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Effect of Slow-Release Nitrogen Fertilizer with NBPT Inhibitor on Popcorn (*Zea mays* L. *everta*) Yield and Quality

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A B S T R A C T

This study was conducted to determine the effect of slow-release nitrogen with NBPT inhibitor [(N-(n-butyl) thiophosphoric triamide (NBPT)] fertilizer dosages on yield, yield components and quality of popcorn (*Zea mays* L. *everta*) under second crop conditions of Sanliurfa in 2022 and 2023. The experiment was conducted in a randomized block trial design with three replications. The R-997 popcorn variety was employed as the crop material in the research. Slow-release urea fertilizer doses with NBPT inhibitor were utilized at the following rates: control, 40 kg ha^{-1}, 80 kg ha^{-1}, 120 kg ha^{-1}, 160 kg ha^{-1}, 200 kg ha^{-1}, 240 kg ha^{-1}, 280 kg ha^{-1}, 320 kg ha^{-1}, respectively. The analysis of variance revealed that slow-release nitrogen dose applications had a statistically significant impact on several key traits, including the number of kernels per ear, ear diameter, ear length, thousand grain weight, and grain yield ($P \leq 0.01$). Furthermore, some quality parameters, including protein ratio, popping volume and unpopped kernel ratio, were also found to be statistically significant ($P \leq 0.01$). It was determined that grain yield, yield components and quality parameters increased with increasing slow-release nitrogen (N) doses. However, this increase continued up to 240 kg ha^{-1} nitrogen application. The analysis of regression indicated that the highest grain yield was achieved with the inclusion of the slow-release N with NBPT inhibitor at a dosage of 240 kg N ha^{-1}, while the lowest grain yield was observed in the treatment where no nitrogen was applied. In similar regions with high evaporation and hot climates where the experiment was conducted, the use of slow-release nitrogen fertilizers may be recommended. Also this study demonstrates that NBPT can be a promising companion to nitrogen fertilizer, as no adverse effects were observed with increasing levels of slow-release nitrogen applications.

1. INTRODUCTION

The world average nitrogen uptake efficiency is approximately 50%, although this figure can vary according to production management practices and crop varieties (Ibrikci et al., 2012). It has been stated that unconscious and excessive fertilizer use not only causes economic losses, but is also an important factor in terms of sustainable soil fertility (Karaman et al., 2007).

The response of crops to fertilizers is dependent upon many factors, including the fertility level of soils, other environmental conditions and genotypes. Nitrogen is a vital element for the vegetative growth, yield, and quality of corn (Yigit et al., 2024). The majority of nitrogen is lost through many processes, including leaching, denitrification, volatilization, soil erosion and immobilization (Cahill et al., 2010).

Losses of gaseous nitrogen (N) to the atmosphere can occur, for example, in the form of greenhouse gases (GHG), nitrous oxide (N_2O) or - especially - the reactive gas ammonia (NH_3) (Guardia et al. 2021). Slow-released fertilizers prevent nitrogen losses in gas form and increase the efficiency of the utilization of fertilizer (Canterella et al., 2018).

Controlled-release fertilizers ensure that conventional fertilizers are coated or microencapsulated, making them continuously available to the plant (Morales-Morales et al., 2019). The long-term effects of slow-release fertilizers, which have been used in recent years, are currently being investigated in a variety of plant species (Guerdal, 2009;Ucgun et al.,2021; Denizhan et al., 2021;). The dissolution rate of these fertilisers is slow, resulting in high efficiency and minimal losses through washing (Wang et al., 2021).

The urease inhibitor (NBPT) in slow-release urea fertilizer minimizes nitrogen losses by delaying the conversion of urea. Because this inhibitor delays the hydrolysis (dissolution) of urea and slows down its conversion to ammonium form, thus preventing ammonia losses to the atmosphere (Trenkel, 2021).

Even if rainfall is insufficient, it can remain on the soil surface for 2 weeks. Barut et al. (2022) reported that statistically significant increase in stem diameter and yield values resulting from the application of Nutrisphere-N-Urea. Ozbek & Akgun (2020) demonstrated that slow-release fertiliser applications effectively improved grain quality.

The production and popularity of popcorn (Zea mays L. everta) are steadily increasing in Turkey. Popcorn differs from other maize varieties in terms of its grain structure. When exposed to heat, the endosperm within the grain expands, causing the hard outer shell to rupture and resulting in a significant increase in volume. Due to its rich vitamin and mineral content, popcorn is directly consumed as a snack. Additionally, its low carbohydrate content, ability to promote satiety, and capacity to absorb stomach acid make it a preferred choice in various diets (Oktem & Kahramanoglu, 2021).

Popcorn, a C4 plant, produces a considerable quantity of dry matter per unit area. Insufficient fertilizer application during the development stages of corn results in a low yield (Koca, 2013). The nitrogen uptake of the corn plant increases in the middle of vegetative development and reaches a maximum level before the tassel flowering period (Subedi & Ma, 2009). Fertilizer should be applied in a correct, balanced and sufficient manner. Therefore, it is essential for productivity to have sufficient nitrogen in the soil during the development period until the tasseling period.

In traditional popcorn top dressing, all nitrogen should be given when the plants reach 40-50 cm in height. Since the plants grow quickly, applying top dressing with ground equipment in later periods is impossible. In addition, not all of the nitrogen given can be used by the plants, some of it is absorbed by surface runoff, some by seeping into the depths of the soil, or some of it is mixed into the atmosphere in the form of ammonia gas. However, this problem can be eliminated because slow-release nitrogen fertilizer remains in the soil for a long time without being lost and continuously nourishes the plant.

The nitrogen required by the popcorn plant during its vegetative and generative development can be met by using slow-release nitrogen fertilizers that remain in the soil for a long time and do not disappear, and nitrogen use efficiency can be increased. It can also reduce environmental and water pollution. Since nitrogen is not lost from the soil, less fertilizer can be used. Therefore, the amount of slow-release nitrogen fertilizer to be given to popcorn needs to be determined.

The objectives of this study was to determine the most appropriate dose of slow-release nitrogenous fertilizer containing NBPT inhibitor for popcorn and to determine its effects on yield, yield components and quality.

2. MATERIALS AND METHODS

This study was conducted in Sanliurfa (altitude: 465 m; coordinates 37^0 08' N and $38^0$46' E) in 2022 and 2023 on second crop growing conditions. Some climatic and soil characteristics of the study area are given in Tables 1 and Table 2, respectively.

Table 1. Some climate data of the growing season 2022-2023 and long term about the experimental area[ɱ]

Month	Temperature (^{0}C) Maximum			Minimum			Average			Total Rainfall (mm)			Average Relative Humidity (%)		
	2022	**2023**	**LT[ƚ]**	**2022**	**2023**	**LT**	**2022**	**2023**	**LT**	**2022**	**2023**	**LT**	**2022**	**2023**	**LT**
6	41.0	39.8	34.6	19.9	17.8	20.5	26.7	28.7	28.1	1.2	0.0	4.3	42.7	31.9	32.6
7	40.7	43.3	38.8	26.8	22.9	24.3	28.9	33.3	32.0	0	0.0	2.0	42.9	22.7	29.3
8	40.4	44.6	38.4	23.3	20.7	23.9	26.9	34.1	31.5	0	0.1	3.4	32.4	26.2	32.0
9	37.0	38.8	34.0	21.7	18.3	20.0	22.7	29.1	27.2	0	0.0	4.6	30.4	29.5	35.0
10	33.0	31.1	27.1	1.9	15.3	14.5	16.5	22.5	20.6	10	2.3	26.5	48.3	42.1	44.1

ƚ : LT: Belongs to the average of long term, *; 6 June, 7 July, 8 August, 9 September, 10 October

ɱ : The State Meteorological Service of Turkey (2022, 2023 and Long Term period).

Table 2. Some soil properties of the test area

Deep (cm)	Phosphorus (g cm³)		Sand (%)		Clay (%)		Silt (%)		pH		Org. Mat. (%)		$CaCO_3$ (%)	
	2022	**2023**	**2022**	**2023**	**2022**	**2023**	**2022**	**2023**	**2022**	**2023**	**2022**	**2023**	**2022**	**2023**
0-30	1.37	1.28	20.4	20.3	54.0	53.0	25.60	25.74	7.15	7.16	1.33	1.28	7.90	7.86
30-60	1.39	1.42	20.4	20.6	52.0	53.0	27.60	27.86	7.44	7.42	1.31	1.20	9.50	9.15

As can be seen in Table 1, during the growing season of corn, temperature degrees exceed 40 ^{0}C. The minimum temperatures indicate the values recorded during the night. Relative humidity was under 50 %. The experimental area has from arid to semiarid climatic conditions.

To eliminate the residual effect, the experiment was set up in an area where no crops had been grown for many years, and no fertilization had been applied. The trial area displayed a deficiency in organic matter and a pH level of approximately 7. The concentration of $CaCO_3$ was found to be at a medium level. In the research, R-997 popcorn variety (*Zea mays* L. *everta*) was used as plant material. The experimental plots were treated with pure phosphorus at a rate of 90 kg ha^{-1} at the time of sowing, applied via band (Oktem & Ulger, 1998).

Slow-release urea (46% nitrogen) with urease inhibitor NBPT [(N-(n-butyl) thiophosphoric triamide (NBPT)] was used as a source of nitrogen. Thanks to its inhibitor (NBPT), it prevents nitrogen losses in gaseous form. Slow-release nitrogen dosages were organized as control, 40, 80, 120, 160, 200, 240, 280 and 320 kg ha^{-1}. The nitrogen fertilizer was applied in two stages, with half of the dose incorporated at the time of sowing in a band and the remainder applied when the plants had seven to eight leaves.

The land was prepared for planting through plowing and tilling, followed by a single pass of the disc harrow to establish an optimal seedbed. The experiment was conducted using a randomized complete block design (RCBD) with three replications. Sowing took place in the latter half of June in both years. Each plot measured 5 meters in length, with a row spacing of 70 cm and an intra-row spacing of 20 cm. The plots were arranged in four rows.

Weeds were removed when their presence was recognized. The initial hoeing of the plants was conducted when they reached a height of approximately 15-25 cm, and the subsequent hoeing was performed when the plants reached a height of 40-45 cm. The germination of seeds was undertaken using the sprinkler irrigation method. Thereafter, the furrow irrigation method was employed, and an equal volume of water was applied to the plots. In order to prevent the passage of water and fertilizers between the plots, a three-meter space was maintained between them, and each parcel was surrounded by a barrier comprising soil.

Grain moisture was measured at the harvest and grain yield was calculated based on 15% grain moisture. The ears of the plants situated in the central two rows of each plot were harvested. The ear diameter, number of kernels per ear and 1000 grain weight values were calculated by taking the mean of 10 randomly selected ear samples from each plot. The protein content of the seeds obtained from each plot was determined by the Kjeldahl method in accordance with ICC Standard No. 167 (Kacar & Inal, 2008).

To determine the Popping volume ($cm^3 g^{-1}$), a total of 150 g of samples were taken from the grains of the sample plants obtained from each plot of the experiment, the grains were operated for approximately 150 seconds using an electric blasting machine until the explosion sound stopped, and then determined according to the formula given below (Dofing et al., 1990).

Popping volume ($cm^3 g^{-1}$) = total popped grain volume (cm^3) / sample weight (g)

The percentage of unpopped kernels was determined according to the given below formula,

Unpopped kernels (%) = number of unpopping kernels / total number of kernels X 100.

An analysis of variance (ANOVA) was performed according to randomized block design in order to evaluate statistically significant differences between the results using SAS statistical package. The difference between the means was compared using the least significant difference (LSD) test at a significance level of $P \leq 0.05$. To assess the interaction between grain yield and slow-release N doses, regression analysis was performed.

3. RESULTS AND DISCUSSION

Grain Yield (kg ha^{-1})

The results of variance analysis for the years 2022, 2023 and averages of two years are given in Table 3. According to the analysis of variance, slow-release nitrogen applications were found to be statistically significant in both years ($P \leq 0.01$). According to average of two years, the highest grain yield was obtained from the 240 kg ha^{-1} slow-release N application (8651.6 kg ha^{-1}), while the lowest value was measured in the control plot (2502.4 kg ha^{-1}).

Table 3. Results of the analysis of variance for 2022, 2023 and the average of the two years.

Source of Variation	DF	Grain yield	Ear diameter	Ear length	Kernel number per aer	Thousand kernel weight	Protein content	Popping volume	Percentage of unpopped kernel
				Mean of squares values					
				Growing season of 2022					
Rep.	2	234631.5	0.07	0.178	988.17	2.936	3.506	0.129	0.20
N	8	20290712.88**	101.20**	9.270**	29137.92**	32.86**	1.712**	28.30**	31.95**
Error	16	115538.55	0.25	0.361	508.8	1.62	0.055	0.2397	0.38
Total	26								
				Growing season of 2023					
Rep.	2	27708.5	0.36	0.017	523.705	2.82	0.090	3.189	0.08
N	8	140898883.5**	103.92**	5.094**	7946.46**	237.76**	1.351*	23.38**	119.00**
Error	16	99017.543	0.99	0.672	589.16	22.87	0.186	1.7051	0.31
Total	26								
				Average of two year					
N	8	3.38e+7**	201.08**	10.387**	32446.3 **	205.92**	2.671**	48.33**	132.82**
Error 1	2	59209.3	0.14	0.0713	1425.58	4.67	0.045	2.3013	0.13
Year X N Dosages	8	624831**	4.03 **	3.976**	4638.12 **	64.70 **	0.391 *	3.34 *	18.13 **
Error 2	32	107278.05	0.62	0.5166	549.0	12.25	0.121	0.9724	0.35

*, ** Statistical significance at $P \leq 0.05$ and $P \leq 0.01$, respectively; DF: Degree of freedom

The mean value of two years indicated an increase in grain yield of up to 240 kg ha^{-1} with the application of slow release nitrogen doses, although a decrease in yield was observed at higher doses after this point (Table 4).

Nitrogen is the most important element required for photosynthesis. In the plant, nitrogen is incorporated into the structure of organic compounds that perform vital functions, including protein, amino acid, amide, nucleic acid, and chlorophyll. Plants generally take nitrogen from the soil through their roots. As the amount of nitrogen dose increases, the vegetative organs of the plant develop better and therefore produce dry matter by photosynthesizing more and more nutrients are transported to the ear, which positively affects yield (Oktem et. al., 2001).

In the study area, air temperature rises above 40 °C and relative humidity is below 40% during the maize growing season, which increases nitrogen losses through evaporation. As in the research area, nitrogen losses in the soil increase due to high evaporation in the summer months. With the application of slow-release nitrogen fertilizer, it is thought that nitrogen is used more effectively by the plant and this has a positive effect on grain yield.

As can be seen from the regression analysis (Figure 1), a polynomial curve was found between grain yield and slow-release nitrogen dosages. The curve demonstrates that the optimal slow-release nitrogen dosage was determined to be 240 kg N ha^{-1} of application. The relationship between slow-release nitrogen and grain yield was determined as $y = -0.0683x^2+42.025x+1844.1$ with $R^2 = 0.9488$.

Table 4. Effect of slow-release nitrogen with NBPT inhibitor applications on grain yield and ear diameter of popcorn

Applications (kg ha^{-1})	Grain Yield (kg ha^{-1})			Ear Diameter (mm)		
	2022	**2023**	**Average**	**2022**	**2023**	**Average**
Control	2369.9 f	2634.9 g	2502.4 G †	19.20 e	19.52 e	19.36 E
40	2554.0 f	3600.8 f	3077.4 F	19.57 e	20.54 e	20.05 E
80	3818.2 e	4600.8 e	4209.5 E	20.88 d	26.20 d	23.54 D
120	4488.1 d	5958.7 d	5223.4 D	30.92 b	32.37 b	31.64 B
160	7091.3 c	7069.1 c	7080.2 C	31.35 b	32.50 b	31.93 B
200	8288.1 ab	7834.8 b	8061.4 B	31.79 b	33.10 b	32.45 B
240	8760.3 a	8542.9 a	8651.6 A	33.58 a	35.63 a	34.61 A
280	8027.8 b	8205.6 ab	8116.7 B	30.01 c	33.73 b	31.88 B
320	7973.8 b	7804.8 b	7889.3 B	29.93 c	30.43 c	30.18 C
LSD	**588.3**	**544.7**	**385.2**	**0.87**	**1.72**	**0.84**

†: There is no statistically significant difference between the means in the same letter group at 0.05 level according to LSD test

Our findings align with those of other researchers in the field. For instance, Lakshmi et al. (2020) observed that maize grain yield in low-fertility soils increased with nitrogen application until reaching an optimal threshold, beyond which additional nitrogen had no effect or a negative impact on yield. Similarly, Jokela and Randal (1989) found that increasing the nitrogen (N) rate from 0 to 150 kg ha^{-1} significantly enhanced grain yield, while a further increase to 225 kg ha^{-1} did not result in a substantial additional yield improvement. Bucak and Akgun (2024) reported that the highest grain yield was achieved with the application of slow-release nitrogen at a rate of 200 kg N ha^{-1}. Additionally, Oktem and Oktem (2006) noted that the highest nitrogen application led to only a marginal yield increase, which they attributed to excessive vegetative growth. Several studies on maize have demonstrated that nitrogen application rates ranging from 150 to 240 kg ha^{-1} are optimal for maximizing grain yield (Blumental et al., 2003; Mayer et al., 2012; Safdarian et al., 2014; Chen et al., 2015; Avsar et al., 2018).

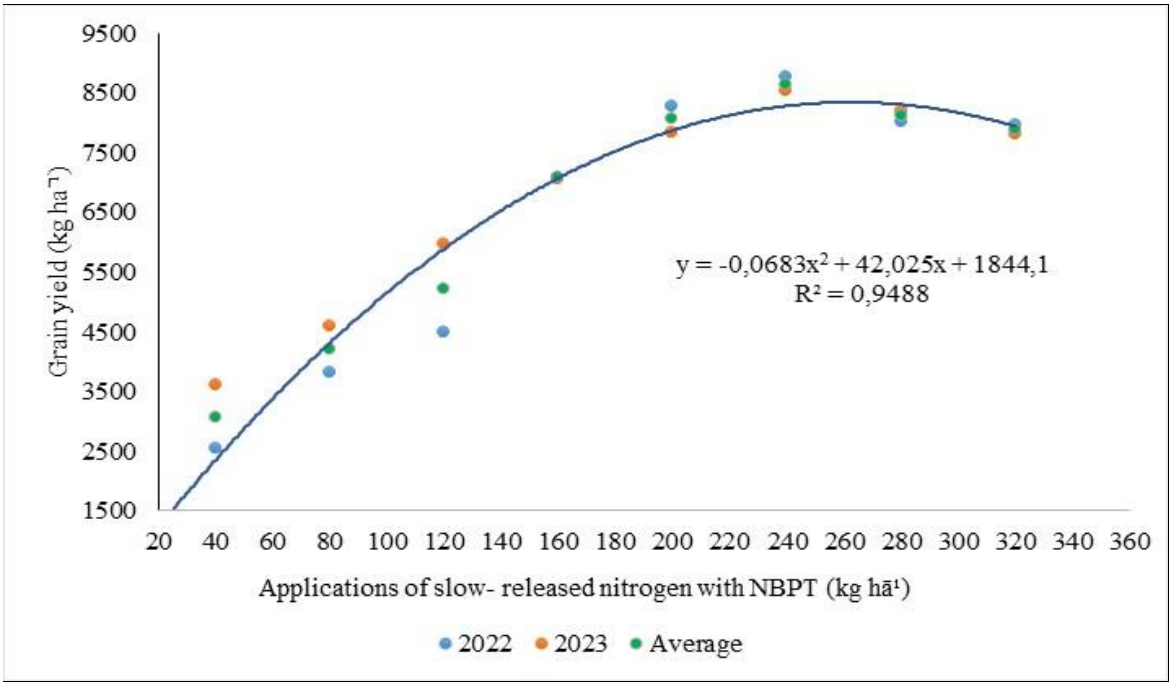

Figure 1. Analysis of regression for grain yield

Ear Diameter (mm)

The analysis of variance revealed that the differences between the slow-release nitrogen applications in terms of ear diameter were statistically significant (P≤0.01). According to the two-year averages, it was determined that the ear diameter values varied between 19.36 mm (Control) and 34.61 mm (240 kg ha^{-1}) (Table 4). The diameter of the ear is a significant determinant of ear size and, subsequently, grain yield. The heritability of ear diameter has been demonstrated to be relatively low (Saleh et al., 2002), while environmental factors have been shown to exert a more pronounced influence (Oktem & Oktem, 2006; Eser, 2014). The results of the experiment showed that the ear diameter value increased as the nitrogen dose increased. However, this observed trend showed a decrease after the application of 280 kg ha^{-1} nitrogen dose. In general, the application of slow-release nitrogen fertilizers had a positive effect on ear diameter.

Ear length (cm)

The analysis of variance demonstrated that the impact of the slow-release nitrogen doses on ear length was statistically significant in 2022 and 2023 (P≤0.01). The ear length values exhibited ranging from 24.33 - 19.02 cm, 23.87 - 19.17 cm, and 23.01 - 19.09 cm in 2022, 2023, and the two-year average, respectively (Table 5).

Table 5. Effect of slow-release nitrogen with NBPT inhibitor applications on ear length and kernel number per ear of pop corn

Applications(kg ha^{-1})	Ear length (cm)			Kernel number per ear (number)		
	2022	**2023**	**Average**	**2022**	**2023**	**Average**
Control	19.02 g	19.17 d	19.09 D†	479.89 e	539.40 d	509.64 F
40	19.78 fg	21.70 bc	20.74 C	482.52 e	567.71 d	525.12 F
80	20.66 ef	22.40 bc	21.53 BC	573.67 d	618.79 c	596.23 E
120	21.67 de	21.30 c	21.48 C	625.66 c	676.38 ab	651.02 CD
160	23.12 b	21.55 bc	22.33 AB	681.59 b	642.81 bc	662.20 C
200	23.36 ab	22.67 abc	23.01 A	715.70 b	675.23 ab	695.46 B
240	24.33 a	21.63 bc	22.98 A	758.33 a	689.21 a	723.77 A
280	22.82 bc	22.80 ab	22.81 A	690.96 b	660.05 abc	675.51 BC
320	21.84 cd	23.87 a	22.85 A	612.74 c	652.59 abc	632.66 D
LSD	**1.04**	**1.42**	**0.83**	**39.04**	**42.03**	**27.55**

†: There is no statistically significant difference between the means in the same letter group at 0.05 level according to LSD test

The results indicated that based on two-year average the lowest ear length value was recorded in the treatment that did not include nitrogen application, while the highest value was observed in the treatment that included application of a nitrogen dose of 200 kg ha^{-1}.

Nevertheless, it can be observed that the 200, 240, 280 and 320 kg ha^{-1} slow-release N applications are found to be within the same statistically group. The application of slow-released nitrogen was observed to have a beneficial impact on ear length. As observed by other researchers, an increase in nitrogen dose was found to result in a increase in ear length (Oktem & Oktem, 2005; Safdarian et al., 2014; Saracoglu & Oktem, 2021).

Kernel number per ear

According to analysis of the variance results based on 2022, 2023 and the average of the two years, the number of kernels per ear was found to be statistically significant (P≤ 0.01). The results of the study showed that the control plot and 40 kg ha^{-1} N had the lowest value, while the highest value was observed in the application of 240 kg ha^{-1} N in both years (Table 5). Some researchers reported a significant increase in the number of seeds per ear with increasing nitrogen doses (Sabir et al. 2000; Mehmood et al. 2001).

Slow release nitrogen fertilizer applications caused a statistically significant increase in the number of kernels per ear. It is thought that the increase in photosynthetic efficiency positively affected yield and yield elements such as the number of kernels per ear. This can be attributed to higher net photosynthesis and dry matter content resulting from improved photosynthetic efficiency. Increased nitrogen application enhances plant growth and development, which subsequently improves yield-related traits, such as ear length, ear diameter, and the number of kernels per ear.

Table 6. Effect of slow-release nitrogen with NBPT inhibitor applications on 1000 kernel weight and protein content of popcorn

Applications (kg ha^{-1})	**Thousand kernel weight (g)**			**Protein content (%)**		
	2022	**2023**	**Average**	**2022**	**2023**	**Average**
Control	136.08 c	135.40 d†	135.74 D	13.13 d	11.90 d	12.52 F
40	140.67 b	153.93 c	147.30 C	13.37 d	12.67 c	13.02 E
80	140.67 b	154.60 c	147.63 C	13.50 d	13.60 ab	13.55 D
120	141.17 b	158.83 abc	150.00 C	14.27 c	13.53 ab	13.90 BCD
160	144.53 a	156.40 bc	150.47 C	14.57 c	13.07 bc	13.82 CD
200	146.01 a	163.77 ab	154.93 AB	14.67 bc	13.43 ab	14.05 ABC
240	146.70 a	165.33 a	156.02 A	14.67 bc	13.97 a	14.32 AB
280	140.83 b	161.40 abc	151.12 BC	15.00 ab	13.95 a	14.48 A
320	140.63 b	160.83 abc	150.73 C	15.23 a	13.70 ab	14.47 A
LSD	**2.20**	**8.28**	**4.12**	**0.41**	**0.75**	**0.451**

†: There is no statistically significant difference between the means in the same letter group at 0.05 level according to LSD test

Thousand kernel weight (g)

According to the results of the variance analysis, statistical significance was determined between the slow release nitrogen doses in terms of thousand kernel weight. (Table 3). Based on the average of two years the maximum thousand kernel weight was obtained from the application of 240 kg ha^{-1} nitrogen (156.02 g), while the lowest values were found on the control plot (135.74 g).

The thousand kernel weight value demonstrated an upward tendency, commencing at 40 kg ha^{-1} nitrogen dose and attaining its peak at 240 kg ha^{-1} nitrogen dose. Thereafter, a decline was discernible at the 260 kg ha^{-1} nitrogen dose (Table 6).

Thousand kernel weight values for corn vary depend on to variety and growing conditions (Oktem & Oktem, 2020). It was explained that nitrogen fertilizers caused an increase in the leaf area of the plant during vegetative development and, as a result, the dry matter accumulation in the grain filling was high and, as a consequence, the thousand kernel weight increased with the application of nitrogen (Saracoglu & Oktem, 2021).

On the other hand, Aydın (1991) stated that the increase in nitrogen fertilizer doses increased the thousand grain weight, but the increase after 20 kg N da^{-1} application was not much and made comments that supported our findings

Protein content of kernel (%)

The results of the variance analysis indicated that nitrogen applications had a statistically significant impact on the protein content of the kernel in 2022 and 2023 (P≤ 0.01 and P≤0.5, respectively). The protein content of the kernel was found to range from 14.48% to 12.52% on average of the two-years. However, the 280 kg ha^{-1} and 320 kg ha^{-1} treatments were included in the same statistical group.

As the dose of slow-release nitrogen fertilizer increased, protein content of kernel also increased. The protein content of the kernel is one of the significant quality parameter and it is influenced by multiple factors including genetic variation, climate and cultivation conditions (Oktem et al. 2010). Nitrogen plays an important role in the formation of a large number of organic compounds in plants, including amino acids, proteins and nucleic acids, which positively affects the grain protein ratio (Oktem & Oktem, 2005 and 2020). In this study, as the amount of N in the soil increased, the N uptake of the plant from the soil and the protein content of the grain increased. In accordance with the findings of Oktem et al. (2010), the presence of N deficiency in soil is associated with adverse effects on nitrogen metabolism, particularly with respect to protein synthesis. Dong et al. (2016) observed that the protein content of corn increased by 61.38-113% when fertilizers containing nitrification inhibitors were used. There are many studies reporting that the protein content increases with increasing nitrogen dose. (Patricio Soto et al., 2002; Keskin et al., 2005; Celebi et al., 2010; Oktem et. al., 2010).

Popping volume (cm^3 g^{-1})

The difference between the doses of slow-release nitrogen in terms of popping volume was found to be statistically significant (P≤ 0.01) in both years (Table 3). Popping volume ranged from 20.05 cm^3 g^{-1} to 28.63 cm^3 g^{-1} based on average of the two years. The highest popping volume value was observed with the application of 240 N kg ha^{-1}, while the lowest value was measured at control and application of 320 N kg ha $^{-1}$ (Table 7).

Applying heat to popcorn kernels initiates a series of events that lead to the expansion of water vapor within the kernel, thereby creating internal pressure. The kernels have a hardness characteristic of their physical composition, and the outer shell lacks the capacity for permeation. Concurrently, the starch present within the endosperm undergoes a transformation that is induced by the applied heat. Once a threshold pressure inside the kernel is attained, the external shell undergoes rupture, under the effect of the pressure, the starch inside the kernel jumps out of the kernel, thereby forming the popcorn (Oktem & Oktem, 2020).

Table 7. Effect of slow-release nitrogen with NBPT inhibitor applications on popping volume and percentage of unpopped kernel of popcorn

Applications (kg ha^{-1})	Popping volume (cm^3 g^{-1})			Unpopped kernel (%)		
	2022	2023	Average	2022	2023	Average
Control	19.83 f	21.00 e	20.41 F †	11.30 b	10.58 c	10.94 C
40	22.17 e	21.73 de	21.95 E	10.80 b	9.16 d	9.98 D
80	24.27 d	23.87 cd	20.07 D	9.07 c	8.36 d	8.71 E
120	25.43 c	24.27 bc	24.85 CD	8.87 c	7.10 e	7.98 F
160	26.47 b	25.20 bc	25.83 BC	8.43 c	6.63 e	7.53 F
200	26.67 b	26.33 ab	26.50 B	7.33 d	4.84 f	6.09 G
240	28.83 a	28.43 a	28.63 A	6.27 d	3.70 g	4.98 H
280	26.20 bc	21.80 de	24.00 D	11.43 b	18.29 b	14.86 B
320	20.37 f	19.73 e	20.05 F	17.43 a	22.61 a	20.02 A
LSD	**0.85**	**2.26**	**1.16**	**1.07**	**0.97**	**0.69**

†: There is no statistically significant difference between the means in the same letter group at 0.05 level according to LSD test

The volume of popping is a significant quality criterion and high popping volume value is a desirable feature. It is of great importance for the commercial success of the product that the popcorn kernels are of a substantial size (Oktem & Kahramanoglu, 2021). The quality of the product is affected by many factors, including the weight of the kernel, the moisture content, growing conditions, climate and genotype (Oktem & Oktem, 2020). In this study, it was observed that the application of slow release nitrogen with NBPT positively affected the thousand grain weight (Table 6) and the explosion volume value (Table 7). The increase in grain size contributed to the increase in the explosion volume values. It has been reported that as the grain size increases, the explosion volume also increases (Soylu & Tekkanat 2007; Ozturk et al., 2016; Oktem & Kahramanoglu, 2021).

Percentage of unpopped kernel (%)

Based on the analysis of variance, slow-release nitrogen fertilizer applications were found to be statistically significant ($P \leq 0.01$) in terms of the percentage of unpopped kernels (Table 3). According to the average of two-year data, the highest percentage of unpopped kernels was obtained from the 320 kg ha^{-1} N application, while the lowest value was observed in the 240 kg ha^{-1} N application (Table 7). The presence of unpopped kernels is one of the quality-reducing characteristics of popcorn. Consequently, it is desirable to maintain a minimum level of unpopped kernels (Cihangir & Oktem, 2019). As the popping volume increases, the rate of percentages of unpopping kernel decreases. In the study, it was observed that the percentage of unpopped grains was the highest in 280 kg ha^{-1} and 320 kg ha^{-1} N applications. High nitrogen amount promotes vegetative growth of the plant. In this case, ripening of the grain is delayed and as a result, it is thought that high moisture content in the grain causes an increase in the rate of unpopped grains.

4. CONCLUSION

The application of slow-release nitrogen had a positive impact on grain yield and popcorn quality. Specifically, grain yield, ear length, thousand-kernel weight, the number of kernels per ear, and quality parameters such as protein content and popping volume increased with the application of slow-release nitrogen containing an NBPT inhibitor. As the nitrogen dose increased, grain yield and most tested parameters improved up to a threshold of 240 kg N ha^{-1}, beyond which a decline was observed. Regression analysis identified 240 kg N ha^{-1} as the optimal slow-release nitrogen dose. The use of slow-release nitrogen fertilizers is recommended in regions with high evaporation and hot climates, such as the study area. Additionally, this study suggests that NBPT can be a promising additive to nitrogen fertilizers, as no adverse effects were observed with increasing levels of slow-release nitrogen applications.

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