

Impacts of Calcium Cyanamide Application as a Nitrogen Source on Growth, Yield, Quality, and Storage Durability of Short-day Onion

Mzwakhile Petros Zakhe Simelane and Puffy Soundy

Tshwane University of Technology, Department of Crop Sciences, Private Bag X680, Pretoria, 0001, South Africa

Martin Makgose Maboko

Tshwane University of Technology, Department of Crop Sciences, Private Bag X680, Pretoria, 0001, South Africa; and Hygrotech SA, Pty. Limited, Pyramid, Pretoria, 0001, South Africa

Keywords. *Allium cepa*, bolting, calcium cyanamide, complementary growth patterns, fertilization, storability

Abstract. Rapid leaching of soluble nitrogen (N) sources in soil poses a significant challenge in agricultural practices. Therefore, gaining a comprehensive understanding of crop responses to slow-release N application rates has become crucial to contributing valuable insights to optimize N management strategies in agriculture. A field study was conducted to investigate the influence of preplant calcium cyanamide fertilizer on the growth, yield, quality, and shelf life of short-day onion. Six levels of calcium cyanamide (CaCN_2 , 19.8% N), 0, 90, 120, 200, 400, and 600 $\text{kg}\cdot\text{ha}^{-1}$ CaCN_2 , which are equivalent to 0, 17.82, 23.76, 39.6, 79.2, and 118.8 $\text{kg}\cdot\text{ha}^{-1}$ N, respectively, replicated four times were broadcasted and incorporated into the top 5 to 10 cm of soil. Using 400 $\text{kg}\cdot\text{ha}^{-1}$ of CaCN_2 yielded noteworthy improvements in various parameters of onion growth, such as plant height, leaf count, bulb weight per plant, bulb diameter, bulb length, and overall plant weight, as indicated by the study results. The application of different levels of CaCN_2 as an N source exerted a significant influence on these growth factors. Moreover, the study revealed a direct correlation between CaCN_2 application levels and the storage life of onions. Specifically, the findings demonstrated that the application of 400 $\text{kg}\cdot\text{ha}^{-1}$ CaCN_2 resulted in enhanced yield and overall onion plant growth. However, the application of 600 $\text{kg}\cdot\text{ha}^{-1}$ CaCN_2 increased the incidences of bulb weight loss, rots, and sprouting during the 8-week storage period at room temperature. These findings provide valuable insights for onion investors and farmers in the region and offer practical recommendations for optimizing fertilizer use and storage practices to improve onion production and minimize postharvest losses.

Agricultural practices are in a constant state of evolution and driven by the combined efforts of researchers and farmers to achieve the highest possible levels of crop productivity, quality, and sustainability. Within this dynamic landscape, the strategic utilization of fertilizers emerges as a crucial factor in the quest for optimal growth and yield. Among

these fertilizers, nitrogen (N) takes on a particularly significant role because of its status as a vital macronutrient with far-reaching implications for plant development, nutritional content, and overall performance (Sutton et al. 2022). This relentless pursuit of agricultural improvement extends to the cultivation of short-day onions, which is a staple crop essential to global cuisines. The increasing demand for onions in culinary preparations persists and drives ongoing efforts to improve production while maintaining high-quality standards (Department of Agriculture, Land Reform and Rural Development 2021). The intricate relationships between N fertilizer application and onion growth, yield, quality, and storage longevity have captivated researchers (Elouattassi et al. 2023). Regarding mineral fertilizers, N plays a crucial role in influencing the development and yield of onions (Ncayiyana et al. 2018). As a necessary component of proteins, amino acids, and chlorophyll, N has a significant effect on photosynthesis, root development, and general plant health

(Sutton et al. 2022). However, a delicate balance must be struck because excessive N can lead to detrimental outcomes such as environmental pollution, leaching, and reduced postharvest shelf life (Bibi et al. 2016).

Onions require several mineral nutrients, particularly N (Mozumder et al. 2007). Managing N levels effectively is of paramount importance for onions because of their shallow and unbranched root systems (Brewster 1994). This makes them susceptible to nutrient deficiencies. To attain the best possible yields, it becomes essential to apply N frequently in small quantities, place it as near to the root zone as feasible, and apply it in forms that are easily accessible. This approach yields strong and favorable responses from onions when fertilizers are applied, as documented by Brewster (1994) and Ndjaji et al. (2022). Tandon (1987) and Vojnović et al. (2023) highlighted the substantial nutrient requirements of onions, notably, their utilization of approximately 120 kg N, 50 kg phosphorus (P_2O_5), and 160 kg potassium (K_2O) per hectare to achieve a yield of 35 tons. This underscores the critical link between nutrient uptake and the potential onion yield.

The impact of mineral fertilizers on onion growth and yield has been a subject of extensive investigation in the existing literature. Noteworthy studies conducted by Bhattacharjee et al. (2013), Mozumder et al. (2007), and Ncayiyana et al. (2018) have specifically delved into the role of N in shaping various aspects of onion development. These investigations collectively underscore the positive association between increased N levels and the yield of diverse onion cultivars, as articulated in the findings reported by Bhattacharjee et al. (2013) and Mohammad and Moazzam (2012). Despite these positive correlations, a critical gap in the literature is the absence of fertilizer guidelines tailored to specific regions. This deficiency in region-specific guidance has resulted in notable production challenges (Vojnović et al. 2023). Subsequently, these challenges manifest as subpar bulb yields, compromised product quality, and reduced storage longevity, thereby further emphasizing the significance of developing targeted fertilizer recommendations to optimize onion cultivation outcomes across different geographical areas (Ndjaji et al. 2022). Therefore, the existing literature underscores the importance of bridging this gap in knowledge to enhance the overall efficiency and sustainability of onion production systems. Despite the essential role that N plays in enhancing onion size and yield, conventional beliefs among onion growers indicate that excessive N could hinder proper ripening and result in bulbs with inferior storage quality (Hafez and Geries 2018; Sheikh et al. 1987; Vojnović et al. 2023). Studies have indicated that providing onion plants with the correct amount of N is crucial because it fosters plant development, boosts yield, and improves onion bulb quality (Biesiada and Kolota, 2009; Shaheen et al. 2010). Al-Moshileh (2002) also noted that the highest onion yield was obtained after applying 200 $\text{kg}\cdot\text{ha}^{-1}$ N and stressed that it would not be

Received for publication 11 Dec 2023. Accepted for publication 10 Jan 2024.

Published online 30 May 2024.

We thank Hygrotech Pty. Limited for their invaluable support, for furnishing essential agricultural inputs, and for granting us access to their research farm. We thank the Tshwane University of Technology for their generous financial assistance, which significantly bolstered our research endeavors.

M.M.M. is the corresponding author. E-mail: mabokom@tut.ac.za.

This is an open access article distributed under the CC BY-NC-ND license (<https://creativecommons.org/licenses/by-nc-nd/4.0/>).

economically feasible to apply more N than this level to increase crop productivity.

Urea stands out as a widely embraced conventional fertilizer in agriculture because of its partial absorption by plants (Swify et al. 2024). However, a notable challenge associated with this fertilizer is its susceptibility to leaching. Leaching occurs when water carries the soluble nutrients from the fertilizers beyond the reach of plant roots, potentially leading to groundwater contamination (Ahmad et al. 2021). Using slow-release fertilizer sources such as Perlka (calcium cyanamide) presents a unique approach to solving the problem of N leaching losses in horticultural crops, and it could also help address this issue in agronomic crops (Dixon 2017; Klasse 1996; Simelane et al. 2023). Therefore, Perlka, which is a granular fertilizer product containing calcium cyanamide, has been proposed as a promising fertilizer alternative that could solve the problem of N leaching losses (Bletsos 2006; Leytur et al. 2018).

Calcium cyanamide, a compound that provides both N and calcium to plants (Dixon 2017; Hahn 1951; Sala et al. 2016), undergoes hydrolysis upon soil application and releases ammonia and cyanamide. The released ammonia can be converted to ammonium ions, which bind more tightly to soil particles, thus reducing leaching risks compared with nitrates. Slow-release calcium cyanamide offers the advantage of minimizing N leaching because of its inherent properties (Brzozowski et al. 1953; Sala et al. 2016). This is particularly advantageous in environments with high rainfall or areas where overhead irrigation is used. The gradual release of N from the fertilizer aligns better with the plant's growth stages and nutrient uptake patterns (Dixon 1984, 2017; Leytur et al. 2018). This can result in improved nutrient use efficiency and reduced N wastage. Slow-release fertilizers like Perlka provide a sustained supply of nutrients to plants over an extended period. This can reduce the frequency of fertilizer applications and labor costs.

There has been limited scientific exploration of how calcium cyanamide specifically affects the various aspects of onion cultivation. The central objective of this study was to establish the optimal calcium cyanamide fertilizer levels. Improvements in onion growth, yield, bulb quality, and postharvest storage longevity should result from these levels. This investigation aimed to guide the promotion of efficient and sustainable onion production methods by combining insights from recent research findings with real-world applications. This investigation holds potential benefits for farmers, agronomists, and researchers alike.

Materials and Methods

Description of the study area. A 2-year experiment was conducted at the Hygrotech Experimental Farm in Dewagensdrift, Pretoria, from Mar to Nov 2019 and 2020. The geographic coordinates of the site are 25.4580 °S latitude and 28.6411 °E longitude, with an elevation of 1214 m. Climatic weather conditions during the experimental

period are shown in Table 1. The mean minimum annual temperature was 18.5 °C, with a corresponding maximum of 23.6 °C, whereas an average of 640 mm of rainfall occurred (South African Weather Service 2020). The crop water requirement (ETc) for the growing season during this study was determined using the crop coefficient (Kc) and potential evapotranspiration of the study area. The result is given as $ET_c = K_c \cdot ET_o$. Based on crop, soil, and climate data, irrigation scheduling was projected using the FAO model CROPWAT software 8.0. Bunds of soil were created around each plot's edges to stop nutrients from moving between plot blocks. Weeding and hoeing were performed manually. A total of 600 mm of irrigation was applied in 2019; the plants were irrigated 25 mm during the first week, 35 mm during the following week, and 620 mm during the growing season of 2020, or approximately 35 to 40 mm per week. When at least 50% of the plant leaves began to fall, the irrigation was turned off. Then, the plants were pulled up and the dirt was shaken off. The plants were spread out to cure by hanging in sacks beneath a cover. For each treatment and replication, well-cured onion bulbs (5 kg) were chosen, weighed, and stored at room temperature between 17 to 28 °C, with 45% to 75% relative humidity (RH). The percentage of the total weight loss of the bulbs during a 3-month storage period from 22 Dec to 22 Feb was used to determine the storability of the bulbs in each of the two seasons. Throughout the storage period, the remaining bulbs (sound bulbs) were weighted after each month's inspection and storage to remove any sprouted or rotted bulbs. The calculation of the percentage of the total physiological weight, representing weight loss, was ascertained on a monthly basis.

Soil sample collection and analysis. Land was prepared by ploughing to a soil depth of 25 to 30 cm and discing and rotovating the soil. Before planting, the experimental plots were meticulously prepared by manual harrowing to achieve a fine and even tilth. Before planting the seeds in the soil, a comprehensive assessment of the experimental soil was performed to evaluate the distinctive root structure of onions. Onion plants typically feature shallow roots with limited branching primarily concentrated in the upper 30 cm of soil. Before sowing seeds, an evaluation of soil properties was conducted by gathering samples from 18 distinct locations at depths ranging from 0 to 15 cm and 15 to 30 cm. Approximately 600 g of soil was bulked from each composite sample; this soil was then dried to allow a consistent analysis (Lawrence et al. 2020; Murindangabo et al. 2023). A subsequent analysis of these samples encompassed both chemical and physical properties and adhered to the procedures delineated in the soil and plant laboratory manuals (Álvaro-Fuentes et al. 2019). The results were similar to those reported by Simelane et al. (2023). Physical properties were as follows: sand, 54.10%; silt, 41.30%; and clay, 4.60%. Chemical properties were as follows: pH, 5.5; calcium, 61.6%; magnesium, 20.7%; potassium, 7.4%; phosphorus, 47%; sodium, 1.34%; ammonium

nitrogen, 0.29 mg·kg⁻¹; and nitrate nitrogen, 0.50 mg·kg⁻¹.

Experimental design and treatments. The study used the short-day onion cultivar Texas Grano as the experimental crop. The experiment was subjected to six CaCN₂ (19.8% N) treatments (0, 90, 120, 200, 400, and 600 kg·ha⁻¹) equivalent to 0, 17.82, 23.76, 39.6, 79.2 and 118.8 kg·ha⁻¹ N applied by broadcasting on the plot surface and then incorporated into the soil at a depth of 5 to 10 cm. Calcium cyanamide underwent watering and was kept consistently moist for 8 d before the seeding process. The experiment followed a randomized complete block design with four replications. Onion seeds were directly sown into sandy loam soil, with each planting performed in plots measuring 6 m². Within these plots, the area was further divided into five single rows. After the seedlings emerged, thinning was performed to attain intrarow spacing of 7.5 cm, resulting in each row accommodating 40 plants. All plots maintained the recommended 20 cm interrow spacing to guarantee strong growth. Each plot was separated by 1 m, and blocks were separated by 1.5 m. The application of preplant fertilizer was determined based on the soil analysis, with the following components being broadcasted: 300 kg·ha⁻¹ superphosphate (10.5% P); 150 kg·ha⁻¹ potassium sulfate (22.4% K and 18.4% S); and 150 kg·ha⁻¹ magnesium sulfate (10% Mg and 13% S). For the control treatment, 2000 kg·ha⁻¹ calcitic lime was exclusively applied, and no N fertilizer was administered. Additionally, potassium sulfate was applied at a rate of 50 kg·ha⁻¹ per week from weeks 6 to 10 after sowing, with five applications across all treatments, irrespective of the N level.

Determination of storage weight loss. A sample of 20 onion bulbs were selected per treatment and replication and subjected to curing in the field. They were dried by suspending them in sacks at room temperature. The initial weight of each onion bulb was noted before storage, and the respective sack was labeled for convenient identification. The total weight loss of the onion bulbs was determined by comparing their initial weights before storage, with the weights recorded at 7-d intervals over an 8-week storage period. This weight loss was expressed as a percentage using the storage weight loss (SWL) method recommended by Waskar et al. (1992) and Kukanoor (2005):

$$SWL (\%) = \frac{1 - W_f}{W_i} \cdot 100 \quad [1]$$

where W_i is the initial onion bulb weight (g) before storage and W_f is the final onion bulb weight (g) after storage.

Measuring storage rot losses. After physical inspections during which each bulb's firmness was felt with the hand, the number of rotten onion bulbs was tallied at the end of every seventh day. The moment the onion bulb softened, it was deemed rotten. Then, Eq. [2] that was applied to cocoyam was used to determine the percentage of storage rot

Table 1. Average weather data over a 2-year period (2019–20) during the experimental study.

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2019												
Average maximum temperature (°C)	27	27	26	23	21	18	18	21	24	25	26	27
Average minimum temperature (°C)	19	18	17	14	10	6	6	9	13	15	16	18
Mean precipitation (mm)	110	80	80	50	20	0	0	0	40	90	100	110
2020												
Average maximum temperature (°C)	28	28	27	25	21	18	18	23	25	26	27	27
Average minimum temperature (°C)	19	18	18	16	12	6	6	8	14	17	17	18
Mean precipitation (mm)	120	90	80	60	20	0	0	0	40	100	100	110

loss (SRL) by Obeta (2007):

$$SRL (\%) = \frac{1 - Nr}{Nt} \times 100 \quad [2]$$

where Nr is the number of rotten onion bulbs and Nt is the total number of onion bulbs.

Measuring storage sprout losses. To determine the percentage of storage sprout losses (SSLs) in onion bulbs at specified storage intervals, the method involved identifying bulbs displaying sprouting, recording their numbers, and segregating them from the bulk. A sprouted onion bulb was defined as one in which the stored bulb exhibited the development of green leaves, as opposed to scale leaves, as outlined by Kukanoor (2005). Additionally, Eq. [3] was used to calculate the percentage of sprouts, which measured the percentage of onion bulbs that had sprouted at the end of the storage period. Obeta (2007) previously used this method for cocoyam.

$$\text{Sprouted onions } (\%) = \frac{1 - NH}{Nt} \times 100 \quad [3]$$

where Nh is the number of healthy bulbs retained and Nt is the total number of stored onion bulbs.

Statistical method. This study used a randomized complete block design and was replicated over a 2-year period. The data were subjected to a separate analysis of variance (ANOVA) for each year and adhered to the specified experimental design. The ANOVA was conducted using the general linear model procedure in SAS software (version 9.4; SAS Institute Inc., Cary, NC, USA). Additionally, the observations from both years were consolidated for a comprehensive single ANOVA (John and Quenouille 1977). To facilitate combined analyses, the uniformity of experimental error variances was evaluated through the F-test (Snedecor and Cochran 1989). When error variances exhibited variation, an ANOVA was performed with inverse variance weighting. Residuals were carefully examined for deviations from normality, and outliers that caused skewness were systematically eliminated. Fisher's least significant difference was computed at a 5% significance level to compare means for significant effects (Meier 2006).

Results and Discussion

Bolting. The utilization of CaCN₂ as an N source fertilizer had a notable effect on

reducing the bolting percentage in onions, whereas the year of cultivation and CaCN₂ had no discernible interaction effect (Table 2). The reduction in the bolting percentage with increasing levels of CaCN₂ as a N source fertilizer can be attributed to the influence of N on the growth and development of onion plants. This study indicates that applying 90 kg·ha⁻¹ (17.82 kg·ha⁻¹ N) and 120 kg·ha⁻¹ (23.76 kg·ha⁻¹ N) CaCN₂ resulted in significant reductions of 8.8% and 20% in the bolting incidence, respectively, compared with the control treatment. The reduction in bolting can be explained by the effect of N on the vegetative stage of onion plants. Furthermore, N plays a crucial role in promoting vegetative growth and delaying the onset of flowering. The findings align with those of previous research conducted by Abdissa et al. (2011), who demonstrated that inadequate levels of N could induce bolting in onion plants. When onion plants receive an ample supply of N, they tend to invest more energy in vegetative development before transitioning to the reproductive phase. This delay in flowering can help prevent premature bolting. The control plants, which likely experienced N limitation, exhibited a higher bolting percentage compared with the fertilized plants (Abdissa et al. 2011; Jilani 2004). In this case, the cool growing periods from June to October and potential N limitation in the control treatment may have contributed to a higher bolting percentage (Jilani 2004).

Physiological maturity. Fascinatingly, irrespective of the level of CaCN₂ applied, it was observed that CaCN₂ extended the

duration of physiological maturity by ~4 d in comparison with the untreated condition, resulting in a total of 101 d for physiological maturity. This extension is attributed to the delay in the onset of the flowering phase and the promotion of robust vegetative growth caused by N fertilization, as explained by Yamasaki and Tanaka (2005) and Abdissa et al. (2011). This phenomenon aligns with the findings of Sørensen and Grevsen (2001), who discovered that elevated N levels promoted excessive vegetative growth and postponed the maturation process.

Split bulbs. The development of split bulbs in onions appears to be significantly influenced by CaCN₂ and its interaction with the year of cultivation (Fig. 1). The impact was particularly notable in the second tested season growing season, during which the percentage of split bulbs was substantially higher compared with that of the previous year (the first tested season). Among the various CaCN₂ application levels, the highest occurrence of split bulbs was observed with a dosage of 600 kg·ha⁻¹ CaCN₂ in the second tested season (2.216%). Conversely, the control treatment, which received 0 kg·ha⁻¹ CaCN₂, exhibited the lowest incidence of split bulbs in both years, with 1.236% recorded in the first tested season and 1.403% recorded in the second tested season. Generally, an increase in the CaCN₂ application increased split bulbs. The reason for this could be the elevated temperatures in the second tested season (Table 1), which accelerated the metabolic processes in plants. High temperatures might lead to faster growth and enlargement of bulbs (Khokhar 2017; Steer 1980). When this rapid growth happens in conjunction

Table 2. Effect of calcium cyanamide (CaCN₂) applications on bolting, physiological maturity, plant height, number of leaves, leaf length, leaf diameter, split bulbs, and neck thickness of short-day onion.

CaCN ₂ (kg·ha ⁻¹)	Bolting (%)	Days to physiological maturity	Plant ht (cm)	Leaf number plant ⁻¹	Leaf length (cm)	Leaf diam (cm)	Neck thickness (cm)
0	3.96 a	101.03 b	48.56 e	6.16 f	42.47 d	0.765	1.290 c
90	3.61 b	105.41 a	56.85 d	6.75 e	47.38 c	0.763	1.305 b
120	3.16 bc	105.28 a	57.3 c	7.2 d	47.69 b	0.767	1.312 b
200	2.42 c	105.16 a	57.34 c	8.08 c	47.93 b	0.765	1.316 b
400	2.5 c	105.28 a	57.74 b	8.72 a	48.28 a	0.768	1.343 a
600	3.38 b	105.32 a	57.92 a	8.36 b	47.89 b	0.766	1.349 a
LSD 0.05	0.7628	0.3265	0.3485	0.2146	0.4666	NS	0.0143
Year × CaCN ₂	NS	NS	NS	NS	NS	NS	NS

Using Fisher's protected *t* test, values in a column that are followed by the same letter are not significantly different.

P ≤ 0.05.

LSD = least significant difference; NS = not significant.

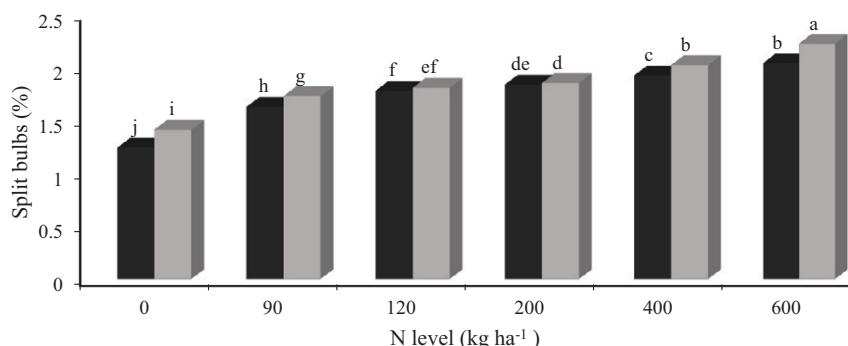


Fig. 1. Effect of calcium cyanamide (CaCN_2) applications on onion split bulbs. Bars with the same letter are not significantly different.

with excessive N, the outer layers of the bulb might not expand uniformly, leading to bulb splitting (Khokhar 2017).

The results showed that CaCN₂ fertilization increases the percentage of onions that split, in accordance with the findings of Hassan and Ayoub (1978). Bigger bulbs resulting from N and P applications displayed more splits and doubles than smaller bulbs from control plots, according to the findings of Hassan and Ayoub (1978). Specifically, when compared with the control treatment, the applications of 90 kg·ha⁻¹ and 180 kg·ha⁻¹ CaCN₂ resulted in 14.2% and 13.6% increases in splitting, respectively. Jilani et al. (2004) also noted a comparable pattern in a field study conducted in Pakistan, where the incidence of splitting increased with increased N levels.

Plant height and number of leaves per plant. Onion plant height increased significantly with an increase in the CaCN_2 application (Table 2). There was no significant interaction effect of the year $\times \text{CaCN}_2$ application (Table 2). Applying $90 \text{ kg} \cdot \text{ha}^{-1}$ CaCN_2 specifically produced a height increase of approximately 8.3 cm relative to 48.56 cm observed with the control treatment. This increase in height can be attributed to the vital role of N in amino acids, which are the fundamental building blocks of proteins (Huang et al. 2022). Proteins are crucial for plant growth and encompass essential processes such as cell division and elongation (Huang et al. 2022). When N is supplied, it enhances protein synthesis, thus fostering increased cell division and elongation in onion plant stems and leaves, ultimately resulting in taller plants (Elouattassi et al. 2023). Additionally, N stands out for its remarkable ability to stimulate robust plant growth, serves as an indispensable component in all plant tissues, and plays a pivotal role in vital cellular structures (Elouattassi et al. 2023). As highlighted by Pankievicz et al. (2019), N fulfils a crucial function that makes it an essential nutrient for plant survival and development. The present study findings align with those of Khan et al. (2007), who observed that an elevated N supply consistently led to improved growth traits in onion plants. Similarly, Table 2 demonstrates that the application of CaCN_2 had

a significant impact on onion plant leaf number. The results showed that when $90 \text{ kg}\cdot\text{ha}^{-1}$ CaCN_2 was applied, the number of leaves per plant increased by approximately 9.6%, as opposed to the number of leaves in the control treatment (6.16). Each plant had an average of 8.72 leaves at a CaCN_2 level of $400 \text{ kg}\cdot\text{ha}^{-1}$. However, when the N supply was increased to $600 \text{ kg}\cdot\text{ha}^{-1}$, the number of leaves per plant decreased to 8.36 per plant. This decrease may be explained by N saturation, whereby an abundance of N prevents effective utilization and negatively impacts many aspects of plant growth, including the development of leaves (Liang et al. 2020). This occurrence can be explained by the presence of a saturation point or diminishing returns concerning the influence of N on leaf growth. When a specific threshold is exceeded, supplying additional N may not lead to further improvements in leaf development (Al-Moshileh 2002).

During this study, it became evident that surpassing the 400 kg·ha⁻¹ (79.2 kg·ha⁻¹ N) CaCN₂ threshold did not result in additional benefits for onion plant growth. The decline in leaf count beyond this threshold is caused by the plant's inability to efficiently use the excess N, as observed by Nasreen et al. (2007). The surplus N disrupts the balance of essential nutrients like potassium and magnesium, which are vital for proper leaf development, as highlighted by the study by Xu et al. (2020). The reduction in the quantity of leaves is a result of this nutrient imbalance. Nasreen et al. (2007) found that applying 120 kg·ha⁻¹ CaCN₂ significantly boosted the leaf count; however, further increments in the N supply resulted in a decrease in the number of leaves per plant. These findings align with the outcomes of these study. However, the disparity in N levels, with their study finding 120 kg·ha⁻¹ in contrast to our finding of 79.2 kg·ha⁻¹ N, can be attributed to the choice of N source in both investigations. In our current study, we used CaCN₂, a widely recognized slow-release fertilizer with a proven history of minimal N leaching. This contrasts with the study conducted by Nasreen et al. (2007), in which urea, an N source known for

its ease of leaching, as reported by Simelane et al. (2023), was used.

Leaf length and diameter. In short-day onions, CaCN_2 greatly extended the leaf length without changing the leaf diameter (Table 2). Interestingly, neither the year of cultivation nor its interaction with CaCN_2 had any discernible influence on both leaf length and diameter. Furthermore, it is important to highlight that the longest leaf did not correspond to the highest N application level. Surprisingly, plants fertilized with $400 \text{ kg}\cdot\text{ha}^{-1}$ of CaCN_2 displayed the longest leaves (48.28 cm). In contrast, the shortest leaves were observed with the $0 \text{ kg}\cdot\text{ha}^{-1}$ CaCN_2 treatment (42.47 cm). It is worth reporting that there were no notable variations in leaf length among the treatments comprising $120 \text{ kg}\cdot\text{ha}^{-1}$, $200 \text{ kg}\cdot\text{ha}^{-1}$, and $600 \text{ kg}\cdot\text{ha}^{-1}$ CaCN_2 . The significant increase in leaf length in short-day onions could be attributed to the role of N as a vital component in chlorophyll, which is the pigment essential for photosynthesis (Fathi 2022). Furthermore, N promotes overall plant growth, enhances leaf development, and allows for the production of larger and healthier leaves (Bekele et al. 2018a; Fathi 2022). An adequate N supply ensures efficient photosynthesis, which leads to increased leaf length and, consequently, the overall growth of short-day onions (Bekele et al. 2018a). Nasreen et al. (2007) made similar observations and noted that applying $120 \text{ kg}\cdot\text{ha}^{-1}$ N significantly increased onion leaf length. However, they found no further improvements in leaf growth beyond this level. In contrast, Jilani (2004) and Khan et al. (2007) discovered that applying $200 \text{ kg}\cdot\text{ha}^{-1}$ significantly boosted onion leaf length. These diverse outcomes underscore the complexity of the relationship between the N level and leaf growth of onions, which are influenced by factors such as cultivar, environmental conditions, and nutrient interactions.

Neck thickness. The data in Table 2 demonstrate a clear impact of CaCN_2 as a source of N fertilizer on neck thickness development. Nevertheless, the interplay between the cultivation year and N level did not result in a significant impact on neck thickness. Notably, the controlled treatment showed the least neck thickness (1.290 cm), whereas the application of $600 \text{ kg} \cdot \text{ha}^{-1} \text{ CaCN}_2$ (1.349 cm) produced the highest neck thickness, closely followed by that produced by $400 \text{ kg} \cdot \text{ha}^{-1} \text{ CaCN}_2$ (1.343 cm). According to Yousaf et al. (2021), N is a crucial element for plant growth. The increased N application in this study seemed to encourage thicker necks of plants. This might be explained by the capacity of N to promote vegetative growth, which could result in more cell division and expansion (Sowers 1994). These findings are aligned with those of Jilani et al. (2004), who similarly noted that increased N applications resulted in an increased occurrence of onion bulbs with thick necks. However, it is worth noting that these results diverge from the conclusions drawn by Brewster (1987) and Abdissa et al. (2011), who contested these claims. CaCN_2 , which is characterized by its low leaching tendencies, ensures a sustained availability of N throughout the entire growing season. This

Table 3. Effects of different levels of calcium cyanamide (CaCN₂) as a source of nitrogen (N) on bulb diameter, bulb length, average bulb weight, and dry bulb yield of short-day onion.

CaCN ₂ (kg·ha ⁻¹)	Bulb diam (cm)	Bulb length (cm)	Mean bulb wt (g)	Dry bulb yield (t·ha ⁻¹)
0	6.2 c	5.40	119.23 c	5.36 b
90	7.19 b	5.41	141.98 b	6.41 a
120	7.18 b	5.41	142.36 ab	6.43 a
200	7.16 b	5.43	142.50 a	6.44 a
400	7.25 a	5.44	142.65 a	6.45 a
600	7.24 a	5.42	142.61 a	6.48 a
LSD 0.05	0.018	NS	0.4329	0.0916
Year × N	NS	NS	NS	NS

Values in a column that are followed by the same letter are not significantly different.

$P \leq 0.05$.

LSD = least significant difference; NS = not significant.

extended nutrient availability plays a pivotal role in fostering robust vegetative growth, ultimately contributing to the occurrence of onion bulbs with thick necks. The controlled release of N from CaCN₂ stands in contrast to that of other fertilizers, promoting a more prolonged and balanced nutrient supply, which positively impacts onion development and bulb formation (Simelane et al. 2023).

Bulb diameter and length. The use of CaCN₂ as an N source significantly enlarged the diameter of the onion bulb; however, it had no notable impact on bulb length (Table 3). Furthermore, the year of cultivation × CaCN₂ did not yield any significant changes in either bulb diameter or length. CaCN₂ resulted in a consistent increase in bulb diameter across all application levels compared with the control (6.2 cm). Among these, the plants treated with 400 kg·ha⁻¹ (79.2 kg·ha⁻¹ N) CaCN₂ displayed the most substantial increase, with a diameter of 7.25 cm. The 600 kg·ha⁻¹ (118.8 kg·ha⁻¹ N) CaCN₂ treatment followed closely, with a diameter of 7.24 cm, whereas the 0 kg·ha⁻¹ CaCN₂ treatment exhibited the smallest bulb diameter. Once again, there were no noticeable differences between the treatments comprising 90 kg·ha⁻¹, 120 kg·ha⁻¹, and 200 kg·ha⁻¹ CaCN₂. Additionally, increasing CaCN₂ beyond 400 kg·ha⁻¹ did not lead to a further increase in bulb diameter. Furthermore, there were no appreciable variations between the 400 and 600 kg·ha⁻¹ CaCN₂ treatments. The crucial role that N plays in the growth and development of plants, particularly bulbous crops like onions, may help to explain this (Nasreen et al. 2007). An adequate supply of N is instrumental in stimulating vegetative growth encompassing the crucial enlargement of bulb size. This nutrient, which is mobile within plants, possesses the ability to actively migrate to actively growing tissues (Anwar et al. 2001). In the initial phases of bulb formation, N has a critical role in the accumulation of dry matter within the bulb, thereby contributing significantly to its diameter. However, it is important to note that although N is unquestionably essential, there exists an optimal range for its application that maximizes bulb growth (Al-Moshileh 2002). Beyond this threshold, the incremental addition of N may not yield additional benefits and can even become counterproductive, which is a phenomenon well-

known as the saturation point in the N response (Nasreen et al. 2007).

Mean bulb weight. Table 3 highlights a substantial influence of N fertilizer application on the average weight of onion bulbs. Initially, in comparison with the control (119.23 g), the application of 90 kg·ha⁻¹ CaCN₂ resulted in an increase of ~22.76 g. Because additional N was applied, a significant enhancement in bulb weight was observed, with the 400 kg·ha⁻¹ treatment yielding the highest weight (142.65 g). Remarkably, there was no further increase in bulb weight beyond the application of 400 kg·ha⁻¹ CaCN₂. Various factors contribute to the observed increase in average bulb weight associated with the application of CaCN₂. These factors encompass the increased height of the plants, the production of more leaves with greater length, and the extended physiological maturity induced by fertilization (Geisseler et al. 2022). These factors likely culminated in higher assimilate production and greater allocation of resources to bulb development, ultimately resulting in the production of heavier bulbs (Bekele et al. 2018b). The nuanced understanding of these influencing factors provides valuable insights into optimizing fertilizer application for enhanced onion bulb weight.

Dry bulb yield. CaCN₂ greatly increased the yield of dry onion bulbs (Table 3). Applying CaCN₂ at 90 kg·ha⁻¹ specifically increased the yield over the control by approximately 1.05 t·ha⁻¹. Moreover, the CaCN₂ application was accompanied by an increase in the dry bulb yield. The control treatment yielded 5.36 t·ha⁻¹, which was the lowest yield. Interestingly, dry bulb yields from the 90 kg·ha⁻¹ to the 600 kg·ha⁻¹ treatments did not differ significantly. Furthermore, N, which is a key component in CaCN₂, plays a pivotal role in promoting vigorous vegetative growth. This growth, in turn, leads to increased production of assimilates that are efficiently allocated to bulb development. Previous studies (Adamczyk et al. 2010; Bhattacharjee et al. 2013; Geisseler et al. 2022) have highlighted the positive correlation between N and vegetative growth. Optimal N application within a specific range is crucial for healthy vegetative growth and effective bulb development (Bibi et al. 2016). However, exceeding this optimal range can pose challenges for the plant in terms of using the excess N for bulb formation, potentially leading to reduced yields (Nasreen et al. 2007).

These insights underscore the delicate balance required in N application for maximizing onion bulb yield.

Total fresh bulb yield. CaCN₂ fertilization greatly increased the total fresh bulb yield (Table 4). Plots treated with 400 kg·ha⁻¹ (79.2 kg·ha⁻¹ N) CaCN₂ produced the highest bulb yield (40.98 t·ha⁻¹); plots treated with no N (control) produced the lowest yield (19.93 kg·ha⁻¹). The increased metabolic rate that N application to the plants enables could be responsible for the increase in total bulb yield. This heightened metabolic activity leads to enhanced carbohydrate synthesis, resulting in increased bulb weight and, consequently, a higher total yield (Guesh 2015). The present findings indicate that when a particular threshold is exceeded, additional increments in the N supply do not lead to further enhancements in onion fresh bulb yield. In the context of this study, it became clear that beyond the threshold of 79.2 kg·ha⁻¹ N, there were no observable additional benefits for onion fresh bulb yield. The current study results are consistent with findings of Nasreen et al. (2007), who showed that applying 120 kg·ha⁻¹ significantly boosted total bulb yield. However, further increases in N fertilization led to a decrease in the bulb yield. Additionally, similar findings were reported by Al-Moshileh (2002), who indicated that the utilization of 200 kg·ha⁻¹ resulted in the highest onion crop production. However, exceeding this N threshold of 200 kg·ha⁻¹ was considered economically impractical for achieving higher crop yields. Research performed in northeast Ethiopia by Abdissa et al. (2011) showed that fertilizing onion plants with 69 kg·ha⁻¹ N was sufficient to produce 37.87 t·ha⁻¹ of onions. These results challenge the conventional belief that higher N fertilization rates invariably lead to substantial improvements in both onion bulb yield and quality, which is a notion upheld by several studies (Biesiada and Kolota 2009; Shaheen et al. 2010).

Marketable fresh bulb yield and unmarketable bulb yield. Without affecting the yield of unmarketable bulbs, CaCN₂ greatly increased the yield of marketable fresh onion bulbs (Table 4). Marketable fresh bulb yield and unmarketable bulb yield were not significantly impacted by the year of cultivation or its interaction with CaCN₂. In stark contrast to other treatments, 400 kg·ha⁻¹ CaCN₂, which is equivalent to 79.2 kg·ha⁻¹ N, resulted in the highest marketable yield per plot (34.18 t·ha⁻¹), followed by 118.8 kg·ha⁻¹ N (600 kg), which produced 32.34 t·ha⁻¹ (Table 4). Conversely, the marketable yield of the control plots was the lowest at 14.90 t·ha⁻¹. These results underscore that increasing CaCN₂ application levels beyond 79.2 kg·ha⁻¹ N (400 kg·ha⁻¹) escalates production expenses without a corresponding increase in the yield of marketable fresh bulbs. Jilani et al. (2004) observed comparable results and noted that 120 kg·ha⁻¹ N produced the highest onion marketable yield per plot (6.04 kg), which was considerably different from that of other treatments. When 160 kg·ha⁻¹ N was applied, it produced 5.71 kg/plot, whereas the control

Table 4. Impact of varying nitrogen (N) levels on total fresh bulb yield, marketable bulb yield, unmarketable bulb yield, and total dry biomass.

N (kg·ha ⁻¹)	Total fresh bulb yield (t·ha ⁻¹)	Marketable fresh bulb yield (t·ha ⁻¹)	Unmarketable bulb yield (t·ha ⁻¹)	Total dry biomass (t·ha ⁻¹)
0	19.93 f	14.90 f	5.03	6.08 b
90	32.37 e	26.30 e	6.07	7.49 a
120	35.51 d	27.87 d	7.64	7.44 a
200	36.41 c	29.83 c	6.58	7.48 a
400	40.98 a	34.18 a	6.8	7.52 a
600	39.80 b	32.35 b	7.45	7.52 a
LSD 0.05	0.3736	0.4166	0.358	0.0466
Year × CaCN ₂	NS	NS	NS	NS

Values in a column that are followed by the same letter are not significantly different.

$P \leq 0.05$.

CaCN₂ = calcium cyanamide; LSD = least significant difference; NS = not significant.

treatment produced the least amount of yield (1.38 kg/plot).

Total dry biomass. Table 4 shows that the total dry biomass of onions was significantly affected by CaCN₂. Importantly, the total dry biomass was not significantly impacted by the year of cultivation or its interaction with N. Beyond the application level of 400 kg·ha⁻¹ (79.2 kg·ha⁻¹ N), these traits displayed a tendency to increase with increasing N; however, when that threshold was surpassed, they began to decrease. This increase in total dry biomass could be attributed to the expansion of the photosynthetic area stimulated by the N applied (Fathi 2022). This expansion, in turn, facilitated greater assimilated production and improved partitioning of resources toward bulb development (Fathi 2022; Moradi et al. 2021). The reduction in overall dry biomass below 79.2 kg·ha⁻¹ N may be explained by the presence of a critical threshold. Once this threshold is surpassed, additional N supply does not result in further improvements in total dry biomass, as noted by Hafez and Geries (2018) and Al-Moshileh (2002).

Bulb sprouts percentage. During storage, onions go through a physiological transformation known as sprouting. The application of CaCN₂ significantly influenced the percentage of bulb sprouts ($P < 0.001$). After 2 months of storage, the plots with the highest CaCN₂ application rate (600 kg·ha⁻¹) resulted in the highest incidence of sprouting (7.68%), whereas the plots with the lowest incidence (3.68%) were those with 0 kg·ha⁻¹ CaCN₂ (control). There were no notable distinctions observed between N levels of 120 kg·ha⁻¹ (23.76 kg·ha⁻¹ N) and 200 kg·ha⁻¹ (39.6 kg·ha⁻¹ N). Excessive application of CaCN₂ can disturb the plant's nutrient equilibrium, which, in turn, interferes with the synthesis of hormones responsible for both bulb development and dormancy regulation (Anas et al. 2020; Bekele et al. 2018a). Consequently, this disruption may cause bulbs to prematurely emerge from dormancy and initiate sprouting (Anas et al. 2020). This finding aligns with those of Dankhar and Singh (1991), Sørensen and Grevsen (2001), and Sabale and Kalebere (2004), who noted that higher levels of sprouting were linked to an increased N supply. However, a number of other studies, such as those conducted by Suojala et al. (1998),

Tekalign et al. (2012), and Bekele et al. (2018b), were unable to demonstrate a clear connection between the levels of N applied and sprouting. These contradictory results imply that a variety of factors, including the availability of N, interact to affect the tendency for sprouting. However, compared with bulbs from plants with less or no N deficiency, Maier et al. (1990) noted that bulbs from plants severely lacking N exhibited significantly earlier storage-induced sprouting.

Bulb storage rot percentage. Table 5 shows a significant impact ($P < 0.05$) on the percentage of rotting bulbs caused by the application of N. Plots with 0 kg·ha⁻¹ CaCN₂ exhibited the lowest percentage of bulb rot, whereas those with 600 kg·ha⁻¹ had the highest percentage, reaching 5%. This stark contrast suggests a significant impact of N level on rot incidence. The elevated rot percentage in the plots with 600 kg·ha⁻¹ (118.8 kg·ha⁻¹ N) CaCN₂ can be attributed to the excessive N application. This surplus N led to an accumulation of moisture within the onion bulbs, consequently diminishing their dry matter content (Etana et al. 2019; Kashi and Frodi 1998). This moisture buildup created an environment conducive to rot development, contributing to the observed higher percentage (Geisseler et al. 2022). Conversely, the absence of N in the 0 kg·ha⁻¹ plots prevented such moisture accumulation, resulting in a lower incidence of bulb rot. This finding underscores the critical role of N management in preserving onion quality and minimizing rot-related losses. Bulbs with higher moisture content are more prone to rot because moisture creates an environment conducive to fungal and bacterial growth (Khan et al. 2002). According to the findings of Etana et al. (2019), onion bulbs that were cultivated without N treatment exhibited the lowest rotting rate (2.38%). Conversely, bulbs produced with a higher amount of N displayed the highest percentage of rotting (5%). Dhankar and Singh (1991) reported similar results, indicating that elevating the N application level from 50 to 150 kg·ha⁻¹ resulted in notable increases in onion storage rot throughout 4 to 5 months under normal environmental conditions.

The influence of CaCN₂ as an N source on the weight loss of onion bulbs during

Table 5. Influence of different levels of calcium cyanamide (CaCN₂) on storage rot and storage sprout losses.

CaCN ₂ (kg·ha ⁻¹)	Storage rot loss (%)	Storage sprout loss (%)
0	1.75 f	3.68 e
90	2.00 e	5.82 d
120	2.50 d	6.30 c
200	2.67 c	6.50 c
400	3.81 b	7.33 b
600	5.00 a	7.68 a
LSD 0.05	0.1210	0.2459
Year × CaCN ₂	NS	NS

Values in a column that are followed by the same letter are not significantly different.

$P \leq 0.05$.

LSD = least significant difference; NS = not significant.

storage showed varying patterns over time (Table 6). Initially, during the first 3 weeks postharvest, CaCN₂ fertilization displayed no significant effect. However, starting from the fourth week, N fertilization began to play a crucial role, leading to increased weight loss. Notably, the group that received the highest CaCN₂ amount of 400 to 600 kg·ha⁻¹ (79.2–118.8 kg·ha⁻¹ N) experienced the most significant weight loss, whereas the control group (0 kg·ha⁻¹) exhibited the least. Although no notable distinctions were observed between the groups receiving 0, 90, and 120 kg·ha⁻¹ and those receiving 200, 400, and 600 kg·ha⁻¹ during weeks 4, 5, and 6, a shift in the trend became apparent during the seventh and eighth weeks. Increased N application led to a significant increase in weight loss. The group without N application showed the lowest weight loss, followed by the groups that received 90 and 120 kg·ha⁻¹; the highest weight loss occurred in the groups that received 400 and 600 kg·ha⁻¹. This suggested that avoiding too much N application contributed to better weight preservation. The reason for this phenomenon could involve factors such as moisture regulation, microbial activity, or changes in onion physiology during extended storage (Muluneh et al. 2019).

The substantial weight loss observed from the fourth to the eighth weeks can be attributed to the larger bulb size resulting from higher N application. Higher N levels tend to yield larger bulbs. However, these larger bulbs also have a higher respiration rate, leading to more significant weight loss. Top respiration in plants is a crucial process whereby stored energy is converted to usable forms, releasing carbon dioxide and water (Chope et al. 2012).

Larger bulbs, with their higher metabolic activity, undergo increased respiration. Consequently, during later weeks of storage, these larger bulbs respire at a faster rate, causing a higher weight loss. The increased respiratory activity accelerates the breakdown of stored carbohydrates and other organic compounds within the onion, causing it to lose weight more rapidly compared with that of smaller bulbs. This result is consistent with that of Muluneh et al. (2019), who

Table 6. Effects of calcium cyanamide (CaCN₂) on the cumulative weight loss of onion bulbs stored at room temperature condition for 8 weeks.

CaCN ₂	Wt loss (%)							
	7DS	14DS	21DS	28DS	35DS	42DS	49DS	56DS
0	5.53	7.19	12.14	17.39 b	19.30 b	24.90 b	27.80 c	33.22 c
90	5.50	7.18	12.32	17.39 b	19.25 b	24.87 b	28.08 b	33.64 b
120	5.52	7.19	12.31	17.30 b	19.30 b	24.89 b	28.11 b	33.71 b
200	5.47	7.20	12.31	17.68 a	19.89 a	26.10 a	29.63 a	36.48 a
400	5.56	7.19	12.33	17.72 a	19.91 a	26.21 a	29.63 a	36.55 a
600	5.61	7.21	12.36	17.71 a	19.91 a	26.12 a	29.63 a	36.49 a
F test	NS	NS	NS	*	*	*	*	*
Mean	5.53 h	7.19 g	12.30 f	17.53 e	19.59 d	25.52 c	28.86 b	35.05 a
LSD 0.05	NS	NS	NS	0.1418	0.3931	1.067	1.228	1.118

Values in a column that are followed by the same letter are not significantly different.

$P \leq 0.05$.

DS = days of storage; LSD = least significant difference; NS = not significant.

discovered that over a 3-month storage duration at room temperature, the percentages of bulb rot, bulb sprouting, and weight loss escalated because of excessive N fertilizer application. The highest N level caused the largest cumulative weight loss over the course of 8 weeks of storage according to Tekalign et al. (2012), who conducted a study in northeast Ethiopia to evaluate the impact of various N fertilizer levels on onion quality and storability. In contrast, the control treatment (0 kg-ha⁻¹ CaCN₂) likely produced smaller bulbs because of the absence of N fertilizer. These smaller bulbs, with a lower respiration rate, experienced reduced breakdown of stored compounds, leading to lower cumulative weight loss during the storage period. Therefore, the differences in observed weight loss can be linked to bulb size, which is influenced by N fertilization levels. Larger bulbs resulting from higher fertilizer levels had a higher respiration rate, leading to significant weight loss during later storage weeks. In contrast, smaller bulbs from the control treatment exhibited slower respiration and retained their weight more effectively. Similar findings were also observed by Jilani (2004). In contrast, Ullah et al. (2008) found that the addition of N improved the storability of onion bulbs. They noted that after 180 d of storage, the control treatments exhibited the highest percentage of rotten bulbs (63.75%), whereas crops cultivated with 45 kg-ha⁻¹ N experienced the lowest loss (37.04%).

Conclusion

The optimal agricultural practices for growing onions differ greatly depending on the particular type of onion, production objectives, and surrounding conditions. As a result, there is no single, globally accepted agronomic strategy that covers variables like fertilizer type and level and can be administered consistently across all areas. The results of this study highlight the significant influence that N treatment has on a number of onion cultivation-related factors. There were notable differences between the various treatments in terms of bulb storage capacity, yield metrics, and growth patterns. In particular, this study showed that increasing N fertilization from 0 to 400 kg-ha⁻¹ CaCN₂ (0 to 79.2 kg-ha⁻¹ N) significantly increased onion plant growth, leaf count, and yield overall. The study revealed an interesting

plateau effect related to the N supply. Beyond 400 kg-ha⁻¹ and up to 600 kg-ha⁻¹, increasing the N treatment did not result in a discernible improvement in marketable yield. However, an intriguing trend emerged: excessive N was associated with adverse outcomes, particularly beyond 400 kg-ha⁻¹ CaCN₂. Higher N levels were associated with a significant increase in bulb rot, sprouting percentage, and weight loss, highlighting the significance of a balanced fertilization strategy in onion production. This research emphasizes the nuanced relationship between N application and onion cultivation outcomes. Optimal onion development and yield enhancement were achieved through a targeted CaCN₂ fertilization range of 200 to 400 kg-ha⁻¹. However, exceeding 400 kg-ha⁻¹ in N fertilization may lead to undesirable consequences, including increased risks of bulb rot and weight loss. To ensure the highest level of onion production efficiency and quality, it is crucial to customize fertilizer techniques according to specific conditions. This approach takes into consideration the intricate balance between stimulating growth and mitigating potential drawbacks. Finding this optimal level is essential for promoting robust onion growth while minimizing adverse effects.

References Cited

- Abdissa Y, Tekalign T, Pant LM. 2011. Growth, bulb yield and quality of onion (*Allium cepa* L.) as influenced by nitrogen and phosphorus fertilization on vertisol I. growth attributes, biomass production and bulb yield. *Afr J Agric Res*. 14:3252–3258.
- Adamczyk B, Smolander A, Kitunen V, Godlewski M. 2010. Proteins as nitrogen source for plants: A short story about exudation of proteases by plant roots. *Plant Signal Behav*. 5:817–819.
- Ahmad A, Ijaz SS, He Z. 2021. Effects of zeolitic urea on nitrogen leaching (NH₄-N and NO₃-N) and volatilization (NH₃) in spodosols and alfisols. *Water*. 13(14):1–11. <https://doi.org/10.3390/w13141921>.
- Al-Moshileh AM. 2002. Effect of rate and time of nitrogen application on onion production in the central region of Saudi Arabia. *J King Saud Univ Sci*. 14(1):33–41.
- Álvarez-Fuentes J, Lóczy D, Thiele-Bruhn S, Zornoza R. 2019. Handbook of plant and soil analysis for agricultural systems. <https://core.ac.uk/download/pdf/185619949.pdf>. [accessed 1 Sep 2024].
- Anas M, Liao F, Verma KK, Sarwar MA, Mahmood A, Chen ZL, Li Q, Zeng XP, Liu Y, Li YR. 2020. Fate of nitrogen in agriculture and environment: Agronomic, eco-physiological and molecular approaches to improve nitrogen use efficiency. *Biol Res*. 53:1–20.
- Anwar MN, Sarker JU, Rahman M, Islam MA, Begu M. 2001. Response of onion to nitrogen, phosphorus, potassium, sulphur and zinc. *Bangladesh J Environ Sci*. 7:68–72.
- Bekele M, Mohammed A, Nebiyu A. 2018a. Quality and storage life of onion (*Allium cepa* L.) as influenced by applications of nitrogen, phosphorus and potassium fertilizer, at Jimma, South Western Ethiopia. *J Natl Sci Res*. 8:31–44.
- Bekele M, Mohammed A, Nebiyu A. 2018b. Effects of different levels of nitrogen, phosphorus and potassium fertilization on growth and yield of onion (*Allium cepa* L.) at Jimma, South Western Ethiopia. *J Natl Sci Res*. 8:1–19.
- Bhattacharjee SA, Sultana MH, Sazzad MA, Islam M, Ahtashom MM. 2013. Analysis of proximate composition and energy values of two varieties of onion (*Allium cepa* L.) bulbs of different origin: A comparative study. *Int J Food Sci Nutr*. 2:246–253.
- Bibi S, Naeem A, Dahlawi S. 2016. Environmental impacts of nitrogen use in agriculture, nitrate leaching and mitigation strategies, p 131–157. In: *Soil science: Agricultural and environmental perspectives*. Springer, Cham, Switzerland.
- Biesiada A, Kolota E. 2009. The effect of nitrogen fertilization on yield and nutritional value of onion grown from sets for early cropping. *Veg Crop Res Bull*. 70:145–151.
- Bletsos FA. 2006. Grafting and calcium cyanamide as alternatives to methyl bromide for greenhouse eggplant production. *Scientia Hort*. 107:325–331.
- Brewster JL. 1987. The effect of temperature on the rate of sprout growth and development within stored onion bulbs. *Ann Appl Biol*. 111:463–465.
- Brewster JL. 1994. Onions and other vegetable alliums (1st ed). CAB International, Wallingford, UK.
- Brzozowski J, Jakubowski R, Pietrzykowska A, Rodziejewicz J. 1953. Hygiene of work and health in workers exposed to Azotniak in agriculture. *Ann UMCS Med*. 8:301–320.
- Chope GA, Cools K, Hammond JP, Thompson AJ, Terry LA. 2012. Physiological, biochemical and transcriptional analysis of onion bulbs during storage. *Ann Bot*. 109:819–831.
- Department of Agriculture, Land Reform and Rural Development. A profile of the South African onion market value chain. 2021. Department of Land Reform and Rural Development Directorate: Marketing, Pretoria, South Africa.
- Dhankar BS, Singh J. 1991. Effect of nitrogen, potash and zinc on storage loss onion bulbs (*Allium cepa* L.). *Int J Veg Sci*. 18:16–23.

- Dixon GR. 1984. Calcium cyanamide – a synoptic review of an environmentally benign fertilizer which enhances soil health. *Acta Hortic.* 918:211–217.
- Dixon GR. 2017. Managing clubroot disease (caused by *Plasmiodiophora brassicae* Wor.) by exploiting the interactions between calcium cyanamide fertilizer and soil microorganisms. *J Agric Sci.* 155:527–543.
- Elouattassi Y, Feriou M, Ghachtouli N, Derraz K, Rachidi F. 2023. Enhancing onion growth and yield through agroecological practices: Organic fertilization and intercropping. *Acta Ecol Sin.* 09:1–16.
- Etana MB, Mohammed A, Nebiyu A. 2019. Effects of different level of nitrogen fertilizer application on growth, yield, quality and storage life of onion (*Allium cepa* L.) at Jimma. Southwestern Ethiopia. *J Nat Sci Res.* 9:32–40.
- Fathi A. 2022. Role of nitrogen in plant growth, photosynthesis pigments, and N use efficiency: A review. *Agrisost.* 28:1–8. <https://doi.org/10.5281/zenodo.7143588>.
- Geisseler D, Ortiz RS, Diaz J. 2022. Nitrogen nutrition and fertilization of onions (*Allium cepa* L.)—A literature review. *Scientia Hortic.* 291:1–15.
- Guesh T. 2015. Growth, yield and quality of onion (*Allium cepa* L.) as influenced by intra-row spacing and nitrogen fertilizer levels in central zone of Tigray, Northern Ethiopia (MSc Thesis). Haramaya University, Haramaya, Ethiopia.
- Hafez E, Geries L. 2018. Onion (*Allium cepa* L.) growth, yield, and economic return under different combinations of nitrogen fertilizers and agricultural biostimulants. *Cercet Agron.* 3:69–88.
- Hahn P. 1951. Calcium cyanamide for pre-emergence weed control and fertilization in canning peas. Book Proceedings of the Northeastern Weed Control Conference. 119–123.
- Hassan MS, Ayoub AT. 1978. Effects of N, P and K on yield of onion in the Sudan Gezira. *Exp Agric.* 14:29–32.
- Huang Y, Wang W, Yu H, Peng J, Hu Z, Chen L. 2022. The role of 14-3-3 proteins in plant growth and response to abiotic stress. *Plant Cell Rep.* 41:833–852.
- Jilani MS. 2004. Studies on the management strategies for bulb & seed production of different cultivars of onion (*Allium cepa* L.) (PhD Thesis). Gomal University, Dera Ismail Khan, Pakistan.
- Jilani MS, Ghahoor A, Waseem K, Farooqi JI. 2004. Effect of different levels of nitrogen on growth and yield of three onion varieties. *Int J Agric Biol.* 6:507–510.
- John JA, Quenouille MH. 1977. Experiments: Design and analysis. Charles Griffin, London, UK.
- Kashi A, Frodi BR. 1998. Effect of nitrogen on the yield, quality and storability of edible onion cultivars (*Allium cepa* L.). *Iran J Agric Sci.* 29:589–597.
- Khan AA, Zubair M, Bari A, Maula F. 2007. Response of onion (*Allium cepa*) growth and yield to different levels of nitrogen and zinc in swat valley. *Sarhad J Agric.* 23:933–936.
- Khan H, Iqbal M, Ghaffoor A, Waseem K. 2002. Effect of various plant spacing and different levels of nitrogen on the growth and yield of onion (*Allium cepa* L.). *J Biol Sci.* 2:545–547.
- Khokhar KM. 2017. Environmental and genotypic effects on bulb development in onion—A review. *J Hortic Sci Biotechnol.* 92(5):1–7.
- Klasse H. 1996. Calcium cyanamide – an effective tool to control clubroot – a review. *Acta Hortic.* 407:403–410.
- Kukanoor L. 2005. Post-harvest studies in onion, p 19–144. Department of Horticulture, College of Agriculture, Dharwad University of Agricultural Sciences, Dharwad, India.
- Lawrence PG, Roper W, Morris TF, Guillard K. 2020. Guiding soil sampling strategies using classical and spatial statistics: A review. *Agron J.* 112:493–510. <https://doi.org/10.1002/agj2.20048>.
- Leytur M, Vera A, Sala A, Giardina B, Benedetto A. 2018. Pot growing media amendment with calcium cyanamide and weed control relationships. *Int J Plant Soil Sci.* 23:1–12.
- Liang H, Shen P, Kong X, Liao Y, Liu Y, Wen X. 2020. Optimal nitrogen practice in winter wheat-summer maize rotation affecting the fates of 15N-labeled fertilizer. *J Agron.* 10:1–15.
- Maier NA, Dahlenburg AP, Twigden TK. 1990. Effect of nitrogen on the yield and quality of irrigated onions (*Allium cepa* L.) cv. Cream Gold grown on siliceous sands. *Aust J Exp Agric.* 30:845–851. <https://doi.org/10.1071/EA9900845>.
- Meier U. 2006. A note on the power of Fisher's least significant difference procedure. *Pharm Stat.* 4:253–263.
- Mohammad M, Moazzam HA. 2012. Onion yield, quality and storability as affected with different soil moisture and nitrogen regimes. *Romania Southwestern J Hort Biol Environ.* 3:145–165.
- Moradi S, Kafi M, Aliniaiepard S, Salami SA, Shokrpour M, Pedersen C, Moosavi-Nezhad M, Wróbel J, Kalaji HM. 2021. Blue light improves photosynthetic performance and biomass partitioning toward harvestable organs in saffron (*Crocus sativus* L.). *Cells.* 10:1–23. <https://doi.org/10.3390/cells10081994>.
- Mozumder SN, Moniruzzaman M, Halim GMA. 2007. Effect of N, K and S on the yield and storability of transplanted onion (*Allium cepa* L.) in the Hilly Region. *Bangladesh J Agric Rural Dev.* 5:58–63.
- Muluneh BE, Ali M, Amsalu N. 2019. Effects of different level of nitrogen fertilizer application on growth, yield, quality and storage life of onion (*Allium cepa* L.) at Jimma. *Southwestern Ethiopia. J Nat Sci Res.* 9:32–40.
- Murindangabo YT, Kopecký M, Hoang TN. 2023. Comparative analysis of soil organic matter fractions, lability, stability ratios, and carbon management index in various land use types within bharatpur catchment, Chitwan District, Nepal. *Carbon Balance Manag.* 18:1–21. <https://doi.org/10.1186/s13021-023-00241-1>.
- Nasreen S, Haque MM, Hossain MA, Farid AT. 2007. Nutrient uptake and yield of onion as influenced by nitrogen and sulphur fertilization. *Bangladesh J Agric Res.* 32:413–420.
- Ncayiyana M, Maboko MM, Bertling I. 2018. Yield and nutritional quality of different short-day onion cultivars as affected by nitrogen application. *S Afr J Plant Soil.* 35:215–221.
- Ndjadi SS, Vissoh PV, Vumila RK, Mondo JM, Mugumaarhama Y, Sidou A, Nachigera GM, Ahoton LE. 2022. Yield potential and land-use efficiency of onion (*Allium cepa* L.) intercropped with peanut (*Arachis hypogaea* L.) under organic soil fertility management in South-Kivu. *Eastern DR Congo. Bulg J Agric Sci.* 28:647–657.
- Obetta N. 2007. Evaluation of ventilated underground storage for Cocoyam (Taro). *Agricultural Engineering International: The CIGRE Journal.* 9:1–15.
- Pankiewicz VCS, Irving TB, Maia LGS. 2019. Are we there yet? The long walk towards the development of efficient symbiotic associations between nitrogen-fixing bacteria and non-leguminous crops. *BMC Biol.* 17:1–17.
- Sabale A, Kalebere S. 2004. Storage behaviour of onion (*Allium cepa* L.) varieties under the influence of preharvest and postharvest treatment of maleic hydrazide and carbendazim. *Acta Bot Hung.* 46:395–400.
- Sala A, Williams T, Feuring V, Giardina E, Di Benedetto A. 2016. Physiological changes involved in the use of calcium cyanamide as a slow-release nitrogen fertilizer in *Impatiens wallerana*. *Int J Plant Soil Sci.* 12:116.
- Shaheen AM, Fatma AR, Hoda AMH, El-Baky MMH. 2010. Nitrogen soil dressing and foliar spraying by sugar and amino acids as affected the growth, yield and its quality of onion plant. *Am J Sci.* 6:420–427.
- Sheikh MA, Ansari AH, Qayyum SM, Qayyum MB, Hussain SA. 1987. Technical report on effect of nitrogen doses on the growth and crop yield of onion. *Pak J Agric Sci.* 9:35–40.
- Simelane MPZ, Soundy P, Maboko MM. 2023. Effect of calcium cyanamide as an alternative nitrogen source on growth, yield, and nitrogen use efficiency of short-day onion. *Agron.* 13(11):2746. <https://doi.org/10.3390/agronomy13112746>.
- Snedecor GW, Cochran WG. 1989. Statistical methods (8th ed). Iowa State University Press, Ames, IA, USA.
- Sørensen JN, Greven K. 2001. Sprouting in bulb onions (*Allium cepa* L.) as influenced by nitrogen and water stress. *J Hortic Sci Biotechnol.* 76:501–506.
- South African Weather Service. 2020. Annual state of the climate of South Africa 2020. South African Weather Service, Pretoria, South Africa.
- Sowers KE, Pan WL, Miller BC, Smith JL. 1994. Nitrogen use efficiency of split nitrogen applications in soft white winter wheat. *J Agron.* 86:942–948.
- Steer BT. 1980. The bulbing response to daylength and temperature of some Australian cultivars of onion. *Aust J Agric Res.* 31:511–518.
- Suojala T, Salo T, Pessala R. 1998. Effects of fertilisation and irrigation practices on yield, maturity and storability of onions. *Agric Food Sci.* 7:477–489.
- Sutton MA, Howard CM, Mason KE, Brownlie WJ, Cordovil CM. 2022. Nitrogen opportunities for agriculture, food & environment. UNECE guidance document on integrated sustainable nitrogen management. UK Centre for Ecology & Hydrology, Edinburgh, UK.
- Swify S, Mažeika R, Baltrusaitis J, Drapanauskaitė D, Barčauskaitė K. 2024. Review: Modified urea fertilizers and their effects on improving nitrogen use efficiency (NUE). *Sustainability.* 16:1–20. <https://doi.org/10.3390/su16010188>.
- Tandon HS. 1987. phosphorus research and agricultural production in India, p 160–182. Fertilizer in Development and Consultation Organization, New Delhi, India.
- Tekalign T, Abdissa Y, Pant LM. 2012. Growth, bulb yield and quality of onion (*Allium cepa* L.) as influenced by nitrogen and phosphorus fertilization on vertisol. II: Bulb quality and storability. *Afr J Agric Res.* 7:5980–5985.
- Ullah MH, Hu SMI, Alam MDU, Rahman MA. 2008. Impacts of sulphur levels on yield, storability and economic return of onion. *Bangladesh J Agric Res.* 33:539–548.
- Vojnović Đ, Maksimović I, Tepić Horecki A, Karadžić Banjac M, Kovačević S, Daničić T, Podunavac-Kuzmanović S, Ilin Ž. 2023. Onion (*Allium cepa* L.) yield and quality depending on biostimulants and nitrogen fertilization—A chemometric perspective. *Processes.* 11:1–16.
- Waskar DP, Khedlar RM, Garande VK. 1992. Effect of postharvest treatment on shelf life and

- quality of pomegranate in evaporative cool chamber and ambient conditions. *J Food Sci Technol.* 36:114–117.
- Xu X, Du X, Wang F, Sha J, Chen Q, Tian G, Zhu Z, Ge S, Jiang Y. 2020. Effects of potassium levels on plant growth, accumulation and distribution of carbon, and nitrate metabolism in apple dwarf rootstock seedlings. *Front Plant Sci.* 11:1–13.
- Yamasaki A, Tanaka K. 2005. Effect of nitrogen on bolting of bunching onion (*Allium fistulosum* L). *Engeigaku Kenkyuu.* 1:51–54.
- Yousaf M, Bashir S, Raza H, Shah AN, Iqbal J, Arif M, Bukhari MA, Muhammad S, Hashim S, Alkahtani J, Alwahibi MS, Hu C. 2021. Role of nitrogen and magnesium for growth, yield and nutritional quality of radish. *Saudi J Biol Sci.* 28:3021–3030.