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DOES SPLIT NITROGEN APPLICATION INCREASE GARLIC YIELD AND QUALITY?

Marcos Renan Besen[1*], Juliano Masahiko Ogawa[2], Ricardo Henrique Ribeiro[3], Claudia Aparecida Guginski-Piva[4], Jonatas Thiago Piva[5]

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ABSTRACT - Nitrogen (N) fertilization is essential for obtaining high garlic yields and satisfying commercial requirements for bulb diameter. However, excess nitrogen may favor the development of lateral shoots. This study aimed to examine the effect of different N application strategies on garlic yield and quality. The experiment was conducted in the field using garlic cv. Chonan and four N fertilization strategies (T1, N fertilizer applied at 15-day intervals; T2, N fertilizer applied before and after clove differentiation; T3, N fertilizer applied before clove differentiation; and T4, N fertilizer applied after clove differentiation). All treatments received the same N rate (210 kg ha^{-1}). A single N application before clove differentiation (T3) favored lateral shoot growth, resulting in the highest incidence of this defect (11.66%). The other treatments did not differ in lateral shoot incidence. Four classes (3–6) of bulb diameter were observed, with treatments ranked in decreasing order as T2 > T1 > T3 > T4. There were no significant differences in garlic yield between single N application treatments (T3 and T4). However, garlic yield differed by 73% between T1 (13,329 kg ha^{-1}) and T4 (7,679 kg ha^{-1}), by 55.31% between T2 (11,927 kg ha^{-1}) and T4, and by 36% between T1 and T3 (9,783 kg ha^{-1}). These results indicate that two N fertilization strategies can be adopted in high-quality garlic production: fortnightly N fertilization or split N application before and after clove differentiation. A single N application is not recommended, regardless of application timing, as it promotes lateral shoot growth and reduces garlic quality and yield.
Keywords: *Allium sativum* L., nitrogen fertilization, vernalized garlic, lateral shoot growth.

O PARCELAMENTO DO NITROGÊNIO AUMENTA A PRODUTIVIDADE E QUALIDADE DO ALHO?

RESUMO - A adubação nitrogenada é fundamental para elevadas produtividades de alho com diâmetro comercial que atendam às exigências de mercado. Contudo, o excesso de nitrogênio (N) pode favorecer o superbrotamento. Objetivou-se avaliar estratégias de parcelamento do N no alho. O experimento foi conduzido com a cultivar Chonan, sendo estudadas 4 estratégias de adubação nitrogenada: T1 - cada 15 dias, T2 - antes e após a diferenciação, T3 - antes da diferenciação e T4 - após a diferenciação. Foram utilizados 210 kg N ha^{-1} em todos os tratamentos. A aplicação integral de N antes da diferenciação (T3) favoreceu o superbrotamento com incidência de 11,66%, enquanto demais tratamentos não diferiram. Foram obtidas 4 classes distintas de diâmetro de bulbo, representada pela ordem decrescente, T2 > T1 > T3 > T4, correspondente a classe 6, 5, 4 e 3, respectivamente. Em relação a produtividade, não houve diferença significativa entre T3 e T4, que envolvem uma aplicação de N. Todavia, T2 com 11.927 kg ha^{-1}, aumentou em 55,31% a produtividade em relação a T4 (7.679 kg ha^{-1}). T1 aumentou a produtividade em 36% e 73% em relação a T3 e T4, respectivamente. Na busca por bulbos de alho com maior valor agregado duas estratégias de adubação nitrogenada podem ser adotadas: por meio do parcelamento quinzenal, ou parcelar o N antes e após a diferenciação. Não é recomendável uma única aplicação de N, independente se realizada antes ou após a diferenciação, visto que ocasiona o aumento no pseudoperfilhamento (T3) e redução na qualidade e produtividade.
Palavras-chave: *Allium sativum* L., adubação nitrogenada, alho vernalizado, pseudoperfilhamento.

INTRODUCTION

Brazilian garlic production is concentrated in five states, which account for more than 92% of the national production. The state of Santa Catarina produced 22,793 tonnes of garlic in 2017, ranking third in the country, behind Minas Gerais and Goiás (EPAGRI/CEPA, 2018; IBGE, 2018). Large-scale garlic production in the state began in the 1960s in the municipality of Curitibanos, located in the Santa Catarina Plateau. The activity had great economic relevance, leading the state to become a national reference in noble garlic production (EPAGRI/CEPA, 2018). To this day, garlic is a crop of great economic and social importance in the Santa Catarina Plateau (BIASI, 1991). However, despite the

[1]Universidade Estadual de Maringá (UEM), Maringá, Paraná, Brazil. E-mail: marcos.besen@hotmail.com. *Correspondence author.
[2]Universidade Federal de Santa Catarina (UFSC). Curitibanos, Santa Catarina, Brazil.
[3]Universidade Federal do Paraná (UFPR), Curitiba, Paraná, Brazil.
[4]Engenheira Agrônoma, Doutora em Agronomia, Santa Helena, Paraná, Brazil.
[5]Universidade Tecnológica Federal do Paraná (UTFPR), Santa Helena, Paraná, Brazil.

advances of the last decade in garlic production and yield, Brazil still produces less than half of its domestic consumption and only 0.50% of the worldwide production (FAO, 2018).

Adequate phytosanitary and nutrient management is essential for increased crop productivity. Garlic grows well in fertile soil and is, therefore, responsive to fertilization (PIVA et al., 2017). Nitrogen (N) is the most limiting nutrient for vernalized garlic; the plant extracts about 179 kg N ha^{-1} from the soil (SOUZA et al., 2011). N can be lost from the soil by different processes, particularly ammonia volatilization and nitrate leaching, reducing fertilization efficiency (CQFS/RS-SC, 2016). Therefore, defining the optimal N fertilization rate for garlic fields is challenging. Several factors influence N-use efficiency, making it impossible to standardize the dose of N for a single application under different conditions (FERNANDES et al., 2011; HAHN et al., 2020; HENRIQUES et al., 2019). The economic aspect of N fertilization must also be taken into account to maximize yields and minimize costs (PIVA et al., 2017).

Because of the complexity of determining the optimal rate for a single N application, it is important to consider other N management approaches, such as split fertilization. Split N application had positive effects on bok choy (ZANÃO JUNIOR et al., 2005) but null effects on arugula (CECÍLIO FILHO et al., 2014), potato (BARCELOS et al., 2007), and radish (SANTOS et al., 2018). Resende and Souza (2001) investigated the effects of N fertilizer rates applied at 30, 50, and 70 days after planting on garlic yield. The authors found that yield increased linearly with increasing N rates and application time, but no significant interaction effects were observed between factors.

We highlight that N fertilization should increase garlic yield without promoting the formation of lateral shoots, also known as secondary branching (LIMA et al., 2008). This physiological disorder is a major problem in garlic production, especially for noble garlic cultivars (BÜLL et al., 2002), and may be aggravated by excess N (CQFS-RS/SC, 2016). The hypothesis of this study is that split N application influences garlic quality, lateral shoot incidence, and yield. Thus, the aim was to investigate the effects of split N application regimes on the development and yield of vernalized noble garlic cv. Chonan grown in the Santa Catarina Plateau.

MATERIAL AND METHODS

The experiment was conducted in the field between July and December 2014 at the experimental farm (27°16’22”S 50°30’11”W, 1050 m elevation) of the Federal University of Santa Catarina, Curitibanos, Santa Catarina, Brazil. The climate is classified as temperate oceanic (*Cfb* in the Köppen climate classification system), with average temperatures of 15 to 25°C and an average annual precipitation of 1500 mm. According to Santos et al. (2013), the soil is a typical Haplic Cambisol with clay texture (550 g clay kg^{-1}). Soil chemical properties at the 0-20 cm depth are presented in Table 1.

TABLE 1 - Soil chemical properties in the 0-20 cm depth layer prior to initiation of the experiment.

pH in $CaCl_2$	Ca^{2+}	Mg^{2+}	K^{+}	Al^{3+}	SB	H + Al	P	Cu	Fe	Zn	Mn	BS	OM
	--------------------$cmol_c$ dm^{-3}--------------------						------------------mg dm^{-3}------------------					%	g dm^{-3}
5.90	10.20	3.10	0.18	0.00	13.48	2.95	20.75	2.65	26.98	1.90	59.18	82.05	49.59

pH measured in $CaCl_2$ solution using a soil/solution ratio of 1:2.5 (w/v); exchangeable Ca, Mg, and Al extracted with 1 mol L^{-1} KCl; SB, sum of bases; H + Al, total acidity; P, K, Cu, Fe, Zn, and Mn extracted with Mehlich-1 solution; BS, base saturation; OM, organic matter content determined by wet digestion.

A randomized complete block design with four replications was used. Treatments consisted of the following N fertilization regimes: T1, fortnightly N applications, with the first dose applied 12 days after planting, three doses applied before clove differentiation (75 days after planting), and one dose applied 10 days after clove differentiation, totaling five applications of 42 kg N ha^{-1}; T2, N applications split between 30 days after planting and 10 days after clove differentiation, totaling two applications of 105 kg N ha^{-1}; T3, a single N application at 30 days after planting; and T4, a single N application at 10 days after clove differentiation. The total N rate in all treatments was 210 kg ha^{-1}, applied in the form of urea (45% N). Destructive sampling was used to assess clove differentiation. Cloves were considered differentiated when 50% of sampled bulbs showed small projections close to the central axis.

The cultivar used was ‘Chonan’, selected for the production of Class 5 garlic bulbs with a mean weight of 4 g, according to the garlic size classification of the Brazilian Ministry of Agriculture, Livestock, and Food Supply Ordinance No. 242 of 1992 (MAPA, 1992). Seed bulbs were vernalized for 28 days in a cold chamber at 4°C. Before planting, the bulbs were treated with a fungicide (procymidone) for the prevention of white rot (*Sclerotium cepivorum*) disease.

The soil was tilled with a 1.2 m wide rotary hoe at 40 days before planting. Seed bulbs were planted manually on July 23, 2014, following plant hardiness recommendations for the region. Five rows, marked out with a line marker, were prepared in each experimental unit. The distance between rows was 0.20 m, and the distance between bulbs within rows was 0.10 m. At the time of planting, all plots were fertilized with triple superphosphate (150 kg ha^{-1}) and potassium chloride (300 kg ha^{-1}). The first irrigation was applied shortly after to ensure uniform sprouting. Two weekly irrigations were performed until the clove differentiation stage, when irrigation was suspended. At the end of the differentiation period, irrigation was resumed and maintained until shortly before harvest. Plots were irrigated to field capacity.

Cultural practices, including pesticide application, followed specific recommendations for garlic production (LUCINI, 2004). A selective post-emergent herbicide (ioxynyl octanoate) was applied when weeds had two to four true leaves. Subsequently, weed control was performed manually on two occasions.

Garlic was harvested on December 5, 2014, when plants had 4 to 6 green leaves and bulbs were firm with evident clove markings. Samples were harvested from the three central lines of each plot, excluding borders. The useful area was 0.80 m^2. Plants were exposed to the sun for two days (pre-curing) and then stored in a shed for 30 days (curing). After the curing period, stems were removed and roots were cut. Bulbs were weighed and measured with a digital caliper to obtain the mean bulb diameter (mm). Yield was determined by extrapolating the weight of bulbs harvested from the useful area of each plot to kg ha^{-1}. The occurrence of lateral shoots was assessed visually at the time of harvest (FERNANDES et al., 2011). Lateral shoot incidence was calculated as the number of bulbs with lateral stems divided by the total number of bulbs from the useful area and multiplied by 100.

Data were tested for normality of distribution and homogeneity of variances using the Shapiro–Wilk and Bartlett's tests, respectively. Significant differences were assessed by the F-test, and comparisons between means were performed using Tukey's test at $p < 0.05$.

RESULTS AND DISCUSSION

N application regime significantly influenced bulb diameter, lateral shoot incidence, and yield. Bulb diameter was highest (52.3 mm) in plants fertilized before and after clove differentiation (T2). Fortnightly N application (T1) resulted in higher bulb diameter than a single N dose applied before (T3) or after (T4) differentiation (Table 2).

TABLE 2 - Nitrogen (N) fertilization treatments and their influence on mean bulb diameter and lateral shoot incidence of garlic cv. Chonan.

Treatment	Mean bulb diameter (mm)	Lateral shoot incidence (%)
T1	46.38 b	3.33 a
T2	52.59 a	6.66 ab
T3	40.20 c	11.66 c
T4	36.04 c	3.33 a
CV (%)	5.04	6.09

T1, fortnightly N application; T2, N application split between before and after clove differentiation; T3, single N application before clove differentiation; T4, single N application after clove differentiation; CV, coefficient of variation. *Different letters within columns indicate significant differences by Tukey's test ($p < 0.05$).

Bulbs were categorized into different size classes (Table 2) according to Ordinance n. 242 (MAPA, 1992). Bulb diameter decreased in the following order of treatments: T2 > T1 > T3 > T4. Late N application (after clove differentiation) afforded Class 3 bulbs (32 to 37 mm), and early fertilization (before differentiation) resulted in Class 4 bulbs (37 to 42 mm). Split application every 15 days (T1) and before and after differentiation (T2) afforded Class 5 (42 to 47 mm) and 6 (47 to 56 mm) bulbs, respectively, which are preferred by consumers and have higher value. The effects of N rates on bulb diameter have been previously investigated (MACÊDO et al., 2009; FERNANDES et al., 2010); however, few studies have focused on garlic. The results of the present study on garlic cv. Chonan underscore the importance of N management, as four different size classifications were obtained by applying the same N rate but at different times.

The highest lateral shoot incidence (11.66%) was observed in plants fertilized before clove differentiation. The value differed significantly from those of other treatments, which did not differ between themselves (Table 2). This result shows that a single application close to the time of clove differentiation favors branching and consequently reduces garlic quality; the practice is not recommended. The other treatments had a low lateral shoot incidence (<6.66%), with a mean incidence of 4.44%. Single N application after clove differentiation did not promote branching as, at this time, the number of cloves had already been defined. Split application is an interesting strategy because it did not increase lateral shoot incidence compared with a single application after clove differentiation. Overall, the incidence was low, even though garlic cv. Chonan is susceptible to the disorder. Lateral shoot formation has been associated with high N rates (BÜLL et al., 2002; TRANI et al., 2008; LIMA et al., 2008). According to Moon and Lee (1980), lateral shoot development is influenced by gibberellin content and N fertilization.

In contrast to what was observed in the present study, Moraes and Leal (1986) reported that split N application favors the occurrence of lateral shoots. In the referred study, the lowest branching percentage was obtained with a single N application at the time of planting, regardless of dose. However, the higher the dose and the later the application, the higher the occurrence of branching. Such results were similar to those obtained by Resende and Souza (2001) for garlic cv. Quiteria. The authors applied five N doses (40, 60, 80, 100, and 120 kg ha^{-1}) at three times (30, 50, and 70 days after planting). With application of 120 kg N ha^{-1} at 30, 50, and 70 days after planting, the incidence of lateral shoots was 65.2, 68.8, and 64.8%, respectively.

At a dose of 40 kg N ha^{-1} applied at 30, 50, and 70 days after planting, the incidence was 30, 35, and 42%, respectively. In both studies mentioned above, the incidence of lateral shoot formation was considerably higher than those found in the current study. Some aspects should be considered. Lateral shoot development is strongly associated with short photoperiods, low temperatures, vernalization, excessive irrigation, and excessive N fertilization (RESENDE et al., 2015). These factors may also exert significant interaction effects on the development of the disorder. In addition, susceptibility to branching differs across cultivars used in Brazil. Noble garlic cultivars are known to be susceptible to the disorder, particularly when subjected to vernalization (RESENDE et al., 2015).

Although N application may promote lateral shoot development in susceptible cultivars (RESENDE; SOUZA, 2001; BÜLL et al., 2002), the nutrient is essential to increase garlic yield; therefore, adequate N management is fundamental. In the current study, garlic yield was influenced by split N application (Figure 1). No significant differences were observed between single-application treatments. The yield of garlic fertilized with N before and after clove differentiation (11,927 kg ha^{-1}) was 55.31% higher than that of garlic fertilized before differentiation only (7,679 kg ha^{-1}). The results agree with those of Resende and Souza (2001), who observed that late N application (70 days after planting) resulted in the lowest yield.

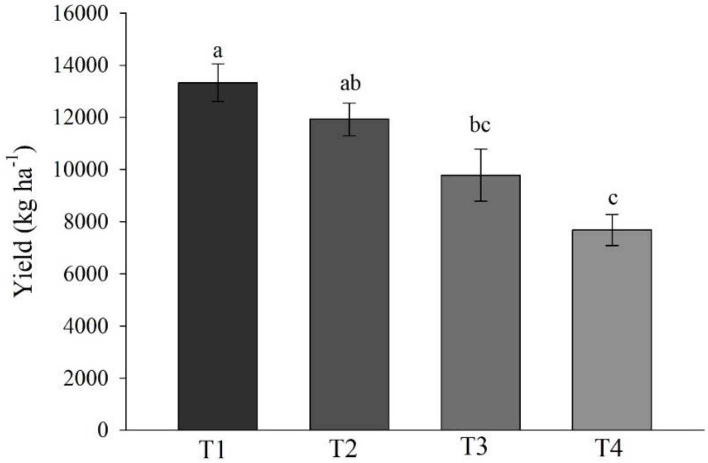

FIGURE 1 - Garlic yield under different nitrogen (N) fertilization regimes. T1, fortnightly N application; T2, N application split between before and after clove differentiation; T3, single N application before clove differentiation; T4, single N application after clove differentiation. Error bars represent the standard deviation of the mean. Different letters above bars indicate significant differences by Tukey's test ($p < 0.05$).

Fortnightly N application increased garlic yield by 36 and 73.5% in relation to single application before and after differentiation, respectively. However, garlic yield did not differ between split application treatments (Figure 1). All treatments received the same dose (210 kg N ha^{-1}), but split application increased the efficiency of N fertilization, leading to considerable gains in yield. In a study conducted by Fernandes et al. (2011), the highest yield (10,100 kg ha^{-1}) of garlic cv. Caçador was achieved by split application of 325 kg ha^{-1}; that is, nitrogen fertilization efficiency was lower than that obtained in the present study.

An adequate N management is that in which the supply of N corresponds to the nutrient requirements of plants. According to Andrioli et al. (2008), nutrient absorption in garlic, particularly that of N, is highest at 75 to 90 days after planting. Therefore, if N is applied early and the climatic conditions are favorable to N losses, whether through ammonia volatilization or nitrate leaching, low amounts of N will be available at the time of high demand. On the other hand, if N is applied after 90 days, crop yield may be compromised, as N plays a vital role in plant functions, such as enzyme activation and synthesis of amino acids, proteins, glycoproteins, lipoproteins, and vitamins (MALAVOLTA et al., 1997).

The soil of the study area had high contents of organic matter (49.59 g dm^{-3}), which indicates high soil N availability (CQFS-RS/SC, 2016). Nevertheless, as shown by the results, the supply of N (mineral or organic) to vernalized garlic is essential, regardless of the N levels made available through organic matter decomposition. Similar findings were reported by Piva et al. (2017), in a study under the same climatic conditions.

The mean garlic yield of Santa Catarina and the municipality of Curitibanos in 2018 was 9,958 and 11,000 kg ha^{-1}, respectively (IBGE, 2019). Municipal and state yields were higher than those obtained in the present study under single application regimes but lower than those obtained under split application regimes. Fortnightly N application increased yield by 21% in relation to the state mean. Garlic farmers generally apply N fertilizer at 20 days after planting and again after clove differentiation. Our results show that split N application is an important strategy to increase the N-use efficiency and yield of vernalized garlic. The recommendations of the present study are in line with those of the Committee of Soil

Chemistry and Fertilization of the states of Rio Grande do Sul and Santa Catarina (2016): splitting N fertilization into three doses, applied at planting, 25 to 45 days after planting, and 10 to 15 days after clove differentiation.

It should be noted that, at the end of the crop cycle, symptoms of N deficiency were evident in plants treated with N only after clove differentiation. Leaves were yellowish, and yields were low. These effects were not observed in other treatments, but it is possible that plants fertilized with N only before clove differentiation may have suffered from hidden hunger. Plants suffering from subclinical N deficiency do not show symptoms, but their development is affected. The phenomenon can be avoided by adequate nutrient management.

Solutions to facilitate the determination of adequate N rates and application times are needed. Hahn et al. (2020) assessed the nutritional status of N in garlic using a portable chlorophyll meter. The authors found that this method can easily provide information for the determination of N rates. However, considering the high potential of N losses in soil and the high response of vegetable crops to N fertilizers, future studies should investigate strategies to increase N-use efficiency by assessing the interaction effects of N source × rate × application time on the yield and quality of vegetables. Such strategies should also seek to lower costs, increase profitably, and reduce environmental impacts.

CONCLUSIONS

Splitting N application into five doses at 15-day intervals increased fertilization efficiency, providing yield gains of up to 73% compared with a single N application.

Two N fertilization strategies can be used for the production of high-quality garlic bulbs: fortnightly application or split application before and after clove differentiation.

Application of a single N dose is not recommended, regardless of whether it is performed before or after clove differentiation, as this fertilization regime promotes lateral shoot growth and reduces garlic yield and quality.

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