PLANTING DENSITY AND NITROGEN FERTILIZER RATE EFFECT ON VIDALIA ONION (ALLIUM CEPA) YIELD AND BULB SIZE DISTRIBUTION.

by

ELVIS PULICI

(Under the Direction of Theodore McAvoy)

ABSTRACT

This study, conducted at the University of Georgia Vidalia Onion and Vegetable Research Center, evaluated the effects of planting density and nitrogen rates on yield, nutrient uptake, and flavor quality of Vidalia onions (*Allium cepa* L.). Three planting densities (58,000, 87,000, and 116,000 plants/acre) and nitrogen rates (80, 100, and 120 lb/acre) were tested. Higher plant density improved marketable yield and promoted preferred jumbo-sized onions. Dry weight yield was boosted at 100–120 lb/acre nitrogen under moderate and high density. Nutrient uptake increased with nitrogen rate and density, but bulb nutrient allocation decreased at high plant density. Pungency levels remained below the threshold (<4.8 µmol/g), while lachrymatory factor and methyl thiosulfinates levels varied, indicating potential flavor differences. The findings highlight the importance of balancing planting density and nitrogen rates to optimize yield, nutrient uptake, and flavor quality in Vidalia onion production.

INDEX WORDS: Vidalia onion, *Allium cepa*, planting density, nitrogen fertilizer, yield, bulb size, nutrient uptake, pungency, lachrymatory factor, agronomic management.

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DEDICATION

To my wife and daughter, who have always believed in my potential and supported me through every moment of this journey.

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Introduction

Onion (*Allium cepa* L.) is an important vegetable in the United States, with the fresh market valued at $1.2 billion (USDA, 2024). Georgia is an important state for vegetable cultivation, especially known for its Vidalia sweet onions, which thrive in the region's low-sulfur soils, mild winters, and abundant rainfall (Boyhan & Coolong, 2017). Vidalia onions were grown on 11,560 acres, making up 14% of Georgia's vegetable production and generating $187 million in revenue (Georgia Farm Gate Value Report, 2025). Their popularity continues to rise due to their mild flavor, national recognition, and regulatory protections (Boyhan & Torrance, 2002).

Optimizing planting density is essential for maximizing yield and maintaining bulb quality. High planting densities can increase overall yield, but they may also lead to smaller bulbs due to competition for water, sunlight, and nutrients. Conversely, low densities might not fully utilize available resources (Caruso et al., 2014; Devulkar et al., 2015; Rumpel & Felczynski, 1997; Walle et al., 2018). Nitrogen is another critical factor influencing onion growth, nutrient uptake, and flavor. While nitrogen promotes high yields, excessive amounts can lead to increased vegetative growth, delayed maturity, and reduced storage quality (Blumenthal et al., 2008; Rodrigues et al., 2018). Research indicates that applying nitrogen at the time of bulb initiation can enhance yield, but high rates may heighten pungency (Coolong et al., 2005; Jilani et al., 2004).

Both planting density and nitrogen rates can affect yield, bulb size, and quality attributes such as pungency, lachrymatory factor (LF), and methyl thiosulfinate levels (Coolong, 2003; Eady et al., 2008). However, limited research has investigated their combined effect on marketable yield, nutrient uptake, and flavor quality. Vidalia growers often adjust nitrogen levels and planting densities to optimize yield and bulb quality, raising the question of whether high planting densities demand high nitrogen levels to sustain plant performance. Previous research has shown that planting density can influence competition for nutrients, light, and water, potentially altering nutrient uptake and yield (Russo, 2008; Geisseler et al., 2022). The findings of this research are expected to provide Vidalia onion growers with practical strategies for optimizing nitrogen use and planting density while sustaining yield and bulb quality.

Research hypotheses

This study hypothesizes that optimal planting densities, when combined with appropriate nitrogen rates, will enhance marketable yield and desirable bulb sizes while potentially influencing flavor quality through nutrient uptake.

Research Objective

The objective of this study was to analyze the effects of three planting densities (58,000, 87,000, and 116,000 plants/acre) and nitrogen rates (80, 100, and 120 lb/acre) on yield, bulb size distribution, nutrient absorption, and flavor quality.

This thesis has two studies that address the research objective:

1) Evaluate marketable yield and bulb size distribution based on different planting densities and nitrogen treatments.

2) Assess the effects of planting density and nitrogen rates on nutrient uptake in onion bulbs and leaves, as well as their impact on flavor-related compounds.

Literature Review

Onion Plant

Onion (*Allium cepa* L.), belonging to the family Amaryllidaceae, is among the widely cultivated and most consumed vegetable crops worldwide (Ochar & Kim, 2023). The precise geographic origin is unclear, but it is believed that onions originated in Asia (Anastassakis, 2022) and were introduced to the Americas by the British (Pareek et al., 2017).

The diversity of onion cultivars is highly adaptable to a variety of climate conditions across different geographical locations, which is why they are cultivated in over 150 countries (FAO, 2025). Onion bulb formation varies in response to photoperiod length (or day length). For this reason, onions are classified into three categories: short-day, intermediate, and long-day varieties, which require 10-13 hours of daylight, 13-14 hours or more than 14 hours of daylight, respectively (Boyhan et al., 2007; Brewster, 1990). However, other factors, including temperature, light quality, plant nutrition, and water availability can also influence bulb formation and growth (Brewster, 1990).

Onions can be consumed raw, but they are commonly utilized as an ingredient in culinary preparations to enrich the flavor of the foods. Several varieties of onions are available in the market, distinguished by color (yellow, brown, red, and white), the shape of the bulb (globe, round, or flat), size (colossal, jumbo, and medium), and taste (sweet or pungent) as well as final use (fresh consumption or dehydrated and processed) (Harrison et al., 2008; Nair, 2021). The genetic composition, environmental conditions, and post-harvest are among the major factors influencing these characteristics (Randle & Lancaster, 2002).

Economic Importance of Onion

Onions are among the most important vegetables cultivated in the United States (U.S.). The U.S. is the fourth-largest producer of dry bulb onions in the world, after India, China, and Egypt (FAO, 2025). In the U.S., onions are the 6th most significant vegetable crop. In 2024, the

U.S. fresh market for onion production was valued at approximately $1.73 billion, with 136,500 acres planted (USDA, 2025).

The State of Georgia ranks 4th place among the top producers of this crop. California is the leading producer in the U.S., followed by Washington, and Oregon (USDA, 2025). According to the Georgia Farm Gate Value Report (2025), in 2023 over 11,000 acres of onions were planted, representing 14.04% of all vegetables produced in the state. With a total value of $187 million, onions are an important crop for the State.

Vidalia Onions

Vidalia onion was named for the town in which they were first cultivated and were officially declared as the state of Georgia's vegetable in 1990 and they are known for the distinct sweet flavor and low pungency (below 4.8 µmol/g) due to the low levels of sulfur compounds in the bulbs (Vidalia Onions Grown in Georgia, 2015; University of Georgia Extension, 2024). These onions are defined as short-day, granex (shape) type yellow varieties that are exclusively cultivated in 20 specific counties in the southeastern region of Georgia as delineated by Federal Marketing Order No. 955 (USDA, 1989).

The success of Vidalia onion production in Georgia is largely due to the region's unique factors characterized by sandy loam soils with low-sulfur content, where mild winters and adequate rainfall supply create favorable environmental conditions for growing sweet onions (Boyhan & Torrance, 2002).

Onion Flavor Attributes

The pungency is the most important characteristic of onions. This characteristic is attributed to the presence of organosulfur compounds, particularly S-alk(en)yl cysteine sulfoxides (ACSOs) (Lancaster & Boland, 1990). The concentration levels of ACSOs vary, directly influencing the pungency of the bulb. The three principal ACSOs are S-1-propenyl cysteine sulfoxide (PRENCSO), S-methyl-cysteine sulfoxide (MCSO), and S-propyl-cysteine sulfoxide (PCSO) and are present in high, medium, and low concentrations, respectively, corresponding to varying degrees of pungency (Boelens et al., 1971; Lancaster et al., 1998).

Pungency in onions is produced when the tissues are mechanically disrupted, such as through cutting or macerating. The enzyme alliinase hydrolyses the ACSOs, resulting in the formation of a range of volatile compounds, including propanethial-S-oxide, which is responsible for the lachrymatory factor, causing ocular irritation and tearing during onion cutting, and is the primary source of the heat and mouth burn (Yoo et al., 2012). Additionally, pyruvic acid, ammonia and volatile sulfur compounds, all of which contribute to the distinctive flavor and aroma of onions (Yoo et al., 2012). Pungency levels are commonly quantified by measuring pyruvic acid, a stable bi-product that is strongly correlated with the total ACSO content in onions (Crowther et al., 2005).

Studies have demonstrated that the intensity of onion flavor is influenced by environmental conditions. The sulfur content in soil is the major environmental factor influencing the flavor of onions, high sulfur levels result in increased pungency, as well as high concentrations of lachrymatory factors and thiosulfinates, which are flavor precursors associated with off-flavors (Randle et al., 1994; Randle & Lancaster, 2002).

Sweetness is another important factor in onion flavor, with sugars like glucose, sucrose, and fructose constituting the majority of the soluble solids in the onion (Crowther et al., 2005). The sugar content directly influences sweetness, while the overall flavor of the onion is determined by the ratio of sugar to pungency (Vavrina & Smittle, 1993).

Nitrogen Management in Onion

Nitrogen (N) is a crucial nutrient for the growth and development of plants, as it is important in various biochemical and physiological processes. Onions primarily absorb nitrogen in the forms of nitrate (NO_3^-) and ammonium (NH_4^+) and adequate nitrogen application significantly enhances both the yield and quality of onions (Leghari et al., 2016; Ohyama, 2010).

Onions have shallow, thin root systems that limit their ability to access deeper layers of soil for the uptake of water and nutrients, which makes them particularly sensitive to soil conditions (Brewster, 2008; Halvorson et al., 2002). As a high-nitrogen-demand crop, onions require proper fertilizer nitrogen application levels to maintain productivity; the insufficiency of nitrogen can lead to significant reductions in yield (Balemi et al., 2007; Khokhar, 2008).

Vidalia onions are grown in sandy loam soils with low sulfur content, along with a good volume of rainfall and irrigation, which can lead to increased nitrogen leaching, making it difficult for growers to maintain adequate nitrogen levels throughout the crop cycle (de Jesus, 2023; de Jesus et al., 2024). Research on nitrogen fertilizer use for short-day onions in this region began in the 1980s and early studies indicated no significant yield differences among nitrogen rates of 84, 168, and 224 kg per hectare (Batal et al., 1994). However, later research showed that splitting nitrogen applications and applying a total of 250 kg per hectare resulted in the high yields (Boyhan et al., 2007).

Additionally, nitrogen levels have a significant impact on the quality of short-day onions, where low nitrogen application can decrease yields, while excessive nitrogen can increase pungency and levels of gallic and pyruvic acids, which can reduce sweetness (da Silva et al., 2022; Kim et al., 2017). Therefore, effective nitrogen management is critical for both yield and quality in Vidalia onion production.

Importance of Planting Density

Optimizing onion plant density in a specific area is crucial for maximizing crop yield. High plant density may lead the plants to compete for essential resources like sunlight, water, and nutrients. On the other hand, in low plant density, available resources may not be fully utilized, resulting in waste (Caliskan et al., 2009; Fekry, 2017).

Onions are categorized by size, which can be colossal (≥3¾ inches), jumbo (≥3 inches), or medium (≥2 inches) (USDA, 2014). Plant density significantly impacts the distribution of onion sizes and overall yield, which affects market preferences and grower profitability (Kanton et al., 2003). Additionally, plant populations can be affected by agronomic practices, physiological disorders such as bolting, and environmental factors including temperature, water availability, and nutrient uptake, all of which influence the quality of onions (Baldwin et al., 2014; Caruso et al., 2014; Russo, 2008). Therefore, choosing the right planting density that aligns with market preferences and the quality of onion yields and bulbs is essential for maximizing economic returns (Visser & van den Berg, 1998).

Previously research has shown that optimizing plant density is essential for enhancing nutrient uptake and maximizing onion yields. Ciampitti & Vyn (2011) highlight that the right planting density is critical for improving resource utilization and overall plant performance. Furthermore, Attaya et al. (2024) emphasize that adjusting plant density is vital for achieving high yields while maintaining bulb size and quality. Additionally, Vidigal et al. (2023) demonstrated that high planting densities increase total nitrogen uptake, suggesting that optimizing plant population may improve nutrient absorption, an important consideration in understanding how density and nitrogen rates interact to influence nutrient uptake in onion plants.

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CHAPTER 2

EVALUATION OF VIDALIA ONION PRODUCTIVITY IN RESPONSE TO PLANT DENSITY AND NITROGEN APPLICATION RATES

Pulici, E., McAvoy, T. Diaz-Perez, J. C., & Sintim, H. Y. To be submitted to a peer-reviewed journal

Abstract

This study investigated whether nitrogen requirements for Vidalia onion (*Allium cepa* L.) may vary with planting density, based on the premise that increased plant populations may demand high nitrogen rates to maintain yield and bulb quality. Conducted at the Vidalia Onion and Vegetable Research Center in Lyons, Georgia, USA, the study tested planting densities of 58,000, 87,000, and 116,000 plants/acre alongside nitrogen rates of 80, 100, and 120 lb/acre. Utilizing a randomized complete block design, the findings revealed that a density of 116,000 plants/acre increased marketable yields while reducing the number of large-sized onions and promoting the preferred jumbo size. Moreover, the interaction between nitrogen rates and planting density affected dry weight yield, with the best outcomes observed at high densities (87,000 and 116,000 plants/acre) using (100 or 120 lb/acre) of nitrogen.

Introduction

Onions are among the most widely cultivated vegetables globally and can be grown in various regions, from cold subarctic areas to warm equatorial zones. However, they thrive best in temperate and subtropical climates (Galmarini, 2018). According to the United States Department of Agriculture (USDA, 2024), the U.S. fresh onion market was valued at approximately $1.2 billion, and Georgia is one of the important producing states. According to the 2025 Georgia Farm Gate Value Report, approximately 11,560 acres of onions were planted, making up 14% of the state’s total vegetable production and contributing $187 million, highlighting the economic importance of onions to Georgia agriculture. Vidalia sweet onions are grown exclusively in southeastern Georgia due to the region's low soil sulfur content, mild winters, and ample rainfall (Boyhan & Coolong, 2017). Over the past decade, their availability has significantly increased, driven by national brand recognition and regulatory protection of the Vidalia name (Boyhan & Torrance, 2002).

For onion cultivation, it is crucial to have the right number of plants in a field to maximize crop yield. When plants are overloaded in the field, they compete for sunlight, water, and nutrients, which can delay their growth and reduce overall yield (Yeshiwas et al., 2024). On the other hand, if there are few plants, the available resources may not be fully utilized, resulting in wasted space and nutrients (Devulkar et al., 2015; Walle et al., 2018). Planting density affects both yield and quality of the bulbs, and it has been investigated in several studies on onion. Caruso et al. (2014) studied the impact of plant density on onion yield and quality in southern Italy and discovered that while total marketable yield increased with high planting densities, the size of individual bulbs tended to decrease. Similarly, Jilani et al. (2009) reported that increased plant density can reduce mean bulb weight and plant height, indicating that overcrowding negatively affects individual plant development.

Contemporary agriculture significantly impacts natural resources due to the rising population and demand for goods, straining land, water, and agricultural systems (Foley et al., 2011). Inefficiencies in resource use, especially nitrogen, can result in environmental issues like soil degradation, eutrophication, groundwater pollution, and ammonia emissions (Spiertz, 2009).

Nitrogen (N) is one of the essential nutrients for crops to have high yields and quality (Blumenthal et al., 2008). However, excessive nitrogen can lead to increased onion vegetative growth by boosting plant water content and protein synthesis, and this overgrowth can reduce disease resistance and negatively affect bulb quality (Rodrigues et al., 2018).

Numerous studies have evaluated the best N application timing and optimal rates to meet crop needs and quality while preventing environmental issues. Coolong et al. (2005) assessed the effects of various N fertilizer rates (75, 105, and 135 lb./acre) and the timing of the final N application at bulb initiation, during growth and maturation on short-day onion production. The results showed that applying the last N at bulb initiation yielded high marketable yield. In contrast, high N rates increased yield and late N applications could raise bulb pungency and impact storage quality. Similarly, Jilani et al. (2004) examined the impact of different N levels (0, 40, 80, 120, 160, and 200 kg/ha) on onion growth and yield. Results indicated that total bulb yield increased with N application up to 120 kg/ha; beyond this point, yields declined. Optimal yields were achieved at 120 kg/ha, while high rates cause excessive vegetative growth and delayed maturity.

Vidalia onion growers use different nitrogen rates and planting densities; however, it is still unclear whether more plants in a field require more nitrogen to maintain good growth and bulb quality. While some studies show that high planting densities can increase competition between plants, there is limited research on how planting density and nitrogen rate work together in Vidalia sweet onion production. To address this, the objective of this study was to conduct this experiment to determine the ideal planting density and nitrogen fertilizer application rates on desirable bulb size distribution, marketable yield, and quality. This information may help growers better understand and make informed decisions regarding the optimal onion plant population and nitrogen application to improve their crop yield and bulb size distributions.

Materials & Methods

Experimental Site and Design

The experiments were conducted at the University of Georgia Vidalia Onion and Vegetable Research Center, located at Lyons, Georgia, USA (latitude 32°17’.17" N, longitude 82°13'12" W), during the winters of 2023 and 2024. This region is well known for mild winters, low-sulfur soils, and sufficient rainwater (da Silva et al., 2022). Seeds of Sweet Magnolia onion variety were planted in nursery onion beds for approximately 8 weeks at a seeding rate of 60-70 seeds per linear foot. Transplants were hand-pulled from nursery beds, bundled in groups of 50 to 80, and secured with a rubber band. Each transplant had an approximate diameter of 7 mm. Seedlings were then transported to the field in mesh bags and transplanted in the first year on 28 Nov 2022 and the second year on 14 Nov 2023. The experiment area was then prepared using a tractor, leveling harrow disc, and tillage equipment. After that, raised beds were created using a tractor and mounted rotary tiller equipment. Beds were spaced 6 feet apart from center to center and were approximately 6 inches tall. Each plot was a single bed which measured 20 feet in length, resulting in a total area of 120 square feet.

Planting Densities and Transplanting Method

The study evaluated three different planting densities: 58,000, 87,000, and 116,000 plants/acre. To ensure precise spacing, holes were made 1 to 2 inches deep using a pegger or hole puncher (Figure 1). Each bed contained four planting lines, with spacing adjusted according to the density.

For the low density of 58,000 plants/acre, the pegger has pins spaced 6 inches apart, resulting in approximately 160 plants/plot. At the medium density of 87,000 plants/acre, the pin spacing was 4 inches, around 240 plants/plot. For the high density of 116,000 plants/acre, twin pins were spaced 6 inches apart, allowing for approximately 320 plants/plot. This method ensured a uniform distribution of plants across all treatments.

Fertilizer Application and Schedule

Three nitrogen fertilizer application rates were used: 80, 100, and 120 lb/acre, distributed over five applications throughout the onion growing season. The first application took place on 13 December 2023 and 2024, utilizing NPK fertilizer (5N-10P-15K) Rainbow Plant Food, Timac

Agro USA. Each treatment received an equal application of 10 lb of nitrogen. The second application occurred on 10 January 2023 and was repeated on 10 January 2024. It employed the NPK fertilizer (6N-6P-18K) Rainbow Plant Food, Timac Agro USA, and was administered equally across all treatments, 18 lb of nitrogen. The third application was conducted on 19 January 2023 and repeated on 19 January 2024 using NPK fertilizer (5N-10P-15K) Rainbow Plant Food, Timac Agro USA. Each treatment received 25 lb. of nitrogen. The final two applications were made at the beginning and end of February, using calcium nitrate fertilizer (15.5N-0P-0K) Yara Liva (Tropicote), Yara, Tampa, FL, USA. The amount of nitrogen administered varied by treatment, with applications of 13.5, 23.5, and 33.5 lb. respectively to 80, 100, and 120 lb/acre. The same methods and applications were used in both years of the experiment, employing a broadcasting method with fertilizer spreading equipment. The experiment was conducted using a randomized complete block design, with four replications and nine treatments, totaling 36 plots for both years of the experiment.

Irrigation and Water Management

The onion plants received water through a center-pivot irrigation system with overhead sprinklers. This irrigation method and procedures were followed by the recommendations of the Onion Production Guide (Boyhan & Torrance, 2002).

Weed and Pest Management

Pre-emergent herbicides were selected and applied approximately one week after planting, following the recommendations for transplanted onions outlined in the Georgia Onion Production Guide (Boyhan & Coolong, 2017). Chemicals, insecticides, and fungicides were used as part of a routine pest management program for the onion crop, following the guidelines in the Georgia Pest

Management Handbook: Commercial Edition (University of Georgia Cooperative Extension, 2025).

Harvest, Curing, and Yield Classification

In 2024, plants experienced bolting. For this reason, all flowing plants were counted prior to harvest, as this could affect quality and yield production. The experiments were harvested when Sweet Magnolia onions showed good maturity with about 50% of the plants having their tops broken or bent down.

Plots were undercut in the first year on 09 May 2023, and the second year on 01 May 2024. After the undercutting process, the onions were left to cure in the field for five days. Following this, the bulbs were hand harvested. The tops and roots were trimmed using a carbon steel onion shear, and the onions were placed in labeled mesh bags. They were then dried for one week at a forced air temperature of 100.4°F. After drying, the bags from the plots were weighed and processed through an onion grading machine (Haines Equipment Inc., New York, USA) to remove unmarketable onions and sort marketable onions by size (Figure 2). According to the U.S. Department of Agriculture (2014), onions were classified by size as follows: colossal (3 ¾ inches or larger), jumbo (3 inches), and medium (2 inches or larger).

After grading, marketable sizes were weighed again. This method of classification and the associated weight specifications were used to determine marketable production yields based on various planting densities and nitrogen application rates.

Statistical Analysis

Statistical analyses were conducted using JMP Pro 17 (SAS Institute Inc., 2023) to evaluate variations in yield, including total dry weight, individual onion sizes (colossal, jumbo, medium), and marketable yield across three planting densities and three nitrogen application rates, as well as their main effects and interactions over both years of the study. A mixed-model analysis of variance (ANOVA) was used to assess significant differences. Year, planting density, and nitrogen rate were considered fixed effects, while replication was treated as a random effect. Response variables included dry weight, size classifications (colossal, jumbo, medium), and marketable and unmarketable yield. Mean separation was conducted using Tukey's HSD test at $P < 0.05$. When significant interactions were detected, analysis was performed, and simple effects analysis was conducted to identify specific differences among treatment combinations using RStudio (Posit Team, 2023).

Results

Effects of Year on Onion Yield and Bulb Size Distribution

A significant difference was observed in onion dry weight, bulb sizes, and both marketable and unmarketable yields between the two years (Table 1). Dry weight was high in 2024 (1,811 bags/acre) compared to 2023 (1,554 bags/acre). Colossal yield remained consistent across both years, averaging 232 bags/acre. However, jumbo yield was high in 2023 (762 bags/acre) than in 2024 (513 bags/acre). Medium-sized onions also had a high yield in 2023 (68 bags/acre) compared to 2024 (21 bags/acre). Consequently, marketable yield was greater in 2023 (1,062 bags/acre) compared to 2024 (750 bags/acre), whereas unmarketable yield was high in 2024 (1,069 bags/acre) than in 2023 (495 bags/acre).

Table 1: Effects of year on onion yield and bulb size distribution.

Year	Yield in 40 lbs. Bags per Acre					
	Dry Weight	Colossal Size	Jumbo Size	Medium Size	Marketable Yield	Unmarketable Yield
2023	1554 b	232 a	762 a	68 a	1062 a	495 b
2024	1811 a	232 a	513 b	21 b	750 b	1069 a

p-value	<.0001*	0.9909	<.0001*	<.0001*	<.0001*	<.0001*

Means followed by different letters within a column are significantly different at p≤0.05 based on Tukey's HSD test.

Effect of Bolting in Relation to Planting Density and Nitrogen Rate in 2024

In 2023, onion bolting did not occur. However, in 2024 (Table 2), a significant difference in bolting was observed among plants cultivated at varying densities. The plants grown at a high planting density of 116,000 plants/acre experienced a high incidence of bolting, with 18,876 bolting plants representing 16.27% of the total population compared to those at low densities of 87,000 and 58,000 plants/acre which exhibited a bolting rate of 2.5%, (2,178 plants bolting) and 0.88% (514 plants bolting), respectively. There was no significant difference in bolting between the two low densities or for nitrogen rates or the interaction between densities and nitrogen rates.

Table 2: Effect of bolting on planting density in 2024.

Density (Plants/Acre)	Bolting (Plants/Acre)	% / Acre
58 000	514 b	0.88 b
87 000	2178 b	2.5 b
116 000	18876 a	16.27 a
p-value	<.0001*	<.0001*

Means followed by different letters within a column are significantly different at p≤0.05, based on Tukey's HSD test. Means followed by the same letter are not significantly different.

Effects of Planting Density on Onion Yield and Bulb Size Distribution

A significant impact of planting density was observed on onion yield, bulb size distribution, and marketable yield among the three planting densities (Table 3). The high dry-weight production occurred at 116,000 plants/acre, yielding (2,021 bags/acre, 40 lb/each). This was followed by 87,000 plants/acre, with a yield of (1,628 bags), and 58,000 plants/acre, which produced (1,398 bags). Colossal-sized onion yield was high at 58,000 plants/acre, yielding (274 bags), and was similar for 87,000 plants/acre, which produced (260 bags). In contrast, 116,000 plants/acre yielded the low amount of colossal onions, with only (161 bags). Jumbo-sized onions yielded the most at 116,000 plants/acre, with (1,043 bags), followed by 87,000 plants/acre, which yielded (571 bags), and 58,000 plants/acre, which produced (299 bags). The yield of medium-sized onions was significantly high at 116,000 plants/acre (93 bags) compared to both 87,000 plants/acre (30 bags) and 58,000 plants/acre (11 bags). Marketable yield followed a similar trend, with the high at 116,000 plants/acre (1,295 bags), followed by 87,000 plants/acre (856 bags) and 58,000 plants/acre (566 bags). Conversely, unmarketable yield showed no significant differences among the planting densities.

Table 3: Effects of planting density on onion yield and size distribution.

Density (Plants/Acre)	Yield in 40 lb. bags/acre					
	Dry Weight	Colossal Size	Jumbo Size	Medium Size	Marketable Yield	Unmarketable Yield
58 000	1398 c	274 a	299 c	11 b	566 c	889 a
87 000	1628 b	260 a	571 b	30 b	856 b	747 a
116 000	2021 a	161 b	1043 a	93 a	1295 a	711 a
p-value	<.0001*	0.0013*	<.0001*	<.0001*	<.0001*	0.0589

Means followed by different letters within a column are significantly different at p≤0.05, based on Tukey's HSD test. Means followed by the same letter are not significantly different.

Interaction Effects of Year and Planting Density on Onion Yield and Bulb Size Distribution

A significant interaction between year and planting density was observed for onion dry weight and medium-sized onion yield (Table 4). At a planting density of 58,000 plants/acre, dry weight did not significantly differ between 2023 (1,142 bags/acre, 40 lb/ each) and 2024 (1,427 bags/acre). However, at densities of 87,000 and 116,000 plants/acre, dry weight was significantly high in 2024, with 1,741 and 2,266 bags/acre, respectively, compared to 2023, which had 1,516 and 1,640 bags/acre, respectively. In both years, the high dry weight was observed at the 116,000 plants/acre density, followed by 87,000 and then 58,000 plants/acre. For medium-sized onions, the yield was significantly high in 2023 at all planting densities compared to 2024. Within each year, the high yield of medium-sized onions was recorded at the 116,000 plants/acre density (130 bags in 2023 and 45 bags in 2024) compared to the low densities. There were no significant interactions between years for other bulb sizes (colossal and jumbo) or for marketable and unmarketable yields.

Table 4: Interaction effects of year and planting density on onion yield and size distribution for dry weight and medium-size onions.

Yield in 40 lb. Bags/Acre					
Variable	Interaction	Plant Density (Plants/acre)			
Dry Weight	Year	58 000	87 000	116 000	p-value
	2023	1142 Ab	1516 Bab	1640 Ba	0.0308*
	2024	1427 Ac	1741 Ab	2266 Aa	<.0001*
	p-value	0.1284	0.0045*	0.0009*	
Medium Size	Year	58 000	87 000	116 000	p-value
	2023	14 Ab	48 Ab	130 Aa	<.0001*
	2024	2 Bb	4 Bb	45 Ba	<.0001*
	p-value	0.0448	<.0001*	<.0001*	

Means followed by different letters indicate significant differences at $p \leq 0.05$ based on Tukey's HSD test. Capital letters indicate comparisons within columns, and lowercase letters indicate comparisons within rows.

Effects of Nitrogen Rate on Onion Yield and Size Distribution

The nitrogen application rates (120, 100, and 80 lb/acre) did not significantly impact onion yield or the distribution of bulb sizes. The dry weight, colossal, jumbo, medium-sized onions, and the marketable and unmarketable yields were similar across all nitrogen treatments (Table 5).

Table 5: Effects of nitrogen rate on onion yield and size distribution.

Yield in 40 lb. Bags/acre

Nitrogen Rate (lb/acre)	Dry Weight	Colossal Size	Jumbo Size	Medium Size	Marketable Yield	Unmarketable Yield
80	1664 a	250 a	600 a	51 a	874 a	790.6 a
100	1684 a	219 a	645 a	42 a	911 a	773.9 a
120	1699 a	225 a	669 a	41 a	932 a	782.3 a
p-value	0.7863	0.6047	0.4290	0.6692	0.6774	0.9755

Means followed by different letters within a column are significantly different at $p \leq 0.05$, based on Tukey's HSD test. Means followed by the same letter are not significantly different.

Interaction Effects of Year and Nitrogen Rate on Onion Yield and Size Distribution

A significant interaction between year and nitrogen rate was observed for onion dry weight (Table 6). At a nitrogen rate of (80 lb/acre), the high dry weight was recorded in 2024 (1,875 bags/acre, 40 lb/each), followed by 2023 (1,318 bags). At 100 lb/acre, no significant difference was detected between years; however, dry weight production was high in 2024 (1,809 bags) compared to 2023 (1,448 bags). Similarly, at 120 lb/acre, dry weight yield was high in 2024 (1,750 bags) versus 2023 (1,532 bags), with no statistical difference between years. Additionally, when comparing nitrogen rates within each year, no statistical differences were observed among (80, 100, and 120 lb/acre). For colossal-sized onions, the interaction between nitrogen rate and year showed a trend suggesting a statistical difference, but this was not observed when comparing nitrogen rates across years or within the same year. At 80 lb/acre, the high yield occurred in 2024 (277 bags), followed by 2023 (175 bags). At 100 lb/acre, the high production was recorded in 2023 (222 bags), while 2024 had a low yield (184 bags). Similarly, at 120 lb/acre, the high yield was in 2023 (233 bags), while the low production occurred in 2024 (187 bags). For marketable yield, at 80 lb./acre, 2024 had the high marketable yield (839 bags), closely followed by 2023 (811 bags), with no significant differences. At 100 lb./acre, the high production was in 2023 (1,084 bags), whereas the low yield for this rate was in 2024 (667 bags). At 120 lb/acre, the high marketable yield was recorded in 2023 (1,058 bags), followed by 2024 (724 bags). No significant interactions or trends were observed for other-sized onions (jumbo and medium) or unmarketable yield.

Table 6: Interaction effects of year and nitrogen rate on onion yield and size distribution

Yield in 40 lb. bags per Acre					
Variable	Interaction	Nitrogen Rate (lb/Acre)			
	Year	80	100	120	p-value
Dry Weight	2023	1318 Ba	1448 Aa	1532 Aa	0.5749
	2024	1875 Aa	1809 Aa	1750 Aa	0.7658
	p-value	0.0025*	0.08	0.29	
Colossal Size	2023	175 Aa	222 Aa	233 Aa	0.5656
	2024	277 Aa	184 Aa	187 Aa	0.128
	p-value	0.10	0.49	0.35	
Marketable Yield	2023	811 Aa	1084 Aa	1058 Aa	0.2639
	2024	839 Aa	667 Ba	724 Ba	0.6192
	p-value	0.87	0.05*	0.05*	

Means followed by different letters indicate significant differences at p≤0.05 based on Tukey's HSD test. Capital letters indicate comparisons within columns, and lowercase letters indicate comparisons within rows.

Interaction Effects of Planting Density and Nitrogen Rate on Onion Yield and Size Distribution

A significant interaction between planting density and nitrogen rate was observed for dry weight production (Table 7). At a nitrogen application rate of 80 lb/acre, no significant differences were detected among the three planting densities. However, the high dry weight production occurred at 116,000 plants/acre, yielding (1,748 bags/acre 40 lb/each), followed by 58,000 plants/acre (1,527 bags) and 87,000 plants/acre (1,514 bags). At 100 lb/acre, a significant difference was noted among planting densities. The high dry weight production was recorded at 116,000 plants/acre (2,050 bags), followed closely by 87,000 plants/acre (1,702 bags). These two densities did not show statistical differences. In contrast, the low dry weight production occurred at 58,000 plants/acre, with (1,134 bags). Similarly, at 120 lb/acre, dry weight production was high at 116,000 plants/acre (2,061 bags), followed by 87,000 plants/acre (1,669 bags). No statistical difference was observed between these two densities. However, the low production was recorded at 58,000 plants/acre (1,193 bags). When nitrogen rates (80, 100, and 120 lb/acre) were analyzed within each planting density (58,000, 87,000, and 116,000 plants/acre), no statistical significance was found. Additionally, no significant interactions were detected for colossal size, jumbo size, marketable yield, or unmarketable yield.

Table 7: Interaction effects of planting density and nitrogen rate on onion yield for dry weight.

Yield in 40 lb. bags/acre					
Variable	Interaction	Nitrogen Rate (lb/acre)			
	Density (Plants/acre)	80	100	120	p- value
Dry Weight	58 000	1527 Aa	1134 Ba	1193 Ba	0.1794
	87 000	1514 Aa	1702 Aa	1669 Aa	0.1526
	116 000	1748 Aa	2050 Aa	2061 Aa	0.3871
	p-value	0.5749	<.0001	0.0002	

Means followed by different letters indicate significant differences at $p \leq 0.05$ based on Tukey's HSD test. Capital letters indicate comparisons within columns, and lowercase letters indicate comparisons within rows.

Discussion

Nitrogen application rates and plant density influenced dry weight, marketable yield, and the desired distribution of bulb sizes, favoring the preferred market jumbo while reducing the production of colossal sizes, which are less desired, with notable annual variations due to different agronomic practices and physiological conditions, such as bolting in 2024.

In 2024, prior to the implementation of the experiment, 2 tons of poultry litter per acre were applied and incorporated into the soil with a composition of 3N–2P–2K with 60% nitrogen availability, contributing approximately 72 pounds of nitrogen per acre across all treatments in which could be disponible for onion plants during the crop cycle. Organic fertilizers primarily contain nitrogen in a form that plants cannot immediately use and must first be broken down by microbes through a process called mineralization, which converts it into usable forms like ammonium and nitrate (Díaz-Pérez et al., 2021). Although this was an unplanned application, it was only acknowledged after the experiment had begun and may have influenced the high dry weight observed in 2024. Mahmoud et al. (2000) found that organic inputs, especially when combined with inorganic fertilizers, significantly enhanced onion growth, dry weight, and nutrient content in bulbs.

However, in this study, the unmarketable yield increased significantly in 2024 by 53%, possibly due to a high incidence of bolting, a physiological disorder. In contrast, marketable yield was high in 2023, showing a 29% increase in total onion yield compared to 2024.

In 2024, the bolting problem significantly affected the marketable yield of onions, resulting in a notable decrease in the number of high-quality onions, particularly at a planting density of 116,000 plants/acre. This issue was observed not only in various field experiments but also in growers' fields in the region, and environmental factors, such as the temperature in 2024, may have prompted the plants to initiate bolting (Madalageri et al., 2024).

According to data from the Georgia Automated Environmental Monitoring Network (n.d.), a comparison of temperature data from two consecutive growing seasons, spanning from November to April, reveals differences that could have impacted Vidalia onions. During the 2022–2023 season, the average daily maximum temperature was 70°F, while the average daily minimum was 49°F, resulting in an overall average of 59°F, with 589 hours below 45°F. In contrast, the 2023–2024 season experienced slightly cooler conditions, with an average daily maximum of 68°F, a minimum of 46°F, and a daily average of 57°F. Additionally, the number of hours recorded below 45°F increased to 694, marking an 18% rise compared to the previous year. This prolonged exposure to chilling temperatures may have influenced vernalization in onion plants, a process known to induce bolting and accelerate flowing (D'Angelo & Goldman, 2018).

Khokhar (2008) found that planting timing and varying seasons can influence onion bolting, bulb yield, and quality, increasing susceptibility to bolting and decreasing marketable yield and bulb quality. Similarly, the onset of bolting in this study likely contributed to the reduction in marketable yield observed in 2024.

Planting density significantly affected the marketable yield and size distribution of Vidalia onions, with the high marketable yield occurring at 116,000 plants/acre (1,295 bags/acre), significantly surpassing yields at 87,000 plants/acre (856 bags/acre) and 58,000 plants/acre (566 bags/acre). These results suggest that the increased marketable yield at high densities is primarily attributed to a greater production of jumbo-sized onions (1,043 bags/acre), which are often preferred in the market due to their commercial value, despite a decline in colossal-sized bulbs at high densities (Wang & Li, 2014). However, the yield of medium-sized onions increased significantly as planting density rose. This finding aligns with previous research indicating that high planting densities generally enhance total marketable yields due to optimized plant populations (Brewster, 2008; Boyhan et al., 2017).

The significant interaction between year and planting density influenced dry weight and medium-sized onion yield. In 2024, dry weight yield increased at high planting densities, with a similar trend observed in 2023, although overall yields were low. For medium-sized onions, yields were consistently high in 2023 across each planting density, particularly at 116,000 plants/acre (130 bags/acre in 2023 and 45 bags/acre in 2024). These results indicate that yearly variability, the influence of seasonal growing conditions, and physiological issues such as bolting in 2024 could have an impact on onion dry weight and medium size yields.

The effects of different growing conditions and environmental factors on onion production were also noted in Salari et al. (2023), where seasons strongly correlate with onion growth, yield, and bulb quality. The findings of this study also align with previous research highlighting the impact of resource competition and stress on onion production. Kanton et al. (2003) examined the effects of planting density on onion growth and yield in Northern Ghana and similarly found that high planting densities resulted in increased total yield but also intensified competition for resources like nutrients, water, and light, leading to smaller bulb sizes and in contrast, low planting densities produced larger bulbs but decreased overall yield. Furthermore, Jilani et al. (2009) observed similar trends, reporting that optimizing planting density significantly affects onion yield and quality by balancing resource availability and plant competition. However, aligning planting density with market preferences for onion size is essential to maximize profitability (Visser & van den Berg, 1998).

Nitrogen application rates did not significantly change onion dry weight, size distribution, marketable yield, or unmarketable yield. On the other hand, the interaction between the year and nitrogen rates affected dry weight, marketable yields, and showed a trend towards colossal-sized bulbs. Additionally, the unplanned application of two tons per acre of poultry litter as organic fertilizer during the fallow period between the 2023 and 2024 growing seasons could have influenced results.

In 2024, applying 80 lbs. of nitrogen/acre increased the dry weight by 29.72% compared to 2023. During the first season, plots at this nitrogen level showed yellow leaves, a sign of nitrogen deficiency (Mateo et al., 2022). This issue was not observed in 2024, indicating that the poultry litter added during the fallow period provided a lasting source of nitrogen that may enhance nutrient availability (Demissie & Shiferaw, 2024). The organic nitrogen in poultry litter likely broke down over time, offering a continuous supply of nutrients throughout the growing season (Chen & Jiang, 2014). This aligns with a previous study by Díaz-Pérez et al. (2018), which noted increased yields and larger bulb sizes with high rates of organic fertilization.

In contrast, high nitrogen applications of 100 and 120 lb/acre did not consistently improve dry weight or size across both seasons, and the plants stayed uniformly green, showing they had enough nitrogen. While there was no significant difference in colossal-sized onion yields across nitrogen rates, a trend was seen with the 80 lb/acre treatment improving yields in the 2024 season. Additionally, marketable yields in 2023 were significantly high at nitrogen rates of 100 and 120 lb/acre compared to 2024, increasing by 38% and 31%, respectively, with a statistical difference noted. In addition, it could be related to the bolting issue in 2024 that affected onion yield. These findings align with those of Díaz-Pérez et al. (2003), who showed that bolting in onions is affected by nitrogen rates and environmental factors, and variability in marketable yield may reflect differences in nutrient uptake efficiency.

The interaction between planting density and nitrogen application significantly impacts onion dry weight. Specifically, the high planting densities are associated with increased dry weights, especially at nitrogen rates of 100 and 120 lb/acre. At a density of 116,000 plants/acre, the dry weight increases by 44% and 42% with nitrogen applications of 100 and 120 lb/acre, compared to low density. This trend suggests that high planting densities can effectively utilize increased nitrogen rates to enhance yield. In contrast, at a nitrogen rate of 80 lb/acre, there is no significant change in dry weight across varying planting densities. This observation aligns with the findings of Zhou et al. (2022), who noted that while high densities promote root length and early growth, they can lead to competition for resources later, which may negatively affect yield.

Additionally, the effectiveness of nitrogen utilization at different densities is emphasized by studies such as those by Lan Yan et al. (2016) and Ciampitti & Vyn (2011), which highlight the importance of balancing nitrogen levels with planting densities to optimize nutrient uptake and overall yield. Attaya et al. (2024) further support this concept by demonstrating the critical role of optimizing both nitrogen and density to maximize yield without compromising bulb size and quality. Furthermore, Vidigal et al. (2023) provide additional evidence that high planting densities increase total nitrogen uptake, confirming the increased nitrogen demand at high densities observed in our study. This evidence underscores the importance of strategic management of nitrogen and planting densities in optimizing onion production while balancing yield and quality.

Conclusion

Optimizing planting density and nitrogen rates is essential. By increasing the density to 116,000 plants per acre, we saw a boost in marketable yield and produced more jumbo-sized onions, which are preferred in the market. In addition, the interaction between nitrogen rates and planting density affected dry weight yield, with the best outcomes observed at high densities (87,000 and 116,000 plants/acre) using (100 or 120 lb/acre) of nitrogen. However, the application of nitrogen can be adjusted based on environmental factors, such as precipitation, which can lead to nitrogen losses, as well as soil and plant tissue analyses. Further research is needed to evaluate Vidalia onion production with different planting densities, combined with varying levels and sources of nitrogen application.

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<u>FIGURES</u>

Figure 1: Equipment hole puncher types for different planting densities.

Figure 2: Onion grading machine (Haines Equipment Inc., New York, USA).

CHAPTER 3

NITROGEN AND PLANTING DENSITY EFFECTS ON NUTRIENT UPTAKE AND FLAVOR QUALITY IN VIDALIA ONIONS

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Abstract

This study evaluated the effects of planting density and nitrogen rates on nutrient uptake and flavor quality in Vidalia onions (*Allium cepa* L.). Conducted at the University of Georgia, three planting densities (58,000, 87,000, and 116,000 plants/acre) and three nitrogen rates (80, 100, and 120 lb/acre) were tested. Results showed that high densities increased nitrogen and sulfur uptake, but the high density (116,000 plants/acre) may have limited nutrient allocation to the bulbs. Nitrogen application at 80 and 120 lb/acre has the best total nitrogen and sulfur uptake. Pungency remained stable below 4.8 µmol/g, indicating good quality, while lachrymatory factor levels and methyl thiosulfinates concentrations suggested an influence on flavor. Overall, balancing nitrogen rates and densities is crucial for optimizing nutrient uptake and flavor quality in onions.

Introduction

Onion (*Allium cepa* L.) is valued for its culinary versatility as well as its multiple health benefits and is one of the most extensively cultivated vegetables worldwide, thriving in both temperate and subtropical climates (Ochar & Kim, 2023). They can grow in many environments, from subarctic to equatorial regions (Galmarini, 2018). In the United States, the fresh onion market was valued at approximately $1.2 billion (USDA, 2024), with Georgia being an important producer. According to the 2025 Georgia Farm Gate Value Report, 11,560 acres were devoted to onion cultivation, which constituted 14% of the state's total vegetable production and contributed $187 million to Georgia's economy. Vidalia sweet onions, renowned for their distinctive mild flavor, are exclusively cultivated in southeastern Georgia. The area's low-sulfur soils, mild winters, and abundant rainfall create optimal conditions for their growth (Boyhan & Coolong, 2017). Over the past decade, the availability and market presence of Vidalia onions have expanded significantly, driven by increased national brand recognition and regulatory protection of the Vidalia name (Boyhan & Torrance, 2002).

In onion production, planting density significantly affects nutrient uptake and bulb quality. If the plant population is excessively high, there can be intensified competition for sunlight, water, and nutrients, which reduces individual bulb growth (Attaya et al., 2024). This competition also impacts sulfur metabolism, which is essential for developing flavor compounds, including pungency, lachrymatory factor (LF), and methyl thiosulfates (Kim et al., 2017). Conversely, low-density plantings might lead to underutilized resources, negatively affecting nutrient efficiency and yield quality (Devulkar et al., 2015; Eady et al., 2008; Walle et al., 2018).

Nitrogen is a crucial nutrient that influences onion growth, quality, and nutrient use efficiency (Blumenthal et al., 2008). Effective fertilizer management optimizes nutrient uptake while reducing production costs (de Jesus et al., 2023). However, applying excessive nitrogen can lead to increased water content in the plants, promote excessive vegetative growth, and low disease resistance, ultimately affecting the quality of the bulbs during storage (Rodrigues et al., 2018). Additionally, nitrogen availability directly impacts sulfur metabolism, which is vital for synthesizing onion flavor compounds (Coolong, 2003).

Previous research has investigated the effects of nitrogen application and planting density on onion yields. However, there is still limited understanding of how these factors influence nutrient uptake and flavor-related compounds in onions. This study aims to evaluate the impact of different nitrogen rates (80, 100, and 120 lb/acre) and planting densities (58,000, 87,000, and 116,000 plants/acre) on nutrient absorption in both onion bulbs and leaves. Additionally, we will assess their effects on pungency, lachrymatory factor (LF), and methyl thiosulfate concentration.

Our goal is to provide insights into optimizing planting density and nitrogen application rates, that enhance nutrient uptake efficiency while maintaining the flavor quality of Vidalia onions.

Materials & Methods

Experimental Site

The experiment was conducted at the University of Georgia Vidalia Onion and Vegetable Research Center, located in Lyons, Georgia, USA (latitude 32°17’17" N, longitude 82°13'12" W), over two consecutive winters in 2023 and 2024. This region is known for its mild winters, low-sulfur soils, and adequate rainfall, which makes it an ideal location for onion cultivation (da Silva et al., 2022).

For this study, Sweet Magnolia onion variety was selected. Seeds were sown in nursery beds and grown for approximately eight weeks before harvesting transplants manually when they had an average diameter of 7mm. The transplants were then bundled into groups of 50 to 80 plants, secured with a rubber band, and transported to the field in polyethylene bags. Transplants were planted on November 28, 2022, for the first season and on November 14, 2023, for the second season.

Before transplanting, land preparation involved leveling, disking, and tillage to improve soil conditions. Raised beds were formed using a tractor-mounted rotary tiller, with beds spaced 6 feet apart from center to center and standing 6 inches tall. Each experimental plot measured 20 feet in length, covering a total area of 120 square feet. The study employed a randomized complete block design, consisting of four replications and nine treatments (3 planting densities and 3 fertilizer rates), resulting in a total of 36 plots for each experimental year. For the second season, 2024 evaluations of nutrient uptake in onion bulbs and leaves, and flavor quality analyses were complemented.

Transplanting and Planting Density

The study examined three different planting densities: 58,000, 87,000, and 116,000 plants/acre. To ensure the proper spacing, planting holes approximately 1 to 2 inches deep were created using a pegger (a hole puncher) on the surface of each bed (Figure 1). Each bed contained four rows, with the spacing between plants determined by the arrangement of pins on the hole puncher. Pins spaced 6 inches apart resulted in a density of 58,000 plants/acre, while 4-inch spacing was used to achieve 87,000 plants/acre. The high density of 116,000 plants/acre was established using twin rows spaced 6 inches apart in between plants.

Fertilizer Application and Nutrient Management

Three different nitrogen fertilizer rates were evaluated: 80, 100, and 120 lb/acre. Nitrogen rates were split into five applications throughout the growing season. The first application occurred on 13 December 2022, and 13 December 2023, using NPK fertilizer (5N-10P-15K), Rainbow Plant Food, Timac Agro, USA, applying 10 lb. of nitrogen per acre across all treatments. The second application took place on 10 January 2023, and 10 January 2024, using NPK fertilizer (6N-6P-18K), Rainbow Plant Food, Timac Agro, USA, with 18 lbs. of nitrogen per acre. The third application was conducted on 19 January 2023, and 19 January 2024, with 5N-10P-15K fertilizer, applying 25 lbs. of nitrogen per acre.

The final two applications were carried out in early and late February for both years, using calcium nitrate fertilizer (15.5N-0P-0K) YaraLiva Tropicote, Yara, Tampa, FL, USA. These final applications of calcium nitrate varied by treatment, with applications of 13.5, 23.5, and 33.5 lbs. N per acre to achieve total season nitrogen application rates of 80, 100 and 110 lb N/acre.

Irrigation and Soil Moisture Management

Irrigation was provided for the experiment using a center-pivot with an overhead sprinkler system; in addition, the schedule followed the recommendations outlined in the University of Georgia Onion Production Guide (Boyhan & Torrance, 2017).

Weed and Pest Control

Weed control was implemented using pre-emergent herbicides applied approximately one week after transplanting onions, and for pest and disease management, we utilized an integrated pest management (IPM) approach, incorporating chemical treatments as necessary. Insecticides and fungicides were applied in accordance with the recommended guidelines specified in the Georgia Commercial Pest Management Handbook (Sparks & Basu, 2025).

Sample Collection

Before undercutting the onion field, ten plants, including bulbs and leaves, were randomly collected from each plot and placed in labeled mesh bags to evaluate for nitrogen and sulfur content in the leaves and bulbs.

After the harvest and all yield measurements were completed, ten bulbs were randomly selected and placed in labeled bags to be sent to the laboratory to evaluate for quality parameters such as pungency, lachrymatory factor, and methyl thiosulfate content in the onion bulbs.

Sample Preparation and Processing

After collecting all samples, they were transported to the laboratory in labeled mesh bags. Using a knife, onion leaves were removed from the bulbs, and the bulbs were then chopped to facilitate the drying process. A scale was used to weigh all samples to record their fresh weights. Next, samples of both leaves and bulbs from each plot were placed in large, labeled paper bags and dried in industrial forced air heating ovens (Model 13-261-28A), Grieve Corporation, Round

Lake, Illinois, USA. The leaf samples were dried at 185°F for 7 days, while the bulbs required a longer drying period of 10 days at the same temperature. After drying, all samples of bulbs and leaves were weighed again to determine their dry weights.

Nutrient and Quality Analysis

To obtain information on the nutrient content in onion leaves and bulbs, all dried samples were sent to the Waters Agricultural Laboratory located in Camilla, Georgia, USA. For analyzing quality attributes such as pungency, lachrymatory factor, and methyl thiosulfate content in onion bulbs, samples were sent to the University of Georgia's Agricultural and Environmental Services Laboratory in Athens, Georgia, USA.

Statistical Analysis

Statistical analyses were conducted using JMP Pro 17 (SAS Institute Inc., 2023) to evaluate the effects of planting density and nitrogen rates on nutrient uptake and flavor quality attributes in Vidalia onions. A mixed-model ANOVA was employed to assess treatment effects, considering planting density and nitrogen rate as fixed effects, while rep was treated as a random effect. The analysis concentrated on nutrient uptake of nitrogen and sulfur in both bulbs and leaves, as well as flavor quality parameters, which included pungency, lachrymatory factor (LF), and the concentration of methyl thiosulfinates. When significant interactions were detected, analysis was performed, and a simple effects analysis was carried out to identify specific differences among treatment combinations using RStudio (Posit Team, 2023).

Results

Effect of Planting Density on Nutrient Uptake

Planting density had a significant effect on nitrogen and sulfur uptake in onion bulbs and leaves (Table 8). The high nitrogen uptake in bulbs was observed at 87,000 plants/acre (69.6 lb

N/acre) and 116,000 plants/acre (67.4 lb N/acre), while the low nitrogen uptake occurred at 58,000 plants/acre (53.6 lb N/acre). In leaves, nitrogen uptake was high at 116,000 plants/acre (58.8 lb N/acre), followed by 87,000 plants/acre (45.2 lb N/acre), and the low uptake was recorded at 58,000 plants/acre (32.7 lb N/acre). Total nitrogen uptake increased with planting density, reaching at 116,000 plants/acre (126.3 lb N/acre) and 87,000 plants/acre (114.8 lb N/acre), while the low total nitrogen uptake was found at 58,000 plants/acre (86.3 lb N/acre).

Sulfur uptake in bulbs was high at 87,000 plants/acre (19.1 lb S/acre) and 116,000 plants/acre (18.3 lb S/acre), while the low sulfur uptake in bulbs was recorded at 58,000 plants/acre (15.4 lb S/acre). Sulfur uptake in leaves was high at 116,000 plants/acre (9.3 lb S/acre), followed by 87,000 plants/acre (7.6 lb S/acre), while the low uptake was observed at 58,000 plants/acre (5.4 lb S/acre). Total sulfur uptake was also high at 116,000 plants/acre (27.6 lb S/acre) and 87,000 plants/acre (26.7 lb S/acre), with the low recorded at 58,000 plants/acre (20.8 lb S/acre).

When examining the percentage of total nitrogen and sulfur uptake allocated to onion bulbs, the highest values were observed at 58,000 plants per acre (62.4% for nitrogen and 74.1% for sulfur) and 87,000 plants per acre (60.7% for nitrogen and 71.7% for sulfur), with no significant differences between them. The lowest percentages were recorded at 116,000 plants per acre (53% for nitrogen and 65.5% for sulfur). These results suggest that increasing planting density enhances total nutrient uptake, but the proportion allocated to bulbs decreases at high density.

Table 8: Nutrient uptake of onion bulbs and leaves in lb/acre by planting density.

Density (Plants per acre)	N Uptake Bulb	N Uptake Leaf	S Uptake Bulb	S Uptake Leaf	Total N Uptake	Total S Uptake	% N Bulb	% S Bulb
58 000	53.6 b	32.7 c	15.4 b	5.4 c	86.3 b	20.8 b	62.4 a	74.1 a
87 000	69.6 a	45.2 b	19.1 a	7.6 b	114.8 a	26.7 a	60.7 a	71.7 a

116 000	67.4 a	58.8 a	18.3 a	9.3 a	126.3 a	27.6 a	53 b	65.5 b
p-value	<.0001	<.0001	0.0001	<.0001	<.0001	<.0001	<.0001	<.0001

Columns with different letters are significantly different (p≤0.05). Columns with the same letters do not indicate significance.

Effect of Nitrogen Application Rate on Nutrient Uptake in Onion Bulbs and Leaves

Nitrogen and sulfur uptake in onion bulbs and leaves varied significantly with nitrogen application rates (Table 9). The high nitrogen uptake in bulbs occurred at 80 lb/acre (68.5 lb N/acre), and 120 lb/acre (65.7 lb N/acre), with the low uptake observed at 100 lb/acre (56.5 lb N/acre). In leaves, nitrogen uptake was also high at 80 lb/acre (50.9 lb N/acre), and low 100 lb/acre (40.8 lb N/acre), while 120 lb/acre (45.0 lb N/acre) was moderate.

Sulfur uptake in both bulbs and leaves did not show significant differences across nitrogen application rates. However, total nitrogen uptake was high at 80 lb/acre (119.5 lb N/acre), and 120 lb/acre (110.7 lb N/acre), while the low was recorded at 100 lb/acre (97.2 lb N/acre). Similarly, total sulfur uptake was high at 120 lb/acre (26.0 lb S/acre) and low at 100 lb/acre (23.7 lb S/acre), while 80 lb/acre (25.5 lb S/acre) had moderate levels.

Overall, the percentage of nitrogen and sulfur content of the bulbs remained consistent across treatments, showing no significant differences.

Table 9: Nutrient uptake in onion bulbs and leaves by nitrogen application rate (lb/acre).

Nitrogen Rate	N Uptake Bulb	N Uptake Leaf	S Uptake Bulb	S Uptake Leaf	Total N Uptake	Total S Uptake	% N Uptake Bulb	% S Uptake Bulb
80	68.5 a	50.9 a	17.7 a	7.7 a	119.5 a	25.5 ab	57.7 a	69.6 a
100	56.5 b	40.8 b	16.6 a	7.1 a	97.2 b	23.7 b	58.7 a	70.2 a
120	65.7 a	45.0 ab	18.5 a	7.4 a	110.7 a	26.0 a	59.7 a	71.5 a
p-value	< .0001	< .0001	0.0773	0.1823	< .0001	< .0001	0.4419	0.3604

Columns with different letters are significantly different (p≤0.05). Columns with the same letters do not indicate significance.

Nutrient Uptake in Onion Bulbs and Leaves by Interaction of Nitrogen Rate and Planting Density

The interaction between nitrogen application rates and planting density significantly influenced nitrogen and sulfur uptake in onion bulbs (Table 10). At 80 and 100 lb N/acre, nitrogen uptake did not differ statistically among planting densities; however, at 120 lb. N/acre, nitrogen uptake varied significantly among densities, with the high uptake at 116,000 plants/acre N/acre), and the low at 58,000 (51.89 lb N/acre), while 87,000 (69.83 lb N/acre) was moderate. When comparing nitrogen rates within each density, no statistically significant differences were found.

Sulfur uptake in onion bulbs showed no significant differences at 80 lb N/acre, though the high uptake occurred at 116,000 plants/acre (23.54 lb S/acre), followed by 87,000 (19.88 lb S/acre) and 58,000 (15.65 lb S/acre). At 100 lb N/acre, sulfur uptake varied significantly, with the high uptake at 87,000 plants/acre (18.80 lb S/acre), followed by 116,000 (15.82 lb S/acre), and the low at 58,000 (15.05 lb S/acre). Similarly, at 120 lb N/acre, sulfur uptake differed significantly among densities, with the high uptake recorded at 116,000 plants/acre (21.45 lb S/acre), followed by 87,000 (18.67 lb S/acre), and the low at 58,000 (15.47 lb S/acre). However, when analyzing sulfur uptake within each density across nitrogen rates, no statistically significant differences were found.

Table 10: Nutrient uptake in onion bulbs by interaction of nitrogen application rate and planting density.

Variable	Interaction	Nitrogen Rate (lb/acre)			
	Density	80	100	120	p- value
Nitrogen Uptake Bulb (lb/acre)	58 000	56.97 Aa	52.03 Aa	51.89 Ba	0.1831
	87 000	74.00 Aa	65.05 Aa	69.83 ABa	0.3176
	116 000	98.18 Aa	52.29 Aa	75.33 Aa	0.1691

	p-value	0.1887	0.0666	0.0449*	
Sulfur Uptake Bulb (lb/acre)	58 000	15.65 Aa	15.05 Ba	15.47 Ba	0.7039
	87 000	19.88 Aa	18.80 Aa	18.67 ABa	0.4306
	116 000	23.54 Aa	15.82 ABa	21.45 Aa	0.3556
	p-value	0.3225	0.0304*	0.0252*	

Means followed by different letters indicate significant differences at p≤0.05 based on Tukey's HSD test. Capital letters indicate comparisons within columns, and lowercase letters indicate comparisons within rows.

Impact of Planting Density on Flavor: Analyzing Pungency, Lachrymatory Factor, and Methyl Thiosulfate Concentration in Vidalia Onions

Planting density significantly impacted the concentration of the lachrymatory factor in Vidalia onions (Table 11). The planting density of 116,000 and 87,000 plants/acre had the high concentration of the lachrymatory factor (1.0 and 0.9 µmol/mL), and the low concentration was recorded at 58,000 plants/acre, (0.8 µmol/mL).

In contrast, neither pungency levels nor methyl thiosulfate concentrations were significantly influenced by planting density. Pungency levels ranged from (3.0 to 3.5 µmol/g), while methyl thiosulfate concentrations varied between (5.1 and 7.1 nmol/mL).

Table 11: Density effects on pungency, lachrymatory factor, and methyl thiosulfate concentration.

Density (Plants per Acre)	Pungency µmol/g	Lachrymatory Factor µmol/mL	Methyl thiosulfate nmol/mL
58 000	3.0 a	0.8 b	5.1 a
87 000	3.4 a	0.9 a	6.1 a
116 000	3.5 a	1.0 a	7.1 a
p-value	0.1240	< .0001	0.1062

Note. Columns with different letters are significantly different (p≤0.05). Columns with the same letters do not indicate significance.

Impact of Nitrogen Application Rates on Pungency, Lachrymatory Factor, and Methyl Thiosulfate Levels in Vidalia Onions

Nitrogen application rates had a significant impact on the concentration of the lachrymatory factor in Vidalia onions (Table 12). The high concentrations, measuring (1.0 µmol/mL), were found at rates of 80 and 120 lb N/acre, while the low concentration, recorded at 100 lb N/acre, (0.8 µmol/mL).

Additionally, the nitrogen rates did not significantly influence pungency and methyl thiosulfate levels. Pungency varied from (3.0 to 3.6 µmol/g), while methyl thiosulfate concentrations ranged between (5.1 and 7.1 nmol/mL).

Table 12: Impact of nitrogen rates lb/acre on pungency, lachrymatory factor, and methyl thiosulfate concentration.

Nitrogen Rate	Pungency µmol/g	Lachrymatory Factor µmol/mL	Methyl thiosulfate nmol/mL
80	3.6 a	1.0 a	6.1 a
100	3.0 a	0.8 b	5.1 a
120	3.4 a	1.0 a	7.1 a
p-value	0.0885	< .0001	0.1190

Columns with different letters are significantly different ($p \leq 0.05$). Columns with the same letters do not indicate significance.

Discussion

This study emphasizes the significant impact of planting density and nitrogen rates on nutrient uptake in onion bulbs and leaves, as well as flavor quality compounds. Importantly, before the experiment began, 2 tons per acre of poultry litter were applied and incorporated into the soil by mistake in this experimental area. The organic fertilizer, with a composition of (3N- 2P- 2K) and 60% nitrogen availability, provided an estimated 72 pounds of nitrogen per acre across all treatments, which could be available through the growing season of onions. This unexpected input, which was recognized only after the experiment started, may have influenced nutrient availability, uptake, and onion flavor compounds (Ncayiyana et al., 2018).

Organic fertilizers can provide nitrogen mainly in organic forms that are not promptly available to plants, and before plants can use this nitrogen, it must go through a process called mineralization, in which microbes convert organic nitrogen into forms that plants can absorb, such as ammonium and nitrate (Díaz-Pérez et al., 2021).

According to Díaz-Pérez et al. (2018), organic fertilizer rates up to 120 kg· ha^{1} nitrogen improved sweet onion root, stem, and bulb biomass but decreased the root-to-shoot ratio. In addition, this study indicated that nutrient deficiencies appeared late in the season, suggesting the need for supplemental nitrogen during later growth stages.

High planting densities, specifically 87,000 and 116,000 plants/acre, resulted in greater total nitrogen and sulfur uptake compared to the low density of 58,000 plants/acre. The competition among plants at high densities may led to more efficient nutrient absorption. Similarly, Alkhateeb et al. (2024) found that increasing plant density to 50 plants/m^2, combined with a nitrogen rate of 244 kg N/ha, improved onion yield and enhanced nutrient uptake, highlighting the positive interaction between planting density and nitrogen management on crop production. A similar trend was reported by Tian et al. (2022), who found that applying 180 kg N/ha combined with a high planting density of 82,500 plants/ha increased nitrogen uptake in maize production. However, in this study, at 116,000 plants/acre, the percentage of total nitrogen and sulfur uptake allocated to onion bulbs was lower than at 58,000 plants/acre. This suggests that competition in high plant densities could limit nutrient allocation to the bulbs. A similar trend was reported by Bleasdale et al. (2016), who found that increasing plant density in *Allium cepa* reduced individual bulb biomass and shifted resource allocation toward shoot growth, suggesting that at high plant densities, competition among plants can limit the availability of nutrients for bulb development, potentially leading to low nutrient concentrations in the storage organs.

Nitrogen application rates also impacted nutrient content in the bulb, and the high nitrogen uptake was observed at 80 lb/acre, which was 17.5% greater than at 100 lb/acre, with no significant difference noted between 80 and 120 lb/acre. Leaf uptake showed a similar pattern, with 80 lb/acre leading to 19.8% high absorption compared to 100 lb/acre. Regarding sulfur uptake in onion bulbs and leaves, no statistical difference was noticed across the different levels of nitrogen application. A low nitrogen rate of 80 lb/acre plants may have improved nutrient uptake, while high rates likely could led to losses through volatilization or leaching (Glass, 2010; Geisseler et al., 2022). Similar findings were reported by Hilman et al. (2014), who observed that increasing nitrogen levels above 265 kg N ha^{1} reduced nutrient uptake in the shallot crop.

The interaction between nitrogen rate and planting density significantly influenced both nitrogen and sulfur uptake in the bulb. The high nitrogen uptake in onion bulb (75.33 lb/acre) was observed at 116,000 plants/acre with 120 lb/acre nitrogen, with a statistically significant effect of nitrogen rate at this density. This suggests that increased nitrogen rates under this planting density can improve nutrient absorption. Attaya et al. (2024) evaluated how varying nitrogen levels and plant densities influence onion growth, nutrient uptake, and bulb quality, and found that balancing plant density with appropriate nitrogen levels is important to maximizing nutrient absorption in onion cultivation.

For sulfur uptake in the onion bulb, significant differences were observed at both 100 and 120 lb/acre nitrogen application rates. At 100 lb/acre, planting density significantly influenced sulfur uptake at moderate plant density 87,000, and at nitrogen at 120 lb/acre, the high sulfur uptake in bulb (21.45 lb/acre) occurred at 116,000 plants/acre, with a significant effect. These findings suggest that both moderate and high nitrogen rates can improve sulfur absorption when combined with high plant populations. These results are consistent with Russo (2008), who found that nutrient uptake improves with high plant populations due to competition when nutrients are adequately available and beyond recommended rates did not improve bulb nutrient content.

At 80 lb/acre, nitrogen and sulfur uptake increased with planting density, though differences were not statistically significant. This implies that moderate nitrogen levels may support efficient nutrient uptake across densities. However, at low planting density (58,000 plants/acre), both nitrogen and sulfur uptake in the bulb declined at high nitrogen rates, possibly due to less plant competition, and nutrients could be lost through leaching or volatilization (Glass, 2010; Geisseler et al., 2022). Similarly, Caruso et al. (2014) emphasized that balancing nitrogen application with planting density is important to improve nutrient uptake in onion crops.

The quality attributes of onion bulbs, specifically pungency, lachrymatory factor, and methyl thiosulfinates, were found to be minimally influenced by the planting density and nitrogen levels used in this study. However, these factors significantly affected the lachrymatory factor. Pungency levels remained generally consistent across varying planting densities and nitrogen rates, with all values below the threshold of 4.8 µmol/g. This indicates that the onions qualify as Vidalia sweet onions (University of Georgia, Agricultural and Environmental Services Laboratories, n.d.). There were slight increases in pungency at high planting densities, with values of 3.0 µmol/g at 58,000 plants/acre and 3.5 µmol/g at 116,000 plants/acre.

Similarly, a nitrogen application of 80 lb/acre resulted in a pungency of 3.6 µmol/g, compared to 100 lb/acre, which had a value of 3.0 µmol/g. However, these differences were not statistically significant. This suggests that other factors such as onion variety or sulfur application levels may have a more substantial impact on pungency than planting density and nitrogen application rates used in this study. Differently, Liu et al. (2009) found that nitrogen and sulfur both influence the growth and pungency of onions, with sulfur enhancing yield, nutrient absorption, and pungency across all tested cultivars.

In contrast to pungency, both planting density and nitrogen rate had a significant impact on the lachrymatory factor (LF), with increased planting densities resulting in high LF levels (0.8 µmol/mL at 58,000 and 1.0 µmol/mL at 116,000 plants/acre). Likewise, LF was influenced by nitrogen levels, with the high LF concentrations (1.0 µmol/mL) occurring at 80 and 120 lb/acre, while 100 lb/acre had low levels (0.8 µmol/mL), however being bellow the threshold of 2.2 µmol/ml to be consider with superior flavor quality. This suggests that high planting densities and nitrogen rates are associated with sulfur absorption and metabolic processes, which can increase precursor production and LF activity. Randle et al. (2005) found that sulfur application can improve the synthesis of flavor compounds related to pungency and the lachrymatory factor (LF). Different factors like different genotypes, planting density, and nitrogen application might affect LF concentrations by enhancing sulfur metabolism in onions (McCallum et al., 2011; Bhat et al., 2010)

Methyl thiosulfate levels were not significantly influenced by planting density or nitrogen rate; however, a slight increase was observed at high planting densities, with levels rising from 5.1 nmol/mL at 58,000 plants/acre to 7.1 nmol/mL at 116,000 plants/acre. Similarly, methyl thiosulfate levels increased from 5.1 nmol/mL at 100 lb N/acre to 7.1 nmol/mL at 120 lb N/acre. For optimal flavor in Vidalia onions, methyl thiosulfate levels should remain below 0.43 nmol/mL, as high concentrations may lead to undesirable tastes, however if the concentration is not high enough to change the concentration above threshold for pungency, onions can be considering a Sweet Vidalia onion (University of Georgia Extension, n.d.). According to the University of Georgia Extension

Onion Variety Trial Report (2024), methyl thiosulfinates concentrations varied widely among onion varieties, ranging from 2.7 to 16.6 nmol/mL, highlighting the strong influence of genetic factors on this flavor-related compound. This supports the observation that while planting density and nitrogen rate showed minor trends in methyl thiosulfinates levels, varietal differences are likely one of the primary drivers of these changes.

Conclusion

This study demonstrates that both planting density and nitrogen application levels significantly influence nutrient uptake and the quality of Vidalia sweet onions. High planting densities, specifically 87,000 and 116,000 plants/acre, improved the total uptake of nitrogen and sulfur at 80 and 120 pounds of nitrogen application. However, at the high density of 116,000 plants/acre, competition among the plants may have limited the allocation of nutrients to the bulbs.

Regarding quality attributes, the pungency of the onions remained stable across all treatments, staying below the 4.8 µmol/g threshold, which classifies them as sweet Vidalia onions. However, levels of the lachrymatory factor (LF) increased at high planting densities and nitrogen rates, but still remained below 2.2 µmol/mL, ensuring superior flavor quality. The compound methyl thiosulfate, which can affect onion taste, exceeded the optimal threshold of 0.43 nmol/mL, indicating that variations in planting density and nitrogen levels may influence flavor. It's important to note that variations in onion flavor can also arise from genetic factors, agronomic practices, environmental conditions, and sulfur metabolism. These findings underscore the importance of balancing nitrogen rates and planting densities to optimize nutrient uptake and maintain onion quality. Further research is needed to validate these results and develop refined strategies for Vidalia onion production.

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FIGURES

Figure 3: Heating oven, model: 13-261-28A (Grieve Corporation, Round Lake, Illinois, USA).