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Original paper

Effect of Fertigation with Urea-Ammonium Nitrate on the Seed Yield of Maize Maternal Lines

MYKOLA MARENYCH[1], KRISTINA KOBA[1], VOLODYMYR HANHUR[1], ANATOLII SEMENOV[1]*, OLEKSANDR LEN[1], LIUDMYLA YEREMKO[1], ALLA BAGAN[1], SVITLANA YURCHENKO[1], BAUYRZHAN YELEUSSINOV[2]

[1]Poltava State agrarian University, Poltava, Ukraine
[2]Institute of Professional Development in Kyzylorga Region, Kyzylorga, Kazakhstan

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Fertilisation plays a crucial role in managing corn yields. Research conducted in 2021 − 2023 in the Central Forest-Steppe of Ukraine under unstable moisture conditions demonstrated the positive impact of urea-ammonia mixture (UAN) on the yield and sowing properties of maize maternal lines seeds across different maturity groups (P6/240, P5/320, P4/440). Applying 80 L/ha of UAN during the V10 (BBCH 20) phase increased seed yield by 10.6 − 11.9% compared to the control. The highest seed yield was achieved with 120 L/ha of UAN, resulting in increases of 22.5% for P6/240, 21.3% for P5/320, and 16.4% for P4/440. However, increasing the UAN dose to 160 L/ha led to a slight decrease in yield for lines P5/320 and P6/240. Statistical analysis confirmed that fertilisers significantly influenced seed yield, accounting for 37% of the yield variance, with the genetic characteristics of the maternal lines contributing 34%. The positive effect of liquid nitrogen fertilisers on the 1,000-seed weight varied from 3.4% to 21.8%, depending on lines genetics and fertiliser dose.

Key words: maize (*Zea mays* L.), maternal lines, fertigation, fertiliser, application rate, seed crops, yield

In today's environment, fertiliser use plays an important role in maximising yields and growing efficiency. Fertilisation plays a crucial role in providing essential nutrients, such as nitrogen, phosphorus and potassium, which are vital for plant growth, cob formation and ultimately yield maize improvement. A lack of any of these nutrients can lead to a reduction in plant structural elements and yield. Additionally, there are other methods of seed stimulation in the pre-sowing treatment of crops (Abera *et al.* 2019; Banger *et al.* 2020).

Nitrogen fertilisers help intensify assimilation processes, positively impacting the quantity and quality of the maize crop (Banger *et al.* 2020; Kühling *et al.* 2021; Liu *et al.* 2021).

The most appropriate doses of nitrogen fertilisers contribute to the maximum and efficient use of available resources, such as water and soil nutrients, by plants, which improves the conditions for their growth and development (Gotosa *et al.* 2019; Davies *et al.* 2020). The authors of Morris *et al.* (2018) argue that nitrogen is essential for optimal growth

Mykola Marenych, Kristina Koba, Volodymyr Hanhur, Anatolii Semenov (*Corresponding author), Oleksandr Len, Liudmyla Yeremko, Alla Bagan, Svitlana Yurchenko, Poltava State Agrarian University, 1/3, Skovorody, St., Poltava, 36003, Ukraine. E-mail: asemen2015@gmail.com
Bauyrzhan Yeleussinov, Branch of JSC «NCPD Orleu», Institute of Professional Development in Kyzylorga Region, Kyzylorga, Kazakhstan

development and yield of maize, and its proper application is a key technological aspect.

The use of nitrogen fertilisers is important for increasing maize yields. Studies (Batista *et al.* 2019; Omar *et al.* 2022) have shown that nitrogen application increases grain yields and helps to increase protein and starch content. Maize yields in studies (Ichami *et al.* 2019) almost doubled with nitrogen fertilisation.

Mid-season nitrogen application for maize can be beneficial in different circumstances. This approach allows for additional support of plant nutrient requirements and provides optimal conditions for active growth and development of the crop (Rutan *et al.* 2018). The additional nitrogen helps plants to form more biomass and generative organs, which in turn leads to higher grain yields (Vettorazzi *et al.* 2018; Nasielski 2019; Nasielski *et al.* 2020).

In production, there are different ways of applying nitrogen fertiliser to maize that can be used de-pending on the conditions, available equipment and requirements of a particular field. Studies (Oyebiyi *et al.* 2019; Özer *et al.* 2022) indicate that the choice of nitrogen fertiliser application method for maize may depend on various factors, such as the availability of special agricultural machinery, soil and climatic conditions, as well as field-specific characteristics and yield requirements. By considering these aspects, fertiliser use for maize can be optimised to maximise yields and production efficiency, while also taking into account economic and environmental benefits (Rodriguez *et al.* 2019; Sharma *et al.* 2020; Lu *et al.* 2021).

Fertigation can be an effective way of applying nitrogen fertiliser to maize to help maximise yields and optimise nutrient use. Liquid fertilisers applied by fertigation dissolve quickly in water and are absorbed by plants through the roots. This allows you to instantly influence the growth and development of the crop and improve the realisation of its productive potential under irrigation conditions. This method is particularly effective for optimising the fertilisation system for crops such as maize, which may require different amounts of nitrogen at different stages of organogenesis (Srivastava *et al.* 2018; Steusloff *et al.* 2019; Dahal *et al.* 2020).

The use of liquid fertilisers allows for the combination of fertilisation and irrigation (Phillippi *et al.* 2019). This helps to use water efficiently, as the fertiliser is delivered directly to the root zone of the plants during irrigation. The application of liquid fertilisers can help avoid nutrient losses due to evaporation or fixation in the soil, as they dissolve quickly in water and are available for plant uptake. The choice of liquid fertiliser is important. Using urea-ammonia mixture (UAN) can be an effective way to feed corn, allowing it to meet its nitrogen requirements and contribute to high yields (Li *et al.* 2021; Flynn *et al.* 2023).

Studies (Ma *et al.* 2021) indicate that the application of UAN as a traditional fertiliser method increased grain yields by 1.8−2.4%, while the use of fertigation increased grain productivity by 6.6−7.6%. The use of UAN can help to ensure efficient nutrient uptake, as it provides nitrogen to the crop in a form that is easily available for plant uptake (Woodley *et al.* 2018; Sharma *et al.* 2021).

Thus, applying urea-ammonia mixture to corn by fertigation is an effective and environmentally friendly way of plant nutrition that maximises yields and ensures high quality of the crop.

The aim of the research is to identify ways to increase the seed yield of maize maternal lines based on the analysis of the impact of liquid nitrogen fertilisation.

Research objective: evaluation of the effect of different doses of UAN fertiliser on grain yield and weight of 1,000 grains of three maize maternal lines with different FAO indicators.

MATERIAL AND METHODS

The experimental studies were conducted under unstable moisture conditions in the Central Forest -Steppe of Ukraine, which, according to agroclimatic zoning, belongs to a region with insufficient and variable moisture supply (Figure 1).

Due to the significant fluctuations in precipitation both over seasons and years, this zone is called «unstable moisture». Keeping the soil sufficiently moist is becoming increasingly difficult due to numerous dry periods and uneven rainfall distribution, at a time when maize plants are in critical need of water. Hence, agricultural production is highly dependent on water management and avoidance of water stress. Climate falling within the division referred to as continental manifests cold winters and hot summers. The thermal resources accessible to the crops in the region are characterised by the sum of active temperatures (temperatures beyond 10°C) during the maize growing period being 2,200 – 2,250°C. The average annual temperature on the farm is 9°C. January is the coldest period over the years of research, with a temperature of minus 2.6°C, and the warmest is August (23.3°C). The beginning of frosts is observed in the first decade of October. The duration of the frost-free period is 175 − 180 days.

Dynamics of the average monthly rainfall during the corn-growing season are presented in Figure 1. Dynamics of the average monthly air temperature over the years of research are presented in Figure 2.

The highest rainfall during the corn growing season was in 2022 − 322.4 mm. It is also worth noting that this year the highest monthly rainfall of 90 mm was recorded in September.

Maize is a plant that requires moderate moisture supply throughout the entire period of growth and development, but some phases of development can be particularly critical in terms of water consumption. Analysing monthly data, we conclude that not only the total amount of precipitation during the growing season is important, but also its distribution by crop development stages. In 2021, at the initial stages of growth, the amount of precipitation was 90 mm, and during the critical phase of panicle ejection, it was only 46 mm. In 2022, the highest rainfall was in the V3-V12 (BBCH13-22) phase − 61 mm, and in the VT phase (BBCH51-59) − 59 mm, which is not enough for normal growth and development of corn. The best water supply during critical phases was recorded in 2023; the initial stages − 40 mm and the panicle ejection phase − 94 mm.

The soil is a fertile heavy loamy black soil, characterised by the following agrochemical parameters. The humus content in the topsoil (0 − 20 cm) varied between 3.8 − 4.2%. Humus reserves in the one-metre layer are 250 − 300 tonnes per hectare. The topsoil (0 − 20 cm) contained 9.8 − 10.2 mg/kg of nitrate nitrogen, 24.3 mg/kg of mobile phosphorus, and 264 mg/kg of exchangeable potassium. These indicators correspond to low nitrogen availability, low phosphorus availability, and medium potassium availability. The phosphorus and potassium contents were determined using the Kirsanov method in the mo-

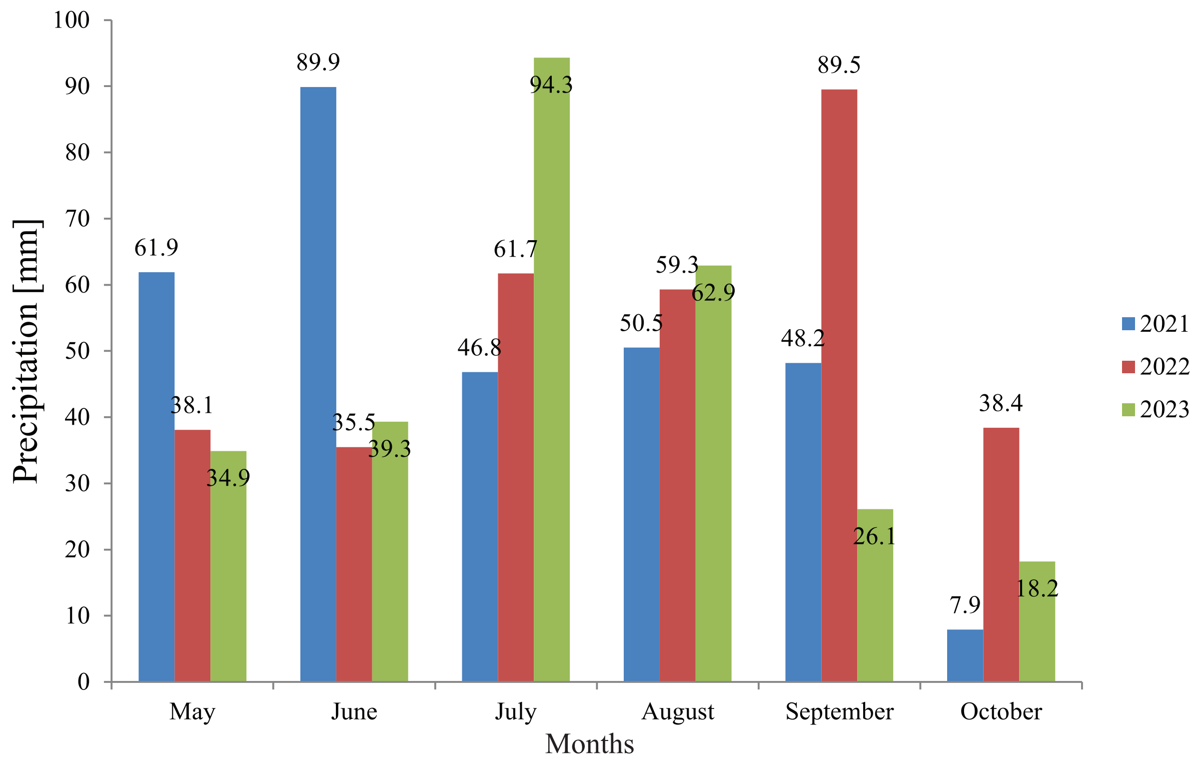

Figure 1. Average monthly rainfall during the corn growing season.

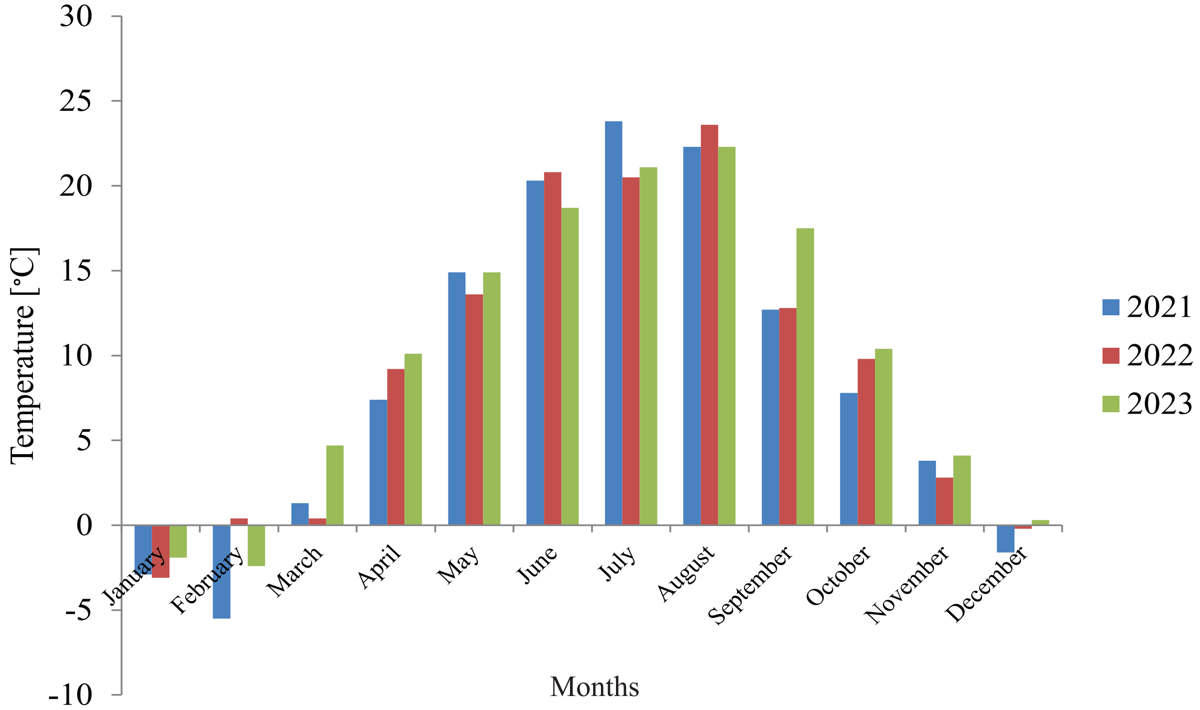

Figure 2. Monthly average air temperature during the years of research (2021 – 2023).

dification of TsINAO. The reserves of productive moisture in the one-metre soil layer at the time of sowing are within 135 – 140 mm.

The soil has a high absorption capacity due to the high content of highly dispersed silt particles. The absorption capacity of the topsoil is 40 mg equivalent/100 g of soil. The soil density is 1.15 – 1.16 g/cm³. The soil reaction is slightly acidic, with a pH of 5.9 – 6.1, as measured in KCl.

The experimental design included: assessing the impact of weather conditions on seed yield in the years of research (2021 – 2023) (factor A); studying the productivity of maternal lines of hybrids of different maturity groups P4/440, P5/320, P6/240 (factor B); the impact of UAN application rates (urea-ammonia mixture, grade 32) – 80, 120, 160 L/ha (factor C). The sown and recorded area for each maize hybrid maternal lines was 1.0 ha. The experiment was conducted according to a design that included four fertiliser application rate variants (80, 120, 160, and 0 L/ha) and three maize maternal lines (P4/440, P5/320, P6/240). Each variant was arranged in plots measuring 134 m × 100 m, replicated within a block measuring 402 m × 400 m. The arrangement of the plots followed the principle of a latin rectangle to minimise the effect of soil heterogeneity. The replication of the experimental variants was done three times. The placement of the variants was randomised by the rate of UAN application. Sowing – the first decade of May, the predecessor is corn. A 16-row Kinze seeder was used for sowing.

UAN was applied by fertigation (through irrigation) at the V10 stage (BBCH 20-21). In addition to fertigation, watering was used at critical stages of corn development: V4 (BBCH 14) – 20 mm, V8 (BBCH 18) – 20 mm, VT (BBCH 51-59) – 45 mm.

Maternal Lines of Maize

P4/440 (FAO 440) toothy grain type. It has excellent moisture return (grain loses moisture quickly after ripening) and drought resistance. Suitable for monoculture cultivation. Areas of application: grain, ethanol. Recommended for cultivation in the forest steppe and steppe zones. Late harvesting should be avoided.

P5/320 (FAO 320). It has excellent drought tolerance and moisture retention. Resistance to smut diseases is 7/9. It is suitable for growing in monoculture and with minimum tillage technology. Recommended sowing dates are early and optimal (late April – first half of May). Recommended cultivation zone – forest steppe, steppe.

P6/240 (FAO 240). The grain type is toothed. Areas of application − grain, ethanol, starch. Suitable for monoculture cultivation. Late harvesting is not recommended. Cultivation areas: Forest-steppe and Polissya. Apply insurance herbicides in accordance with the recommended stages of crop development.

Harvesting and moisture determination were carried out at the stage of full grain ripeness with an Oxhbo 2460 combine harvester from each plot. Corn grain yield was converted to a standard moisture content of 14%. The weight of 1,000 seeds was determined from two samples of 500 seeds each. Each sample was weighed to the nearest 0.1 g, converted to the weight of 1,000 seeds, and the average weight was determined.

To analyse the data, we used descriptive statistics to summarise the results, regression analysis to explore the relationship between fertiliser rates and seed yield, and ANOVA (analysis of variance) in STATISTICA 10.0 software to identify significant differences. The least significant difference (*LSD*) was calculated at a 5% significance level (*LSD*) to compare the effects of different treatments.

RESULTS AND DISCUSSION

Fertilisation is considered the most effective way to manage yields. Research results show that the use of 80 L/ha of nitrogen fertilisers in the form of UAN allows to increase in the seed yield of maize hybrid mother maternal lines by 0.54 − 0.6 t/ha compared to the control (Table 1). An increase in the rate of UAN application to 120 L/ha contributed to an increase in seed yield by 0.96 − 1.13 t/ha compared to the control and by 0.41 − 0.55 t/ha compared to 80 L/ha of

T a b l e 1

Seed yield depending on genetic characteristics and fertiliser [t/ha]

Maternal lines	Application rate [L/ha]	Years			Average 2021 − 2023
		2021	2022	2023	
P4/440	Control	5.95	5.64	5.94	5.84
	80	6.33	6.16	6.67	6.39
	120	6.84	6.55	7.01	6.80
	160	6.93	6.75	6.85	6.84
P5/320	Control	5.27	4.68	5.39	5.11
	80	5.65	5.26	6.05	5.65
	120	6.17	5.88	6.53	6.20
	160	6.12	6.02	6.36	6.17
P6/240	Control	5.19	4.63	5.28	5.03
	80	5.77	5.17	5.94	5.63
	120	6.16	5.96	6.35	6.16
	160	5.96	5.57	6.25	5.92
Average by year		6.03	5.69	6.22	–
LSD_{05}	Year (A)				0.05
LSD_{05}	Maternal lines (B)				0.05
LSD_{05}	Application rate (C)				0.06
LSD_{05}	AB				0.09
LSD_{05}	AC				0.10
LSD_{05}	BC				0.12
LSD_{05}	ABC				0.18

Note: LSD_{05} – Least significant difference at the 5% significance level.

UAN. The subsequent increase in the fertiliser dose by 40 L/ha or 33.3% was not effective, because, in the variants with a rate of 160 L/ha of UAN, even a decrease in yield was observed, which was noted in the maternal lines of maize P5/320 and P6/240. Similar trends were observed in Abdelhamid *et al.* (2020), where increasing the nitrogen rate above the optimum did not lead to further yield improvement in spring barley, and in some seasons caused a slight decline. Our data for 2021–2023 confirm that excessive nitrogen input under unstable moisture can negatively affect yield formation, likely due to an imbalance between vegetative growth and reproductive development.

As shown by the calculations of the research results, the seed yield of maternal lines can be significantly affected by the conditions of the years of cultivation (Figure 3). The most favourable weather conditions were in 2023 when the average seed yield was the highest (6.22 t/ha), and the difference compared to 2021 and 2022 was 0.19 and 0.53 t/ha or 3.2 and 9.3%, respectively.

The research results show that, on average, according to the maternal lines, the lowest seed yield was naturally formed in the variant without mineral fertilisers – 5.47 t/ha (Figure 4). The highest increase in corn seed yield compared to the control was obtained in the variant with UAN application at a rate of 120 L/ha, where it was 0.92 t/ha or 16.8%. It should be noted that the application of UAN at a rate of 80 and 160 L/ha also contributed to a significant increase in seed yield compared to the control, respectively 0.45 and 0.87 t/ha or 8.2 and 15.9%. However, the level of seed yield of maize maternal lines against the background of the above norms of UAN application was inferior to the best variant by 0.05−0.47 t/ha or 0.8−7.9%. Comparable yield gains from optimal nitrogen rates have been reported in peas under arid conditions, where fertiliser rate and sowing date interactions improved yield by 15–19 % (Amantayev *et al.* 2024).

The results of the analysis of variance showed that among the factors studied in the experiment, the greatest influence on seed yield was the application of mineral fertilisers − 37% (Figure 5). The share of the influence of genetic characteristics of lines on the level of seed productivity of maternal lines was 34%. In the presented experiment, the complex effect that characterised the conditions of the years of cultivation was 24%. Thus, the main factors for the formation of seed yield of maize maternal lines forms under conditions of unstable moisture are regulated, in particular, biological characteristics of maize biotypes and fertilisation system. It is worth

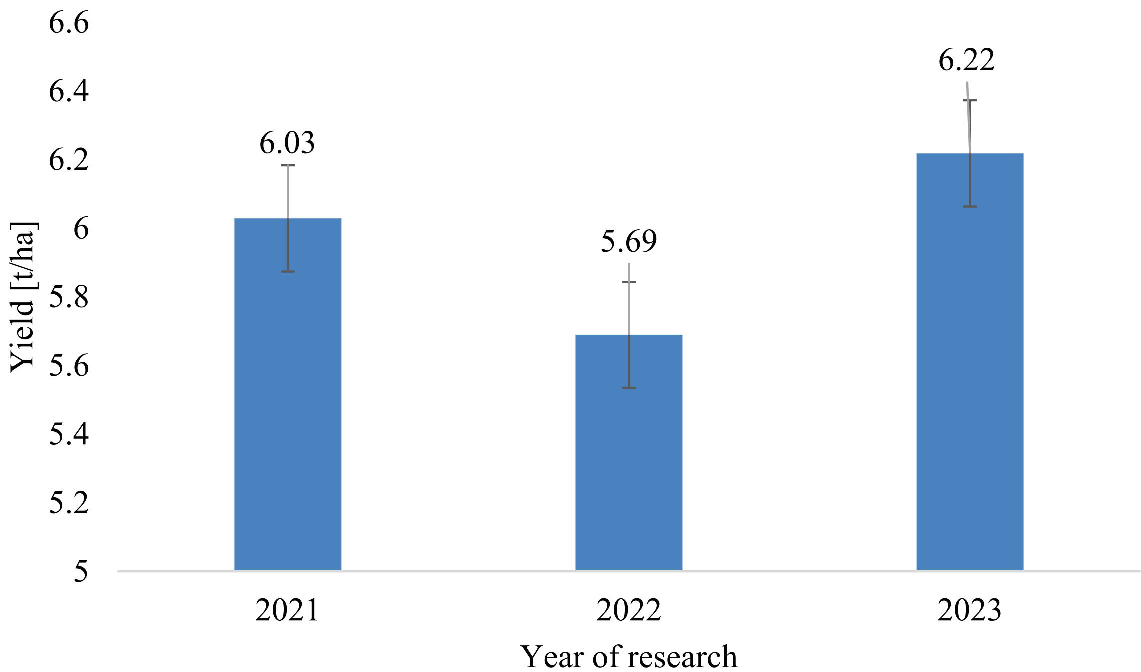

Figure 3. Influence of growing year conditions on the yield of maize maternal lines.

noting the statistically significant interaction of the factors studied in the experiment. Despite its small share, which did not exceed three percent, it was statistically significant.

An important indicator of seed characteristics that plays a significant role in the formation of its sowing qualities is the weight of 1,000 seeds. According to the results of the research, the pattern of fertiliser application on the weight of 1,000 seeds is similar to their effect on the formation of the yield. The use of 80 L/ha of UAN contributed to an increase in the above indicator, depending on the genetic

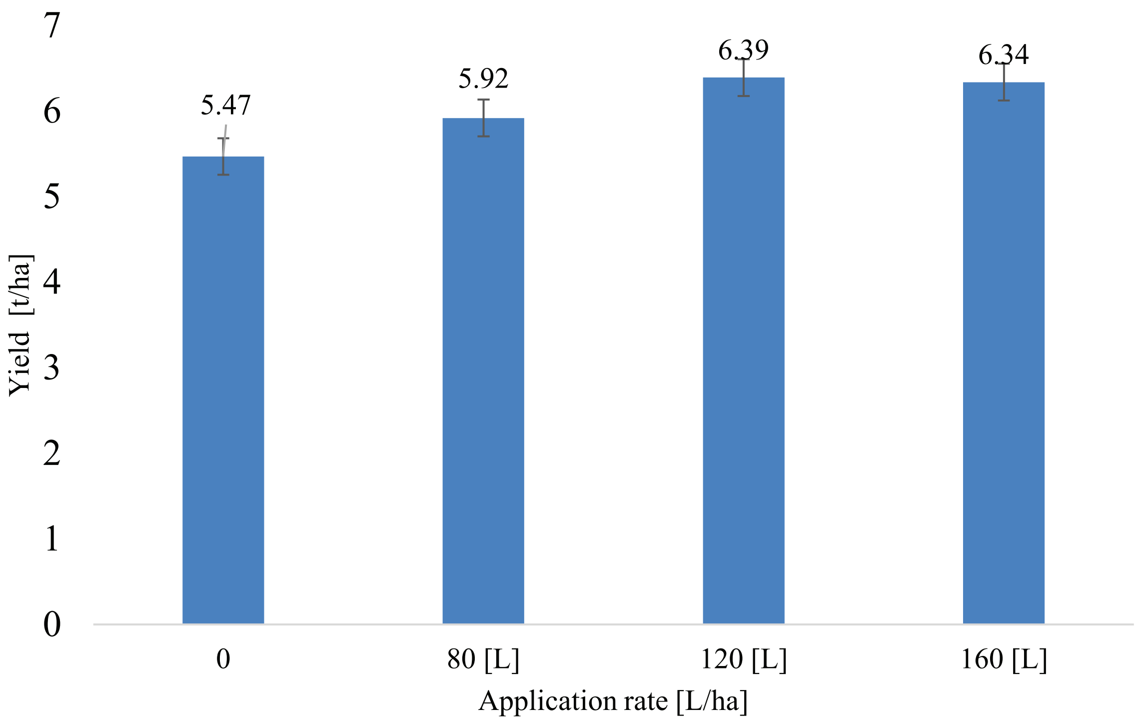

Figure 4. Effect of fertilisation on maternal lines yields (average for 2021 – 2023).

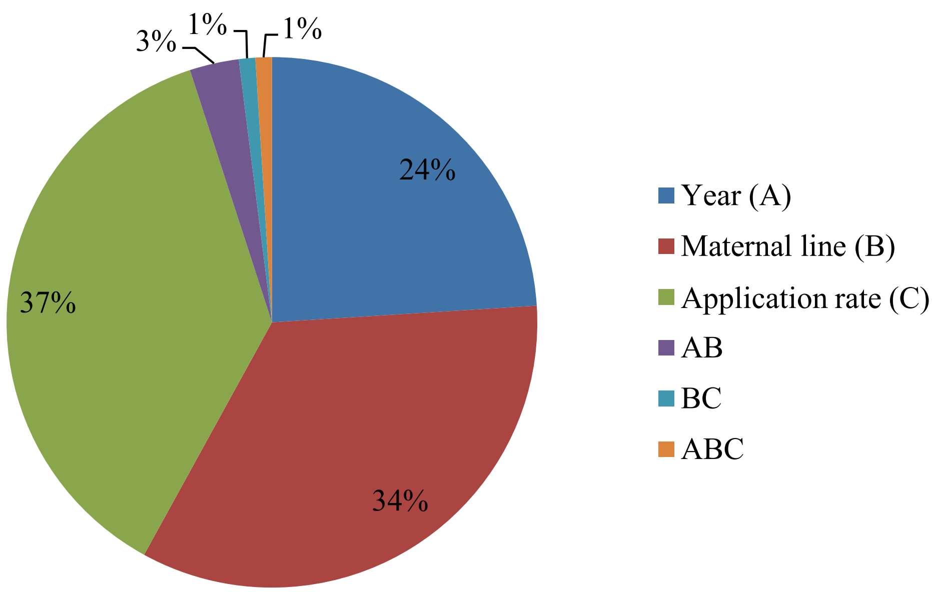

Figure 5. Share of influence of factors and their interactions on seed yield formation.

T a b l e 2

Weight of 1,000 seeds depending on genetic characteristics and fertiliser [g]

Maternal lines	Application rate [L/ha]	Years			Average
		2021	2022	2023	
P4/440	Control	279	244	275	266
	80	283	253	289	275
	120	307	290	316	304
	160	308	291	311	303
P5/320	Control	236	220	239	232
	80	244	235	289	256
	120	269	275	294	279
	160	266	289	290	281
P6/240	Control	231	209	236	225
	80	243	217	270	243
	120	284	249	288	274
	160	279	243	280	267
Average	–	269	251	282	–
$LSD_{0.05}$	Year (A)				1.33
$LSD_{0.05}$	Maternal lines (B)				1.40
$LSD_{0.05}$	Application rate (C)				1.84
$LSD_{0.05}$	AB				2.30
$LSD_{0.05}$	AC				2.67
$LSD_{0.05}$	BC				2.79
$LSD_{0.05}$	ABC				4.60

Note: LSD_{05} – Least significant difference at the 5% significance level.

characteristics of the maternal lines, by 9−24 g compared to the control (Table 2). An increase in the rate of UAN application to 120 L/ha made it possible to increase the weight of 1,000 seeds by 23−31 g. Further increase in fertiliser rates to 160 L/ha did not lead to a significant increase in this indicator and sometimes had the opposite effect. Thus, it is important to establish the optimal rates of nitrogen fertiliser application in order to achieve the highest efficiency in terms of their impact on both the level of realisation of the productive potential of maize maternal lines and the weight of 1,000 seeds.

As can be seen from Figure 3, there is an average direct correlation between fertiliser application rates and seed yield of the maternal lines. A direct strong correlation was recorded between the weight of 1,000 seeds and yield, which indicates the importance of taking this indicator into account as a possible parameter for characterising the yield potential of future seed material.

The use of multiple regression analysis allowed us to establish certain patterns for the formation of indicators of 1,000 seeds' weight and yield (Figure 6). A direct relationship between them and the fertiliser rate was observed only before the application of 120 L/ha, and then there was a tendency for an inverse relationship. This trend is described by the following regression equation:

$$Y=1.28+0.07x+0.02y-0.0002x^2-0.0008xy+0.0006y^2.$$

The results of the research presented in Figure 4 indicate that under this fertilisation system, there is a virtually linear effect of fertiliser rates on the formation of 1,000 seeds and the level of yield, but further increase in nitrogen rates can lead to a significant decrease in both yield and quality of seed material.

Modern fertilisation methods for maize include a variety of technologies and approaches aimed at maximising efficiency and ensuring precise and cost effective nutrient application. Numerous scientific studies support the application of fertiliser through the irrigation system. This allows for precise dosing of fertilisers and their application directly to the area where the plant root system operates. This method allows for efficient use of fertilisers, avoids evaporation losses and ensures an even distribution of nutrients. In the study (Oyebiyi 2019), nitrogen application increased grain yield by more than 57% compared to the control. The authors of (Ma *et al.* 2021) believe that optimising UAN application rates through fertigation will achieve better corn yields and environmental benefits; during fertigation treatment, grain yield increased by 6.6 – 7.6%. This point of view coincides with our results because in all variants of the experiment, an increase in corn seed yield was observed during fertigation. Thus, on average, in 2021 – 2023, the application of 80 L/ha of nitrogen fertilisers in the form of urea-ammonia mixture improved the conditions for the growth and development of corn and increased the seed yield of the maternal lines P4/440, P5/320, P6/240 by 9.4, 10.6 and 11.9%, respectively, compared to the variant without fertilisers. The application of UAN at a dose of 120 L/ha was more effective in terms of its impact on the formation of seed productivity of maize maternal lines, which contributed to an increase in yield by 16.4 – 22.5%. It should be noted that the lines P6/240 had the highest value of this indicator, and P4/440 had the lowest. The line P5/320 occupied an intermediate position, its yield on the above fertilisation background increased by 21.3% compared to the control. Increasing the dose of nitrogen fertiliser by another 40 L/ha was not effective. As a result of applying this dose of UAN, the seed yield of the maternal line P4/440 increased by only 0.6% compared to the previous variant, and the seed productivity of the lines P5/320 and P6/240 even decreased by 0.5% and 3.9%, respectively. Studies have shown that, on average, by fertiliser variants and years of experimentation with varying degrees of favourable weather conditions, the maximum seed yield (6.47 t/ha) was formed by the maternal line P4/440. According to this indicator, it was ahead of the line P6/240 and the P5/320, respectively, by 0.78 and 0.69 t/ha or 13.7 and 11.9%. According to (Gotosa *et al.* 2019), nitrogen application increased corn yields by 0.25 – 1.6 t/ha compared to the cont-

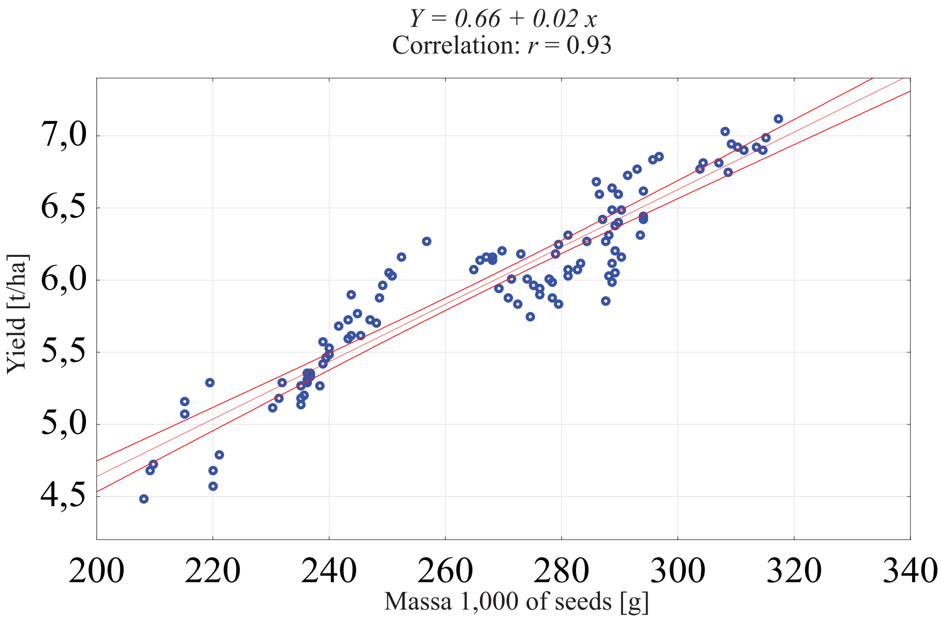

Figure 6. Regression equation of yield dependence on fertiliser rates and weight of 1,000 seeds.

rol, which once again coincides with our results. It is important to note that the study observed a statistically significant interaction between fertiliser and year conditions in terms of the impact on the realisation of the genetic productivity potential of maize maternal lines. Even at relatively small values, not exceeding three per cent, this interaction was statistically confirmed.

Studies Nasielski *et al.* (2019) show that late nitrogen application can increase the potential number and weight of grains, which is confirmed by our research results. Therefore, the use of 80 L/ha of UAN contributed to an increase in the weight of 1,000 seeds, depending on the genetic characteristics of the maternal mother lines of hybrids by 3.4 − 10.3%. It should be noted that the minimum value of the increase in the weight of 1,000 seeds in the late-ripening lines hybrid P4/440, and the maximum − in the mid-ripening lines hybrid P5/320. It was found that the maximum increase in the weight of 1,000 seeds was noted in the variant with the introduction of 120 L/ha of UAN, which in the maternal lines of the early-ripening hybrid P6/240 was 21.8%, the mid-ripening P5/320 − 20.3%, and the late-ripening P4/440 − 14.3%. In the case of increasing the dose of UAN to 160 L/ha, the weight of 1,000 seeds were close or even lower compared to the previous fertiliser variant.

There is a moderate direct correlation between fertiliser application rates and seed yield of maize maternal parental lines, indicating that an increase in fertiliser application has a positive effect on seed yield. The direct strong correlation between the weight of 1,000 seeds and yield indicates the importance of this indicator as one of the possible parameters for predicting the yield potential of seed material in the future.

In turn, since we cannot control weather factors, it is advisable to study the impact of this factor on the yield of maize maternal lines in more detail in future experiments. In addition, the authors of (Ichami *et al.* 2019) believe that strategies to refine fertiliser recommendations should include information on soil types and soil properties. Also, research by (Morris 2018) indicates that nitrogen recommendations need to be improved for economic and environmental reasons. This approach offers a novel perspective on maize seed production by emphasising improved nitrogen management and genetic potential realisation. Incorporating this strategy in future research could enhance seed yield and sustainability in maize cultivation.

CONCLUSIONS

The conducted study over three growing seasons (2021 – 2023) under unstable moisture conditions of the Central Forest-Steppe of Ukraine has demonstrated the high efficiency of applying liquid mineral nitrogen fertilisers in the form of urea-ammonium nitrate (UAN) through fertigation for maize maternal lines. The results provide convincing evidence that fertigation with UAN not only supports stable realisation of the genetic yield potential but also contributes to improved physical parameters of seed material, in particular the 1,000 seed weight, which is a key indicator of seed size and uniformity.

Among the application rates tested, 120 L/ha applied at the V10 (BBCH 20) growth stage proved to be the most effective, ensuring maximum yield performance without the risk of over-fertilisation. This rate provided a balance between vegetative and reproductive development, allowing plants to fully utilise available nitrogen while avoiding excessive biomass accumulation, which can occur at higher doses. Application of 80 L/ha also produced a positive yield effect, making it a potentially viable option where fertiliser resources are limited. Conversely, the highest rate tested (160 L/ha) showed no consistent yield advantage over the optimum and, in some lines, resulted in a measurable decline in productivity, indicating the potential risks of exceeding nitrogen requirements under the given agroclimatic conditions.

These findings are consistent with research on other cereal crops, which has shown that optimal nitrogen supply improves nutrient accumulation in kernels, enhancing seed size and weight. In the context of seed production, these traits are of particular importance, as larger and more uniform seeds are generally associated with improved germination performance and field emergence.

From a practical standpoint, the results emphasise the necessity of precision in nitrogen management. Applying the identified optimum UAN rate through fertigation allows for efficient use of fertiliser resources, supports environmental sustainability by reducing the risk of nitrogen losses, and maintains high seed productivity. For agricultural enterprises specialising in maternal lines maize seed production in regions with unstable moisture supply, the recommended strategy is to integrate fertigation with UAN at the rate of 120 L/ha during the V10 (BBCH 20) stage into their standard production technology. This approach can be adapted for similar agroecological zones globally, contributing to higher economic returns and improved resilience of seed production systems to climatic variability.

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