Regression responses (linear + quadratic components) of N sources within each season were compared using linear contrasts. Because we conducted the analysis jointly across all seasons, we are able to compare seasons.

Results and Discussion

N release from CRU

Preliminary results showed that continuous N release from both CRU fertilizers (CRU-60 and CRU-75) occurred over time under vegetable field conditions during each production season (Fig. 2A–D). Release of N was slower in the longer duration CRU-75 source. During the fumigation period, which lasts 3 weeks before tomato planting [0–21 d after fertilization (DAF)], initial N release from CRUs was lower (8.3% to 24.2%) under early spring season temperatures (22 °C) compared with fall (25.0% to 37.9%), which had early mean soil temperature of 31 °C. Carson et al. (2014) similarly observed faster CRF N release because of warmer fall bed temperatures in southwest Florida and, as a result, CRFs released faster than the manufacturer's stated N release duration. Under north Florida conditions in the 2-year experimental period, CRU N release duration in the field went past the manufacturer's stated release of 60 and 75 d (103–138 DAF) lasting to the harvest period in both fall and spring tomato production.

Soil N

Surface (15-cm soil depth) soil N (no N fertilization) characteristics are summarized

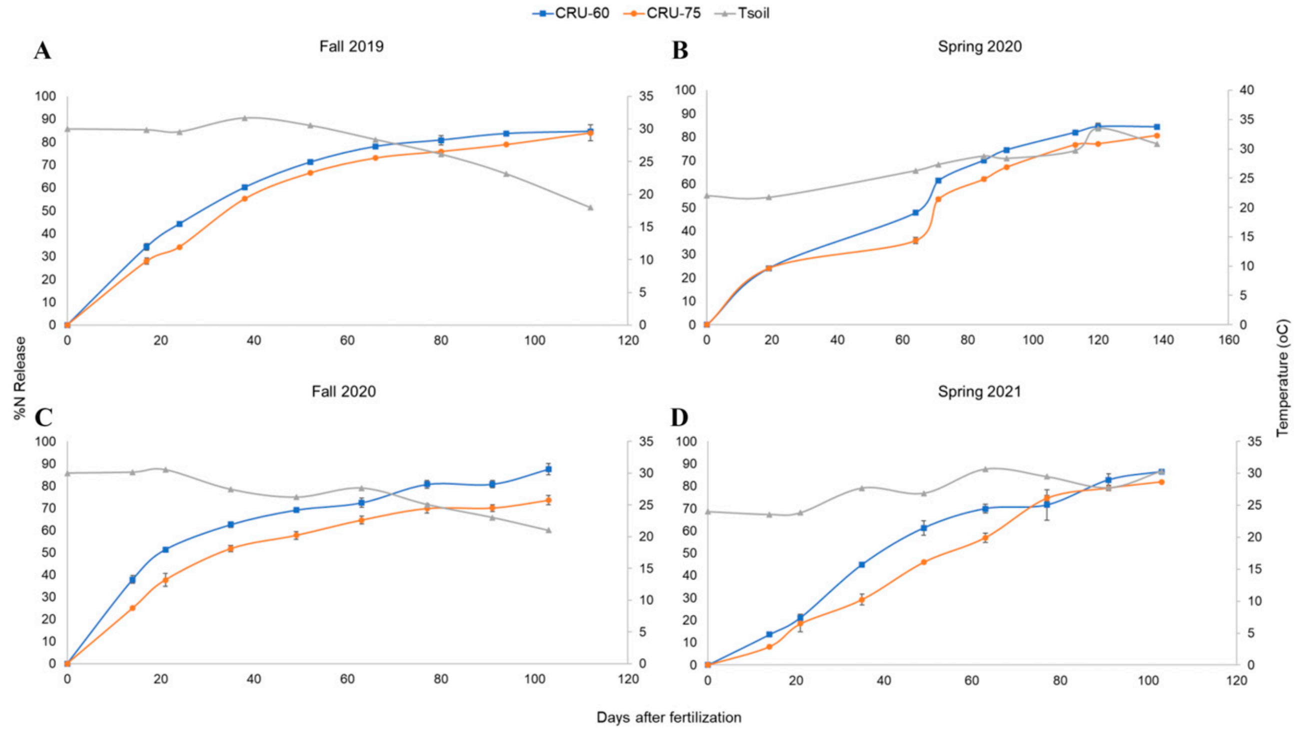

Fig. 2. Cumulative nitrogen (N) released as a percentage of initial weight of N from controlled-release urea (CRU) fertilizers that were buried in the field in mesh bags and mean soil temperatures measured at various mesh bag collection periods during the tomato growing seasons in north-central Florida. The field rate of N release from two CRU fertilizers with different durations of 60 d (CRU-60) and 75 d (CRU-75) are shown. Mesh bags were deployed at the time of bed preparation and were exposed to field conditions (e.g., ambient temperatures, fumigation, drip irrigation, buried in raised beds, and covered in plastic mulch). In each season, mesh bags were first collected after the water was connected and the drip irrigation system was turned on (~17–20 DAF). The irrigation system was scheduled to run at 31.5 cm^3/s per 30.5 m of tape at 69 kPa for three 1-h intervals per day. The final mesh bags were collected at the final harvest period at 112, 138, 103, and 118 d after fertilization (DAF) in Fall 2019 (**A**), Spring 2020 (**B**), Fall 2020 (**C**), and Spring 2021 (**D**), respectively. Because of delays from COVID restrictions, mesh bag collections ceased at 19 DAF and resumed 64 DAF in Spring 2020. During this time (19–64 DAF), irrigation was turned off. Error bars represent standard error of the mean (n = 3).

in each season in Table 3. Climatic conditions and vegetable field management practices heavily affects the mineralization of soil organic N, where net N release of 50–100 $kg \cdot ha^{-1}$ can occur during the growing season (Neeteson 1995). Preplant soil mineral N ($NH_4^+ + NO_3^-$) was 8.6, 11.5, 10.1, and 5.2 $kg \cdot ha^{-1}$, in Fall 2019, Spring 2020, Fall 2020, and Spring 2021, respectively. In-season soil mineral N ranged between 4.6 and 10 $kg \cdot ha^{-1}$ during fall tomato and 34.8 $kg \cdot ha^{-1}$ during spring tomato field conditions. Maximum N mineralization occurs at soil temperatures between 25 and 35 °C (Knoepp and Swank 1998) and mean maximum soil temperatures in north Florida in the 2-year experimental period were 32.6 °C during spring production seasons. Therefore, it can be assumed that mineralization of soil organic N played an important role on N availability for crop use in spring. At harvest, soil mineral N was 10.1, 5.5, 4.1, and 7.8 $kg \cdot ha^{-1}$, in Fall 2019, Spring 2020, Fall 2020, and Spring 2021, respectively. In-season surface soil C:N ratio ranged between 6.1 and 10.2, indicating that mineralization was the dominant N transformation process occurring in soil that received no N fertilization in north Florida (Jalpa and Mylavarapu 2023).

Yield

Tomato fruit yield. The one-time preplant application of polymer-coated CRU and split in-season applications of U similarly improved drip-irrigated tomato yield during all seasons (Table 4). Only in Fall 2019 was there a difference among N sources, where the total tomato yield averaged across all rates was higher for CRU-75 (56.4 $Mg \cdot ha^{-1}$) compared with CRU-60 (50.7 $Mg \cdot ha^{-1}$) and U (52.9 $Mg \cdot ha^{-1}$). For all N sources, the mean tomato yield was 44.3, 49.8, and 39.7 $Mg \cdot ha^{-1}$ in Spring 2020, Fall 2020, and Spring 2021, respectively. Yields were found to meet typical tomato yields in Florida, which averages ~33.6 $Mg \cdot ha^{-1}$ (USDA-NASS 2022). There was a positive yield response to applied N during the Fall 2019 growing season, with yield increasing between 139 and 578 $kg \cdot ha^{-1}$ per kg applied N, compared with the following Spring 2020 growing season with yield increases ranging from 0 to 247 $kg \cdot ha^{-1}$ per kg applied N (Table 4). A similar relationship was observed for the Fall 2020 and the following Spring 2021 growing seasons. In general, a significant linear relationship existed between yield and applied N for all N sources during the two fall growing seasons, except for CRU-60 during Fall 2019. The significant quadratic coefficients for CRU-75 and U enabled us to calculate the maximum response. Derivative of the quadratic tomato yield data showed that yields were maximized at 129 and 131 $kg \cdot ha^{-1}$ of N in Fall 2019 for CRU-75 and U, respectively. For Fall 2020, yield was maximized at 163 and 167 $kg \cdot ha^{-1}$ (data not shown).

The N rates where yield was maximized may be considered low compared with actual N rates applied in commercial tomato production (300–600 $kg \cdot ha^{-1}$). However, our results for tomato production were similar to past studies for this physiographic region. In north Florida, it was observed that seasonal variation from year to year affected marketable yield more so than the range of N fertilization rates applied. A 3-year N rate study on marketable yield resulted in similar yield produced among N rates of 176–330 $kg \cdot ha^{-1}$. Although the same N rates were applied year to year, marketable yield increased on average from 28.0 $Mg \cdot ha^{-1}$ in 2005 to 78.5 $Mg \cdot ha^{-1}$ in 2007 (Zotarelli et al. 2009a). Differences in tomato yield were attributed to low solar radiation in 2005. Nitrogen fertilizer rates as low as 67 $kg \cdot ha^{-1}$ resulted in 41.9 $Mg \cdot ha^{-1}$ and 56.0 $Mg \cdot ha^{-1}$ of marketable tomato and similar or decreases in yield were found in the 269 $kg \cdot ha^{-1}$ N rate (Andersen et al. 1999) from year to year. Results from an eight on-farm trial for fall, winter, and spring tomato production resulted in similar yields with N rates ranging from 224 $kg \cdot ha^{-1}$ to 370 $kg \cdot ha^{-1}$ in all production years and seasons except for one winter season (Ozores-Hampton et al. 2006).

Averaged across all N sources and N rates, yield was at least 20% higher during

Table 4. Contrast analysis for each nitrogen (N) source on total tomato yield. Rate responses were calculated using linear and quadratic regression within each N source. Tomato production seasons were analyzed separately because of different planting times and lengths of data collection for harvests.

	Fall 2019		Spring 2020		Fall 2020		Spring 2021	
N source/rate	Estimate	*SE*	Estimate	*SE*	Estimate	*SE*	Estimate	*SE*
Control	20.8	8.81	31.7	7.28	16.2	3.52	25.0	4.04
60-day controlled-release polymer-coated urea								
140	49.3	8.81	38.3	7.28	50.9	3.52	37.5	4.04
168	41.3	8.81	41.5	7.28	43.5	3.52	47.7	4.04
224	61.4	8.81	49.2	7.28	51.2	3.52	54.5	4.04
Regression coefficients								
Intercept	21.2*	8.38	31.7*	6.69	16.4*	3.9	24.8*	3.57
Linear	0.139	0.1741	−0.003	0.1384	0.325*	0.0784	0.061	0.0711
Quadratic	0.0001	0.0008	0.0004	0.00063	−0.0008	0.00036	0.0003	0.00033
75-day controlled-release polymer-coated urea								
140	57.2	8.81	50.0	7.28	49.3	3.52	32.7	4.04
168	71.0	8.81	54.6	7.28	62.2	3.52	42.9	4.04
224	41.0	8.81	49.6	7.28	48.0	3.52	49.0	4.04
Regression coefficients								
Intercept	20.4*	8.38	31.6*	6.69	15.8*	3.9	24.8*	3.57
Linear	0.674*	0.1741	0.247	0.1384	0.488*	0.0784	0.014	0.0711
Quadratic	−0.0025*	0.0008	−0.0007	0.00063	−0.0015*	0.00036	0.0004	0.00033
Urea								
140	62.2	8.81	32.9	7.28	51.6	3.52	27.0	4.04
168	53.8	8.81	45.4	7.28	45.4	3.52	27.9	4.04
224	42.9	8.81	36.8	7.28	45.9	3.52	38.5	4.04
Regression coefficients								
Intercept	21.0*	8.38	31.4*	6.69	16.4*	3.9	25.1*	3.57
Linear	0.578*	0.1741	0.08	0.1384	0.400*	0.0784	−0.08	0.0711
Quadratic	−0.0022*	0.0008	−0.0002	0.00063	−0.0012*	0.00036	0.0006	0.00033
Contrast *P* values comparing linear and quadratic component								
CRU-60 vs. CRU-75		0.039		0.212		0.160		0.649
CRU-60 vs. Urea		0.087		0.675		0.508		0.184
CRU-75 vs. Urea		0.699		0.400		0.438		0.366

*Regression coefficients significant at $\alpha = 0.05$.

SE = standard error.

fall compared with spring. In contrast, the yields for unfertilized controls were at least 50% higher in spring compared with fall. Andersen et al. (1999) observed unfertilized spring tomato yield of 18.9 $Mg \cdot ha^{-1}$ (cv. Colonial) and 49.3 $Mg \cdot ha^{-1}$ (cv. Equinox) for fall unfertilized tomato yield in north Florida. Differences in seasonal unfertilized tomato were due to planting dates ranging between March to May and July to September.

Temperature plays a major role in the release of soluble N from polymer-coated sources; the temperature in north Florida was favorable to stimulating N release from CRUs during the active tomato growth period (Fig. 2A–D). Most seasons resulted in similar yield among N sources, indicating that fruit production was not negatively affected by using an alternative N source such as polymer-coated CRU. van Eerd et al. (2018) found equivalent yield benefits to using CRFs and soluble sources in cabbage production. However, it was pointed out that meaningful differences due to N sources may be found in light textured soil, which can potentially leach N. Hartz and Smith (2009) summarized vegetable studies that found lower application rates of CRFs were able to achieve comparable vegetable yield to full applications of recommended N rates of soluble N sources. However, these benefits were more prominently seen in production systems in which there was high nutrient leaching potential. Although tomatoes were produced on sandy soils, the use of N fertilizer BMPs such as CRFs and fertigation applied at lower N rates under plastic mulch, seemed to have ensured uptake of N by tomato in the system due to the close contact between roots and N sources. Vegetable production studies (e.g., leafy greens) that found increased yield benefits to CRFs under high leaching potential conditions tended to not use plastic mulch.

Fruit size. The proportion of total fruit yield was categorized by fruit size (small, medium, large, and extra large) and the effects of N source and N rate by season are presented in Fig. 3A–C. Regardless of no N or applied N treatments, it was equally as likely for the proportion of fruit size to be composed mostly of medium, large, and extra-large tomatoes. Doss et al. (1975) also found similar marketable yield and fruit size proportions among N rates of 65–260 $kg \cdot ha^{-1}$. Ayankojo et al. (2020) also did not observe an N treatment effect on the proportion of fruit size among the applied N rates of 179–269 $kg \cdot ha^{-1}$ in both spring and fall production. The same study also found that tomato yield in each fruit size category and total yield was primarily impacted by the deficit irrigation rate tested, indicating that at more than sufficient N levels, restricted water supply can be a major yield limiting factor. The combination of delayed planting and no N application resulted in the only instance where a significantly higher proportion of small tomatoes was produced over larger sizes in Spring 2020. In our study, exposure to warmer temperatures by delayed planting affected the proportion of fruit size of the total fruit yield.

Higher market prices are paid for large and extra-large fruit (Davis and Gardner 1994) and are therefore the desirable target sizes for growers to produce. Ideal marketable yield (large + extra-large fruit) comprised 65% to 68% and 64% to 68% of the total fruit yield in Fall 2019 and Fall 2020, respectively. About 40% and 52% to 55% were of desirable marketable yield size in Spring 2020 and 2021, respectively (Fig. 3A–C). The frequency of small and medium-sized tomatoes of the same cultivar was higher under the warm spring production conditions in north Florida. Everett (1976) also observed increased frequency of small (33%) and medium (43%) tomatoes being produced under spring production seasons, when compared with the fall season, which resulted in mostly medium (36%) and large (35%) tomatoes. Over the decades, N fertilizer rate studies conducted on sandy soils in various locations and seasons of production have consistently concluded that no appreciable increases in tomato yield were observed when N was applied at rates above the Florida recommended N rate of 224 $kg \cdot ha^{-1}$ N (Andersen et al. 1999; Hochmuth and Cordasco 2000; Hochmuth and Hanlon 2014; Jalpa et al. 2020, 2021; Ozores-Hampton et al. 2006; Zotarelli et al. 2009a, 2009b).

Whole-plant N accumulation

Only for CRU-75 was there a significant linear response in whole-plant N accumulation at the fruit-set stage (42 DAT) during Fall 2019, whereas in Fall 2020 a significant linear and quadratic response was observed for all N sources. Because the quadratic component was significant, the maximum N rate could be

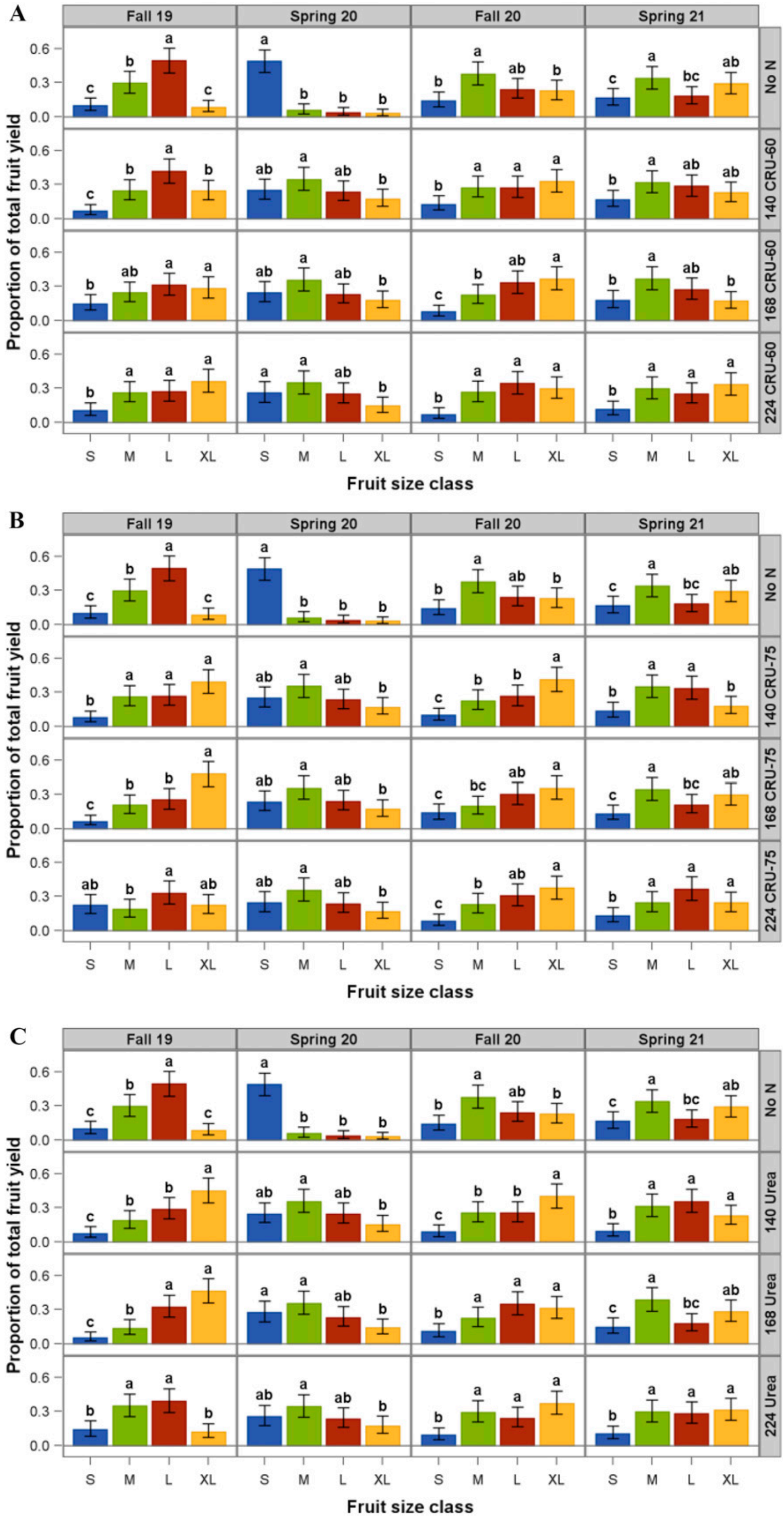

Fig. 3. The effect of no nitrogen (N) and different N rates of N sources on the proportion of marketable ‘HM 1823’ tomato fruit yield by size over a 4-week harvest period for each season in Fall 2019, Spring 2020, Fall 2020, and Spring 2021. N sources were polymer-coated controlled-release urea (CRU) with a 60-day (CRU-60) (**A**) and 75-day (CRU-75) (**B**) N release duration and soluble urea (U) (**C**).

calculated. The lowest maximum N rate was observed for CRU-75 (183.8 kg·ha^{-1}), followed by CRU-60 (204.1 kg·ha^{-1}), followed by U (291.7 kg·ha^{-1}). In general, no differences were observed among N sources for regression coefficients, based on contrasts (Table 5).

During the fruit growth stage (56 DAT), whole-plant N accumulation averaged across all N sources and N rates was at least twice as large during the Fall 2019 growing season compared with the Spring 2021 season (Table 6). There was no effect of N rate on whole-plant N

Table 5. Contrast analysis for each N source on total whole-plant N accumulation in Fall 2019 and Fall 2020 tomato at the fruit-set stage (42 d after transplanting). Rate responses were calculated using linear and quadratic regression within each N source. Tomato production seasons were analyzed separately because of different planting times and lengths of data collection for harvests.

N source/rate	Fall 2019		Fall 2020	
	Estimate	*SE*	Estimate	*SE*
Control	11.41	0.86	4.07	0.86
60-day controlled-release polymer-coated urea				
140	21.26	2.81	21.94	2.81
168	24.93	2.81	25.29	2.81
224	24.13	5.25	23.17	5.25
Regression coefficients				
Intercept	11.40*	0.97	4.06*	0.97
Linear	0.11	0.08	0.20*	0.03
Quadratic	−0.00017	0.000451	−0.00049*	0.000173
75-day controlled-release polymer-coated urea				
140	28.38	2.81	28.21	2.81
168	35.3	5.25	22.29	5.25
224	25.17	2.81	25.9	2.81
Regression coefficients				
Intercept	11.41*	0.97	4.09*	0.97
Linear	0.23*	0.08	0.25*	0.05
Quadratic	−0.00071	0.000430	−0.00068*	0.000267
Urea				
140	21.96	2.81	19.29	2.81
168	25.31	2.81	20.25	2.81
224	31.66	5.25	23.0	5.25
Regression coefficients				
Intercept	11.41*	0.97	4.07*	0.97
Linear	0.05	0.05	0.14*	0.04
Quadratic	0.00020	0.000335	−0.00024	0.000232
Contrast *P* values comparing linear and quadratic component				
CRU-60 vs. CRU-75		0.2710		0.4258
CRU-60 vs. Urea		0.5224		0.2368
CRU-75 vs. Urea		0.0497		0.1134

*Regression coefficients significant at $\alpha = 0.05$.
SE = standard error.

Table 6. Contrast analysis for each N source on total whole-plant N accumulation in Fall 2019 and Spring 2021 tomato during the fruit growth stage (56 d after transplanting). Rate responses were calculated using linear and quadratic regression within each N source. Tomato production seasons were analyzed separately because of different planting times and lengths of data collection for harvests.

N source/rate	Fall 2019		Spring 2021	
	Estimate	*SE*	Estimate	*SE*
Control	23.15	4.91	9.18	4.91
60-day controlled-release polymer-coated urea				
140	54.65	11.32	21.73	11.32
168	65.96	7.41	20.1	7.41
224	64.27	11.32	22.96	11.32
Regression coefficients				
Intercept	22.94	11.66	9.26	5.85
Linear	0.35	0.23	0.12	0.09
Quadratic	−0.00074	0.001056	−0.00025	0.000421
75-day controlled-release polymer-coated urea				
140	46.93	7.41	21.83	7.41
168	90.41	7.41	37.17	7.41
224	50.68	7.41	20.84	7.41
Regression coefficients				
Intercept	21.94	11.66	8.75	5.85
Linear	0.59*	0.23	0.28*	0.09
Quadratic	−0.00193	0.001056	−0.00095*	0.000421
Urea				
140	64.32	11.32	19.16	11.32
168	55.82	11.32	13.25	11.32
224	52.71	4.91	15.9	4.91
Regression coefficients				
Intercept	23.38	11.66	9.35	5.85
Linear	0.50	0.23	0.09	0.09
Quadratic	−0.00168	0.001056	−0.00031	0.000421
Contrast *P* values comparing linear and quadratic component				
CRU-60 vs. CRU-75		0.4828		0.2262
CRU-60 vs. Urea		0.6555		0.8711
CRU-75 vs. Urea		0.7962		0.1723

*Regression coefficients significant at $\alpha = 0.05$.
SE = standard error.

accumulation for any N source and season except for CRU-75 during Spring 2021, where the maximum N accumulation occurred at 147 $kg \cdot ha^{-1}$ applied N.

The mean unfertilized whole-plant N accumulation at harvest was at least 60% to 300% higher in spring compared with fall (Table 7). In-season residual soil mineral N was more limited during fall seasons (4.6–10 $kg \cdot ha^{-1}$) compared with spring (34.8 $kg \cdot ha^{-1}$) (Table 3), which may explain the higher N removal in unfertilized spring tomato. Andersen et al. (1999) observed unfertilized whole-plant N accumulation of 96.2 $kg \cdot ha^{-1}$ for fall tomato and 43.3 $kg \cdot ha^{-1}$ for spring tomato. Lower N accumulation for unfertilized fall tomato observed in this study may be a result of differences in planting dates that were done in early September, whereas fall tomatoes in the experiment by Andersen et al. (1999) were planted in late July.

A consistent whole-plant N accumulation response to applied N across all N sources was observed only during the Fall 2020 season (Table 7). For Fall 2019, only the CRU-75 and U exhibited a significant linear response. In Spring 2020, this was the case only for CRU-75. No significant relationship between applied N and whole-plant N accumulation was observed during the final Spring 2021 season. No statistically meaningful differences among N sources could be established in any season based on contrast analysis. Only during the Fall 2020 season were we able to calculate a maximum response based on a significant quadratic relationship at 174 $kg \cdot ha^{-1}$ for U. At harvest, only spring tomato production seasons showed differences in N source on whole-plant N accumulation. The mean whole-plant N accumulation at harvest was 96, 100, 111, and 103 $kg \cdot ha^{-1}$ in Fall 2019, Spring 2020, Fall 2020, and Spring 2021, respectively (Table 7). Therefore, the typical N uptake or CNR of tomato (‘HM 1823’) was on average 102.5 $kg \cdot ha^{-1}$ under production conditions in north Florida during the 2-year experiment. Reported values of total N accumulation by tomatoes typically range from 150 $kg \cdot ha^{-1}$ to 300 $kg \cdot ha^{-1}$ depending on cultivar, soil, and irrigation system (Broadbent et al. 1980). In north Florida, whole-plant N accumulation in various tomato cultivars ranged between 85 $kg \cdot ha^{-1}$ and 159 $kg \cdot ha^{-1}$ under N fertilization rates of 66 $kg \cdot ha^{-1}$ to 333 $kg \cdot ha^{-1}$ (Andersen et al. 1999; Jalpa et al. 2020, 2021; Scholberg et al. 2000). Tomato N accumulation from this preliminary study was found to be within the range of what is observed for north Florida.

Results from this 2-year study showed that the use of polymer-coated CRU-75 improved tomato N uptake, indicating that there may be benefits to using CRU for improving N uptake efficiency under warm production systems. Under north Florida growing conditions, the management of N fertilizer using fertigation and CRU sources did not lead to negative differences in N removal rates by tomato (102.5 $kg \cdot ha^{-1}$ N) indicating that CRU can be used to successfully maintain the CNR on sandy soils. It is important to consider that both N fertilizer BMPs evaluated (one-time preplant CRU application and in-

Table 7. Contrast analysis for each N source on total whole-plant N accumulation in Fall 2019, Spring 2020, Fall 2020, and Spring 2021 tomato at harvest. Rate responses were calculated using linear and quadratic regression within each N source. Tomato production seasons were analyzed separately because of different planting times and lengths of data collection for harvests.

	Fall 2019		Spring 2020		Fall 2020		Spring 2021	
N source/rate	Estimate	*SE*	Estimate	*SE*	Estimate	*SE*	Estimate	*SE*
Control	25.07		40.68		19.00		60.54	8.69
60-day controlled-release polymer-coated urea								
140	75.85	13.12	70.85	13.12	111.23	13.12	89.43	13.12
168	88.77	19.28	71.67	19.28	94.97	19.28	92.96	19.28
224	103.62	19.28	99.59	19.28	124.27	19.28	117.70	19.28
Regression coefficients								
Intercept	24.97	14.83	40.91*	13.19	19.71	12.88	60.69*	12.12
Linear	0.41	0.29	0.07	0.25	0.78*	0.24	0.08	0.23
Quadratic	−0.00026	0.00132	0.00083	0.00115	−0.00145	0.00111	0.00075	0.00103
75-day controlled-release polymer-coated urea								
140	68.24	8.69	100.72	8.69	95.46	8.69	91.06	8.69
168	122.09	19.28	104.51	19.28	122.75	19.28	112.95	19.28
224	91.40	13.12	94.77	13.12	113.57	13.12	103.94	13.12
Regression coefficients								
Intercept	23.73	14.83	40.61*	13.19	18.45	12.88	60.04*	12.12
Linear	0.70*	0.29	0.76*	0.25	0.91*	0.24	0.40	0.23
Quadratic	−0.00166	0.00132	−0.00231	0.00115	−0.00210	0.00111	−0.00086	0.00103
Urea								
140	105.05	13.12	58.29	13.12	120.65	13.12	63.51	13.12
168	98.74	8.69	76.66	8.69	108.50	8.69	55.41	8.69
224	111.37	8.69	64.68	8.69	111.21	8.69	82.74	8.69
Regression coefficients								
Intercept	25.42	14.83	40.21*	13.19	19.44	12.88	60.93*	12.12
Linear	0.78*	0.29	0.29	0.25	1.13*	0.24	−0.22	0.23
Quadratic	−0.00182	0.00132	−0.00075	0.00115	−0.00325*	0.00111	0.00136	0.00103
Contrast *P* values comparing linear and quadratic component								
CRU-60 vs. CRU-75		0.4775		0.0631		0.7047		0.3346
CRU-60 vs. Urea		0.3680		0.5500		0.3153		0.3563
CRU-75 vs. Urea		0.8466		0.1931		0.5273		0.0665

*Regression coefficients significant at $\alpha = 0.05$.
SE = standard error.

season split applied U) resulted in a constant supply of N to tomato, whereas calculated responses were found at lower N rates compared with N rates typically used by growers. Such practices ensured that tomato N requirements were being met for the average growing period of tomato, which is ~13 weeks for north Florida. Similar practices should be tested in other physiographic regions of Florida to assess the suitability of using polymer-coated CRU in longer seasons of production.

Plant efficiency

Apparent N recovery efficiency. The effect of N rate within N source on tomato APR was significant (Table 8; a, ab, and b lettering). An APR value of zero indicates N accumulation did not differ between the unfertilized plant and fertilized plant (Craswell and Godwin 1984; Mengel et al. 2006). In other words, there was sufficient N available in the soil for crop uptake and N fertilizer input was not required to fulfill the CNR and thus excessive. There were no statistically meaningful differences among N rates detected for CRU-60; the mean APR efficiency across all CRU-60 N rates was 36.4%, 22.1%, 52.7%, and 21.8% in Fall 2019, Spring 2020, Fall 2019, and Spring 2021, respectively. Tomato APR efficiency was not consistent across N rates in CRU-75 and U in every season. For instance, in Fall 2019, APR was highest under the 168 N rate (57.7%) for CRU-75, but all N rates resulted in similar APR (24.1%) for CRU-75 in Spring 2021.

For the two fall seasons, APR among N sources differed statistically meaningfully only at the 140 $kg \cdot ha^{-1}$ rate, with an APR of 57.1%, 36.3%, and 30.8% for U, CRU-60, and CRU-75, respectively, during Fall 2019 and 72.6%, 65.9%, and 54.6% during the Fall 2020 growing season. The APR did not differ statically meaningfully among the remaining two rates (Table 8; x, xy, and y lettering). During the two spring seasons, the APR for U was much

Table 8. The effect of nitrogen (N) rates within N source and the effect of N sources within N rate on tomato apparent recovery of N fertilizer (APR). APR is calculated as the difference in total N uptake between fertilized and unfertilized plots divided by the total amount of N fertilizer applied.

	Fall 2019[i]				Spring 2020				Fall 2020				Spring 2021			
N source/rate	Estimate	*SE*			Estimate	*SE*			Estimate	*SE*			Estimate	*SE*		
60-day controlled-release polymer-coated urea																
140	36.3	8.6	a[ii]	xy[iii]	21.6	8.6	a	y	65.9	8.56	a	xy	20.6	8.6	a	xy
168	37.9	12.4	a	x	18.4	12.4	a	x	45.2	12.4	a	x	19.3	12.4	a	xy
224	35.1	8.6	a	x	26.3	8.6	a	xy	47.0	8.6	a	x	25.5	8.6	a	x
75-day controlled-release polymer-coated urea																
140	30.8	6.1	b	y	42.9	6.1	a	x	54.6	6.1	a	y	21.8	6.1	a	x
168	57.7	12.4	a	x	38.0	12.4	ab	x	61.7	12.4	ab	x	31.2	12.4	a	x
224	29.6	6.12	b	x	24.1	6.1	b	x	42.2	6.1	b	x	19.4	6.1	a	x
Urea																
140	57.1	8.6	a	x	10.5	8.6	a	y	72.6	8.6	a	x	2.1	8.6	ab	y
168	43.8	6.1	ab	x	16.0	6.1	a	x	53.3	6.1	b	x	−3.1	6.1	b	y
224	38.5	6.1	b	x	10.7	6.1	a	y	41.2	6.1	c	x	9.9	6.1	a	x

[i] A joint analysis of all seasons was conducted, but the means were reported separately for each season.
[ii] a, b, ab letters compare N rates within N source.
[iii] x, y, xy letters compare N sources within N rate.
SE = standard error.

Table 9. The effect of nitrogen (N) rates within N source and the effect of N sources within N rate on tomato fertilizer use efficiency (NUE). NUE is calculated as total N uptake divided by the amount of total N fertilizer applied.

	Fall 2019[i]				Spring 2020				Fall 2020				Spring 2021			
N source/rate	Estimate	*SE*			Estimate	*SE*			Estimate	*SE*			Estimate	*SE*		
60-day controlled-release polymer-coated urea																
140	54.2	8.6	a[ii]	xy[iii]	50.6	8.6	a	y	79.5	8.6	a	xy	63.9	8.6	a	xy
168	52.8	12.5	a	x	42.6	12.5	a	xy	56.5	12.5	ab	x	55.3	12.5	a	xy
224	46.2	8.6	a	x	44.5	8.6	a	x	55.5	8.6	b	x	52.5	8.6	a	x
75-day controlled-release polymer-coated urea																
140	48.7	6.3	ab	y	72.0	6.3	a	x	68.2	6.3	a	y	65.0	6.3	a	x
168	72.7	12.5	a	x	62.2	12.5	ab	x	73.1	12.5	ab	x	67.2	12.5	ab	x
224	40.8	6.3	b	x	42.3	6.3	b	x	50.7	6.3	b	x	46.4	6.3	b	x
Urea																
140	75.0	8.6	a	x	34.7	8.6	a	y	86.2	8.6	a	x	45.3	8.6	a	y
168	58.8	6.3	ab	x	34.2	6.3	a	y	64.6	6.3	b	x	33.0	6.3	a	y
224	49.7	4.6	b	x	28.9	4.6	a	y	49.7	4.6	c	x	36.9	4.6	a	y

[i] A joint analysis of all seasons was conducted, but the means were reported separately for each season.
[ii] a, b, ab letters compare N rates within N source.
[iii] x, y, xy letters compare N sources within N rate.
SE = standard error.

smaller than for CRU-60 and CRU-75, tending toward zero, indicating excessive N application. There were no other recognizable patterns among N sources during spring seasons.

N use efficiency. When considering overall N uptake of the fertilized tomato plant alone, NUE trends were similar to tomato APR for the CRU-60 source (Table 9; a, ab, and b lettering). Across all N rates, tomato NUE was 51.1%, 45.9%, 63.8%, and 57.2% in Fall 2019, Spring 2020, Fall 2019, and Spring 2021, respectively. For CRU-75 and U sources, NUE decreased with increasing N rates in all seasons, where NUE ranged between 65% and 86.2% at the 140 N rate. All N sources similarly affected NUE at the 168 and 224 N rate in Fall 2019 (61.4% to 62.2%) and Fall 2020 (45.6% to 52.0%); however, at the 140 N rate, split applied U (75.0% to 86.2%) significantly improved NUE alone in fall (Table 9; x, xy, and y lettering). For spring production seasons, overall tomato NUE was significantly improved by CRU sources (42.3% to 72.0%).

Based on the low APR values found in spring production seasons, it can be concluded that residual soil N is an important source for tomatoes produced on sandy soils in north Florida. According to overall spring NUE values, lower N rates (which inherently consider soil N contributions) combined with polymer-coated CRU sources may be a combination of BMPs benefiting nutrient sustainability of warm season tomato production in north Florida. At the lowest N rate, U significantly improved APR and NUE under cool production seasons. Perhaps weekly doses of a readily available N source benefited tomato N uptake during a fruit growth period in which soil temperatures were less conducive to stimulating soil mineralization (<25 °C) (Fig. 2A–D). High APR values (57.1% to 72.6%) were helpful in indicating that fall tomato was limited by low residual soil mineral N and required N fertilization to help fulfill the CNR. Under spring tomato production, U (APR: 0% to 16.0%) was not considered an efficient N source.

Differences in tomato nutrient uptake between CRF and soluble N sources have been observed, in which the nutrient uptake per plant and per fruit was found to be lower with CRF sources, indicating that nutrient use efficiency was higher for tomatoes produced with CRFs (Kinoshita and Masuda 2011). In addition, Kinoshita and Masuda (2011) found that tomatoes absorbed the bulk of nutrients released from CRFs immediately after they were released from the CRF surface. Because CRF prills are completely and continuously surrounded by plant roots (assuming prills are incorporated into the soil), it can be expected that crop N uptake will be much more efficient. In our study, CRU prills were incorporated within the root zone and continuously released N during growing season (Fig. 2A–D).

Conclusions

Preliminary results from the 2-year study showed that the one-time application of CRU at preplant sustained similar yield and N accumulation when compared with multiple fertigation applications of conventional urea. As such, polymer-coated CRU could be considered a dependable alternative N source for tomato production, in which the ease of applying CRU once during the bed preparation period may be an economical incentive. N rates above 140 $kg \cdot ha^{-1}$ did not lead to appreciable improvements in yield, N accumulation, and APR and NUE efficiencies, indicating that drip-irrigated tomatoes in north Florida may be produced at a 38% reduction of the recommended N rate (224 $kg \cdot ha^{-1}$). This finding is supported by the CNR of tomato, which was on average 102.5 $kg \cdot ha^{-1}$ under production conditions in north Florida. At higher N rates, similar tomato N efficiency was found, indicating increased environmental risk when N rates exceed tomato CNR. Yield, N accumulation, and N efficiency were consistently lower under spring production conditions, indicating that decreases in N rates may greatly benefit the N efficiency of warm season tomato production in north Florida, especially when residual soil mineral N may contribute significantly to the CNR. Improved tomato APR and NUE efficiencies were found in split applied U under fall production seasons, whereas APR and NUE efficiencies were improved under spring production seasons when CRUs were applied at preplant.

References Cited

Andersen PC, Rhoads FM, Olson SM, Hill KD. 1999. Carbon and nitrogen budgets in spring and fall tomato crops. HortScience. 34(4):648–652. https://doi.org/10.21273/HORTSCI.34.4.648.

Ayankojo IT, Morgan KT, Kadyampakeni DM, Liu GD. 2020. Tomato growth, yield, and root development, soil nitrogen and water distribution as affected by nitrogen and irrigation rates on a Florida sandy soil. HortScience. 55(11):1744–1755. https://doi.org/10.21273/HORTSCI15177-20.

Broadbent FE, Tyler KB, May DM. 1980. Tomatoes make efficient use of applied nitrogen. Calif Agr. (Nov–Dec):24–25.

Cantliffe D, Gilreath P, Haman D, Hutchinson C, Li Y, McAvoy G, Migliaccio K, Olczyk T, Olson S, Parmenter D, Santos B, Shukla S, Simonne E, Stanley C, Whidden A. 2009. Review of nutrient management systems for Florida vegetable producers: A white paper from the UF/IFAS Vegetable Fertilizer Task Force. Univ. Florida, IFAS, EDIS Publ. HS1156. http://edis.ifas.ufl.edu/hs1156.

Craswell ET, Godwin DC. 1984. The efficiencies of nitrogen fertilizer applied to cereals in different climates. Adv Plant Nutr. 1:1–55.

Carson LC, Ozores-Hampton M, Morgan KT, Sartain JB. 2014. Nitrogen release properties of controlled-release fertilizers during tomato production. HortScience. 49(12):1568–1574. https://doi.org/10.21273/hortsci.49.12.1568.

Davis JM, Gardner RG. 1994. Harvest maturity affects fruit yield, size, and grade of fresh-market tomato cultivars. HortScience. 29(6):613–615. https://doi.org/10.21273/HORTSCI.29.6.613.

Doss BD, Evans CE, Johnson WA. 1975. Rates of nitrogen and irrigation for tomatoes. J Am Soc Hortic Sci. 100(4):435–437. https://doi.org/10.21273/JASHS.100.4.435.

Everett PH. 1976. Effect of nitrogen and potassium rates on fruit yield and size of mulch-grown staked tomatoes. Proc Annu Meet Fla State Hort Soc. 119:284–288.

FAO. 2021. World Food and Agriculture – Statistical Yearbook 2021. FAO, Rome, Italy. https://doi.org/10.4060/cb4477en.

Florida Tomato Committee. 2022. Florida Tomatoes 2022 Annual Report. https://www.floridatomatoes.org/wp-content/themes/fltomatoes/images/annual%20report%2022.pdf.

Hartz TK, Hochmuth GJ. 1996. Fertility management of drip-irrigated vegetables. HortTechnology. 6(3):168–172. https://doi.org/10.21273/HORTTECH.6.3.168.

Hartz TK, Smith RF. 2009. Controlled-release fertilizer for vegetable production: The California experience. HortTechnology. 19(1):20–22. https://doi.org/10.21273/HORTTECH.19.1.20.

Hills FJ, Broadbent FE, Lorenz OA. 1983. Fertilizer nitrogen utilization by corn, tomato and sugarbeet. Agron J. 75:423–426.

Hochmuth G, Cordasco K. 2000. A summary of N, P, and K research with tomato in Florida. Vegetable Nutrition Management Series. Hort. Sci. Dept., Florida Coop. Ext. Serv., Inst. Food Agr. Sci., Univ. Florida, Gainesville.

Hochmuth G, Hanlon E. 2014. A summary of N, P, and K research with tomato in Florida. Univ. Florida, IFAS, EDIS Publ. SL355. http://edis.ifas.ufl.edu/cv236. [accessed 6 Jun 2015].

Jalpa L, Mylavarapu R. 2023. Current tomato production practices and their effects on plant and soil carbon and nitrogen dynamics. J Plant Nutr. 46(16):1–13. https://doi.org/10.1080/01904167.2023.2220708.

Jalpa L, Mylavarapu RS, Hochmuth GJ, Wright AL, van Santen E. 2020. Apparent recovery and efficiency of nitrogen fertilization in tomato grown on sandy soils. HortTechnology. 30(2):204–211. https://doi.org/10.21273/HORTTECH04480-19.

Jalpa L, Mylavarapu RS, Hochmuth G, Wright A, van Santen E. 2021. Recovery efficiency of applied and residual nitrogen fertilizer in tomatoes grown on sandy soils using the 15N technique. Scientia Hortic. 278:109861. https://doi.org/10.1016/j.scienta.2020.109861.

Kennedy TL, Suddick EC, Six J. 2013. Reduced nitrous oxide emissions and increased yields in California tomato cropping systems under drip irrigation and fertigation. Agric Ecosyst Environ. 170:16–27.

Kinoshita T, Masuda M. 2011. Differential nutrient uptake and its transport in tomato plants on different fertilizer regimens. HortScience. 46(8): 1170–1175. https://doi.org/10.21273/HORTSCI.46.8.1170.

Knoepp JD, Swank WT. 1998. Rates of nitrogen mineralization across an elevation and vegetation gradient in the southern Appalachians. Plant Soil. 204(2):235–241. https://doi.org/10.1023/A:1004375412512.

Lawrencia D, Wong SK, Low DYS, Goh BH, Goh JK, Ruktanonchai UR, Soottitantawat A, Lee LH, Tang SY. 2021. Controlled release fertilizers: A review on coating materials and mechanism of release. Plants. 10(2):1–26. https://doi.org/10.3390/plants10020238.

Mengel K. 1983. Responses of various crop species and cultivars to fertilizer application. Plant Soil. 72:302–319. https://doi.org/10.1007/BF02181970.

Mengel K, Hutsch B, Kane Y. 2006. Nitrogen fertilizer application rates on cereal crops according to available mineral and organic soil nitrogen. Eur J Agron. 24:343–348.

Mikkelsen RL. 2011. The “4R” nutrient stewardship framework for horticulture. HortTechnology. 21(6):658–662. https://doi.org/10.21273/horttech.21.6.658.

Milliken GA, Johnson DE. 2009. Analysis of messy data: Volume 1. Designed experiments (2nd ed). CRC Press, Boca Raton, FL, USA.

Mosier AR, Syers JK, Freney JR. 2004. Nitrogen fertilizer: An essential component of increased food, feed, and fiber production, p 3–15. In: Agriculture and the nitrogen cycle: assessing the impacts of fertilizer use on food production and the environment. Island Press, Washington, DC, USA.

Mylavarapu R, Hochmuth G, Liu G. 2022. UF/IFAS standardized nutrient recommendations for vegetable crop production in Florida: CIR1152/CV002, Rev. 12/2021. EDIS. 2021(6). https://doi.org/10.32473/edis-cv002-2021.

Mylavarapu RS, Wilkinson N, Yvens J. 2024. UF/IFAS Analytical Services Laboratories (ANSERV Labs): Analytical procedures and training manual: Circular 1248/SS312, 1/2024. EDIS. 2024(1). https://doi.org/10.32473/edis-SS312-2002.

Neeteson JJ. 1995. Nitrogen management for intensively grown arable crops and field vegetables, p 295–325. In: Bacon PE (ed). Nitrogen fertilization in the environment. Marcel Dekker, New York, NY, USA.

Olson S, Stall W, Vallad G, Webb S, Taylor T, Smith SA, Simonne E, McAvoy E, Santos B. 2010. Tomato production in Florida, p 291–312. In: Olson S, Simonne E (eds). Vegetable production handbook. Vance Publishing, Lenexa, KS, USA.

Ozores-Hampton MP, Simonne E, McAvoy E, Roka F, Stansly P, Shukla S, Roberts P, Morgan K, Cushman K, Obreza T, Gilreath P, Parmenter D. 2006. Nitrogen Best Management Practice with tomato production in Florida in the 2005-2006 season. Proc Annu Meet Fla State Hort Soc. 119:284–288.

Ozores-Hampton M, di Gioia F, Sato S, Simonne E, Morgan K. 2015. Effects of nitrogen rates on nitrogen, phosphorous, and potassium partitioning, accumulation, and use efficiency in seepage-irrigated fresh market tomatoes. HortScience. 50(11):1636–1643. https://doi.org/10.21273/HORTSCI.50.11.1636.

Ramos C, Agut A, Lidón AL. 2002. Nitrate leaching in important crops of the Valencian Community region (Spain). Environ Pollut. 118(2): 215–223. https://doi.org/10.1016/S0269-7491(01)00314-1.

Sainju UM, Singh BP, Whitehead WF. 2002. Long-term effects of tillage, cover crops, and nitrogen fertilization on organic carbon and nitrogen concentrations in sandy loam soils in Georgia, USA. Soil Tillage Res. 63(3-4):167–179. https://doi.org/10.1016/S0167-1987(01)00244-6.

Saville DJ. 2015. Multiple comparison procedures - cutting the Gordian knot. Agron J. 107:730–735.

Scholberg J, McNeal BL, Boote KJ, Jones JW, Locascio SJ, Olson SM. 2000. Nitrogen stress effects on growth and nitrogen accumulation by field-grown tomato. Agron J. 92(1):159–167.

Sempeho SI, Kim HT, Mubofu E, Hilonga A. 2014. Meticulous overview on the controlled release fertilizers. Advances in Chemistry. 2014:1–16. https://doi.org/10.1155/2014/363071.

USDA. 1991. United States standards for grades of fresh tomatoes. United States Department of Agriculture, Agricultural Marketing Service, Fruit and Vegetable Division, Fresh Products Branch. https://www.ams.usda.gov/sites/default/files/media/Tomato_Standard%5B1%5D.pdf. [accessed 16 Nov 2017].

USDA-NASS. 2022. Vegetables 2017 summary. https://usda.library.cornell.edu/concern/publications/02870v86p. [accessed 21 Feb 2022].

USDA-NRCS. 2022. Web Soil Survey. Websoilsurvey.sc.egov.usda.gov. [accessed 13 Jan 2018].

van Eerd LL, Turnbull JJD, Bakker CJ, Vyn RJ, McKeown AW, Westerveld SM. 2018. Comparing soluble to controlled-release nitrogen fertilizers: Storage cabbage yield, profit margins, and N use efficiency. Can J Plant Sci. 98(4):815–829. https://doi.org/10.1139/cjps-2017-0277.

Zotarelli L, Dukes MD, Scholberg JM, Hanselman T, Le Femminella K, Munoz-Carpena R. 2008. Nitrogen and water use efficiency of zucchini squash for a plastic mulch bed system on a sandy soil. Scientia Hortic. 116(1):8–16.

Zotarelli L, Dukes MD, Scholberg JMS, Muñoz-Carpena R, Icerman J. 2009a. Tomato nitrogen accumulation and fertilizer use efficiency on a sandy soil, as affected by nitrogen rate and irrigation scheduling. Agr Water Mgt. 96(8):1247–1258. https://doi.org/10.1016/j.agwat.2009.03.019.

Zotarelli L, Scholberg JM, Dukes MD, Muñoz-Carpena R, Icerman J. 2009b. Tomato yield, biomass accumulation, root distribution and irrigation water use efficiency on a sandy soil, as affected by nitrogen rate and irrigation scheduling. Agr Water Mgt. 96(1):23–34. https://doi.org/10.1016/j.agwat.2008.06.007.