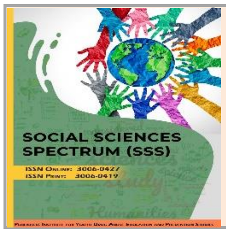

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Improving Autumn Maize Performance by Integrated Management of Nitrogen Form and Herbicide Timing

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Abstract

Herbicides play a crucial role in agriculture, enhancing crop yield by reducing weed-crop competition. In autumn, maize (Zea mays L.) productivity is 20-25% lower than in spring due to environmental conditions that favor weed infestation and heat stress, which can diminish the efficiency of scarce and expensive inputs like nitrogen fertilizers. Consequently, integrated practices are required for managing input resources. This study aimed to test the integrated management of nitrogen fertilizers and weeds by evaluating different nitrogen forms and herbicide application timings. A dedicated factorial field experiment was conducted in a randomized complete block design at the Renala Khurd research farm, University Sub-Campus Depalpur, Okara, in 2021. Experimental treatments included two N forms (standard urea and neem oil coated urea) at 100% and 75% of the recommended N dose, and two herbicide application timings (pre-emergence and post-emergence) plus a weedy check. Each treatment combination was tested in plots measuring 6 m × 3 m and replicated thrice. Data were statistically analyzed at $p=0.05$. The findings revealed that the pre-emergence herbicide (s-metolachlor @ 500 ml/acre) along with neem oil coated urea at 75% was the most effective treatment for reducing weed density and maximizing maize yield. This method is thus recommended as an effective and economic way of managing weeds, especially when conventional urea is substantially costlier.

Keywords: Herbicides, Role in Agriculture, Environmental Conditions, Management of Nitrogen, University Sub-Campus.

1. Introduction

Maize (Zea mays L.), together with rice and wheat, is one of the main pillars of food security worldwide, as it contributes substantially to the caloric and protein requirements of the global population (Hirel et al., 2011; Ranum et al., 2014). Its multiple uses for human consumption, animal feed, and biofuel have led to an expected 16% rise in demand by 2027 (Chen et al., 2011; Dowswell et al., 2019). In Pakistan, maize is grown in two seasons: spring and autumn. Nevertheless, the average productivity of autumn-grown maize is normally 20-25% lower than that of spring-grown maize. This is primarily due to the adverse environmental conditions of the monsoon season, which result in extreme weed pressure, enhanced pest and disease attacks, and improper utilization of nutrients, especially nitrogen (N) (Yousaf et al., 2018; Mehboob et al., 2021).

Weed competition is one of the main yield-limiting factors in maize, with possible yield losses of 20-40% or even greater in unmanaged situations (Khan et al., 2013; Mohammadi, 2007). The large spacing and slow growth of maize at the beginning of its life cycle provide a suitable habitat for weeds to grow and compete with maize for light, water, and nutrients (Guo et al., 2017). Although chemical control is widely practiced, its effectiveness depends on the herbicide used and the timing of its application. For example, farmers tend to prefer post-emergence herbicides in autumn maize because of the supposed low effectiveness of pre-emergence herbicide application in most cases of monsoon rains (Whaley et al., 2006). Nevertheless, the timing of herbicide application may greatly affect the competitive ratio between maize and weeds (Evans et al., 2017).

At the same time, the optimization of N management practices is essential for achieving the high yield potential of modern maize hybrids. Nitrogen is known to be the most limiting nutrient in Pakistani soils (Rashid and Bughio, 1994). The most commonly used N source, conventional urea, is prone to rapid hydrolysis and high losses due to volatilization, leaching, and denitrification, resulting in low N use efficiency (NUE) (Awan et al., 2022). To mitigate these losses and better match N application with crop requirements, enhanced efficiency fertilizers, such as controlled release or inhibitor-coated urea, have been formulated. Neem oil-coated urea (NOCU) is one such promising, cost-effective, and environmentally friendly alternative. Neem (Azadirachta indica) has compounds that work as nitrification inhibitors, thereby slowing down the process of ammonium to nitrate transformation and hence increasing N availability in the soil for a longer period (Prasad, 2009; Patra et al., 2009). It has been observed that NOCU can increase grain yield and N use efficiency in N-demanding crops such as maize, potentially enabling a decrease in the application rate without affecting yield (Ali et al., 2020).

While extensive research exists on the individual effects of herbicide timing or slow-release N fertilizers, there is a scarcity of information on their interactive effects on maize performance (Simić et al., 2020). The timing of N release from the fertilizer could influence the crop's competitive ability against weeds, which is also mediated by the timing of herbicide application. A slow-release N form might give maize a competitive advantage, but this interaction needs to be systematically evaluated. Therefore, this study was designed to explore the integrated management of N form (standard urea vs. NOCU at different rates) and herbicide timing (pre-emergence vs. post-emergence) to improve the productivity and resource-use efficiency of autumn maize. The specific objectives were: (1) to compare standard urea and NOCU at recommended and reduced rates; (2) to evaluate the efficacy of pre-emergence and post-emergence herbicides against autumn maize weeds; and (3) to identify synergistic interactions between N form and herbicide treatments for integrated management.

2. Materials and Methods

2.1. Experimental Site and Design

The field experiment was performed during the autumn season of 2021 at the research area of Renala Khurd Farm (30.85° N latitude; 73.53° E longitude), which is a sub-campus of the University of Agriculture, Faisalabad, Pakistan. The soil type of the experimental site was identified as clay loam. The important properties of the soil are presented in Table 1. The experiment was laid out as a 3 × 4 factorial in a randomized complete block design (RCBD) with three replications. The net plot size was 6 m × 3 m.

Table 1: *Physico-chemical properties of the experimental soil profile.*

Depth (cm)	Soil pH	EC (mS/cm)	Organic Matter (%)	Available P (mg/kg)	Available K (mg/kg)	Saturation (%)	Texture
0-20	8.2	1.4	0.71	4.8	104	54	Clay loam
21-40	8.3	1.5	0.68	5.2	131	52	
41-60	8.3	1.2	0.63	5.6	141	42	
61-80	8.4	1.3	0.62	6.1	125	42	

2.2. Treatments and Crop Husbandry

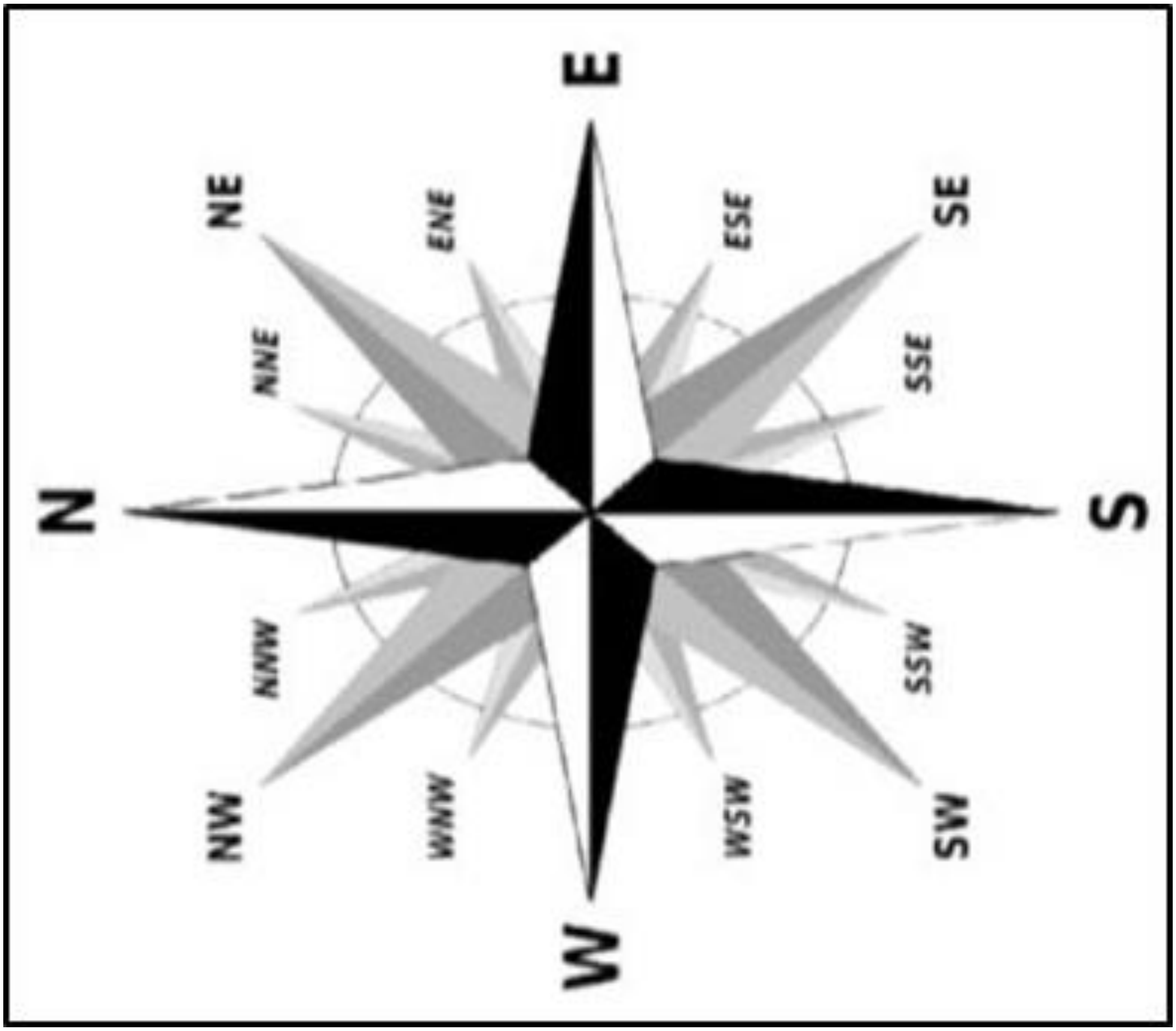
The experiment consisted of two factors. Factor A was herbicide treatment, with three levels: weedy check (Hwc), pre-emergence herbicide (Hpr), and post-emergence herbicide (Hpo). Factor B was nitrogen form, with four levels: 100% recommended dose of N (RDN) as standard urea (SU100%), 75% RDN as standard urea (SU75%), 100% RDN as neem oil coated urea (NOCU100%), and 75% RDN as NOCU (NOCU75%). The full RDN was 270 kg N ha-1. A detailed description of the treatments is provided in Table 2.

Table 2: *Description of experimental treatments*.

Factor	Code	Description
A:Herbicide Treatment	Hwc	Weedy check (No weed control)
	Hpr	Pre-emergence application of s-metolachlor (Dual Gold 960 EC) at 800 ml/acre, one day after sowing.
	Hpo	Post-emergence application of mesotrione + atrazine (Connect 48% SC) at 500 ml/acre, 15 days after sowing.
B:Nitrogen Form	SU100%	100% RDN (270 kg N ha-1) as standard urea.
	SU75%	75% RDN (202 kg N ha-1) as standard urea.
	NOCU100%	100% RDN (270 kg N ha-1) as neem oil coated urea (NOCU).
	NOCU75%	75% RDN (202 kg N ha-1) as NOCU.

The maize hybrid 'DK-8148' was sown manually in the last week of July 2021 on prepared beds with a row-to-row spacing of 70 cm and plant-to-plant spacing of 20 cm. A basal dose of phosphorus (115 kg P2O5 ha-1 as single super phosphate) and potassium (60 kg K2O ha-1 as sulphate of potash) was applied to all plots. Nitrogen was applied in four equal splits: at sowing, at the 5-6 leaf stage, at the 8-10 leaf stage, and at tasseling, according to the respective treatments. Herbicides were applied using a calibrated hand-held sprayer. All other agronomic practices, including irrigation, were kept uniform for all treatments. The crop was harvested manually at physiological maturity.

Figure 1: *Diagram of the experimental field layout.*



2.3. Data Collection

Data on weed parameters were collected 3 weeks after post-emergence spray and 6 weeks after pre-emergence spray. A 1 m2 quadrate was randomly placed in each plot to record the number of plants for each weed species, and their fresh weight. For dry weight, weed samples were oven-dried at 70 °C until a constant weight was achieved.

Maize crop parameters were recorded at harvest. Plant height, stem diameter, cob length, number of cobs per plant, and number of grains per cob were measured from five randomly selected plants per plot. For grain yield, cobs from the net plot area were harvested, shelled, and the grain weight was recorded and converted to Mg ha-1. Aboveground dry biomass was determined by harvesting all plant material from the net plot, sun-drying, and weighing. Other parameters were calculated as follows:

- Harvest Index (%) = (Grain Yield / Aboveground Dry Biomass) × 100
- Agronomic N Efficiency (kg kg-1) = (Grain yield in fertilized plot - Grain yield in control plot) / N applied

2.4. Statistical Analysis

The collected data were subjected to Analysis of Variance (ANOVA) using the Fisher's F-test. The significance of differences between treatment means was determined using the Least Significant Difference (LSD) test at a 5% probability level (p=0.05), following the procedures described by Steel et al. (1997).

3. Results

3.1. Weed Parameters

Both herbicide treatment and nitrogen form, as well as their interaction, had a highly significant (p<0.05) effect on the number of weed plants, fresh weed biomass, and dry weed biomass. The pre-emergence herbicide (Hpr) provided the most effective weed control, resulting in the lowest weed density (19.97 plants m-2), fresh biomass (37.00 g m-2), and dry biomass (5.29 g m-2) (Tables 3, 4, 5). Conversely, the plots with the highest weed infestation were in the weedy check (Hwc) plots. Among the nitrogen treatments, the use of 100% standard urea (SU100%) had the highest weed pressure, while the lowest weed population and biomass were supported by the 75% NOCU treatment (NOCU75%). The interaction results showed that the Hpr treatment combined with NOCU75% was the most effective in reducing weed growth.

Table 3: *Effect of herbicide treatment (H) and nitrogen form (N) on number of weed plants (m-2).*

Nitrogen Form (N)	**Herbicide Treatment (H)**			**Mean (N)**
	H_{wc}	**H_{pr}**	**H_{po}**	
$SU_{100\%}$	81.00 a	27.67 h	51.53 d	53.40 A
$SU_{75\%}$	69.19 b	22.47 i	43.80 f	45.15 B
$NOCU_{100\%}$	66.54 c	17.41 j	42.20 g	42.05 C
$NOCU_{75\%}$	47.29 e	12.33 k	27.45 h	29.02 D
Mean (H)	**66.00 A**	**19.97 C**	**41.25 B**	

LSD (p=0.05): N = 0.73; H = 0.84; H×N = 1.46. Means with different letters differ significantly.

Table 4: *Effect of herbicide treatment (H) and nitrogen form (N) on fresh weight of weed biomass (g m-2).*

Nitrogen Form (N)	Herbicide Treatment (H)			Mean (N)
	H_{wc}	**H_{pr}**	**H_{po}**	
$SU_{100\%}$	92.67 a	42.00 i	70.98 e	68.55 A
$SU_{75\%}$	89.90 b	38.67 j	67.96 f	65.51 B
$NOCU_{100\%}$	86.92 c	35.33 k	64.99 g	62.41 C
$NOCU_{75\%}$	83.97 d	32.00 l	62.00 h	59.32 D
Mean (H)	**88.36 A**	**37.00 C**	**66.48 B**	

LSD (p=0.05): N = 0.29; H = 0.25; H×N = 0.50. Means with different letters differ significantly.

Table 5: *Effect of herbicide treatment (H) and nitrogen form (N) on dry weight of weed biomass (g m-2).*

Nitrogen Form (N)	Herbicide Treatment (H)			Mean (N)
	H_{wc}	**H_{pr}**	**H_{po}**	
$SU_{100\%}$	18.00 a	6.67 g	12.25 d	12.31 A
$SU_{75\%}$	16.08 b	5.30 h	10.42 e	10.60 B
$NOCU_{100\%}$	14.17 c	4.65 h	8.50 f	9.11 C
$NOCU_{75\%}$	12.25 d	4.56 h	6.78 g	7.86 D
Mean (H)	**15.13 A**	**5.29 C**	**9.48 B**	

LSD (p=0.05): N = 0.75; H = 0.65; H×N = 1.29. Means with different letters differ significantly.

3.2. Maize Growth and Yield Components

Herbicide and nitrogen factors significantly affected all measured growth and yield attributes of maize, except the number of cobs per plant, which was non-significant. The Hpr treatment showed the highest plant height (195.00 cm), stem diameter (8.95 cm), cob length (28.03 cm), and 1000-grain weight (270.12 g) (Table 6). Among the nitrogen sources, NOCU75% showed the highest plant height (183.78 cm), stem diameter (8.44 cm), cob length (26.87 cm), number of grains per cob (719.32), and 1000-grain weight (261.44 g). The interaction effect was significant for plant height, grains per cob, and 1000-grain weight, and the combination of Hpr and NOCU75% gave the best result for these traits.

Table 6: *Effect of herbicide treatment (H) and nitrogen form (N) on maize growth and yield components.*

Treatment	Plant Height (cm)	Stem Diameter (cm)	Cob Length (cm)	Grains per Cob	1000-Grain Weight (g)
Herbicide Treatment (H)					
H_{wc}	164.01 C	7.43 C	24.42 C	708.29 C	245.98 C
H_{pr}	195.00 A	8.95 A	28.03 A	724.20 A	270.12 A
H_{po}	180.51 B	8.20 B	25.69 B	716.34 B	258.90 B
Nitrogen Form (N)					
$SU_{100\%}$	181.34 B	8.20 B	26.59 A	717.35 B	259.36 B
$SU_{75\%}$	178.01 C	8.15 B	25.86 B	715.29 C	257.39 C
$NOCU_{100\%}$	176.22 D	8.00 C	24.87 C	713.16 D	255.14 D
$NOCU_{75\%}$	183.78 A	8.44 A	26.87 A	719.32 A	261.44 A
Interaction (H × N)					
$H_{pr} \times NOCU_{75\%}$	198.00 a	9.10	29.00	727.20 a	273.00 a
$H_{wc} \times NOCU_{100\%}$	160.67 k	7.13	23.40	705.00 l	244.00 k

For each parameter, means within a factor followed by different letters are significantly different ($p<0.05$). For interaction, only the highest and lowest values are shown for brevity, with their respective significance letters.

3.3. Grain Yield, Biomass, and Efficiency Indices

Grain yield, aboveground dry biomass, harvest index (HI), and agronomic N efficiency (ANUE) were all significantly influenced by the main effects of herbicide and nitrogen treatments (Table 7). The Hpr treatment showed the highest grain yield (10.55 Mg ha-1), biomass (20.50 Mg ha-1), HI (49.44%), and ANUE (0.0243 kg kg-1). Among the N treatments, NOCU75% showed the highest grain yield (9.72 Mg ha-1), biomass (19.08 Mg ha-1), HI (49.27%), and ANUE (0.0229 kg kg-1). It is worth noting that the 75% NOCU treatment was superior to the 100% standard urea treatment in all these parameters. The interaction of Hpr and NOCU75% was most effective, and it resulted in the highest grain yield of 10.90 Mg ha-1.

Table 7: *Effect of herbicide treatment (H) and nitrogen form (N) on maize yield, biomass, and efficiency indices.*

Treatment	**Grain Yield (Mg ha^{-1})**	**Aboveground Biomass (Mg ha^{-1})**	**Harvest Index (%)**	**Agronomic N Efficiency (kg kg^{-1})**
Herbicide Treatment (H)				
H_{wc}	8.21 C	16.04 C	44.05 C	0.0195 C
H_{pr}	10.55 A	20.50 A	49.44 A	0.0243 A
H_{po}	9.40 B	18.44 B	47.31 B	0.0220 B
Nitrogen Form (N)				
$SU_{100\%}$	9.48 B	18.59 B	47.10 B	0.0222 B
$SU_{75\%}$	9.28 C	17.98 C	44.87 C	0.0217 C
$NOCU_{100\%}$	9.07 D	17.66 D	46.48 BC	0.0211 D
$NOCU_{75\%}$	9.72 A	19.08 A	49.27 A	0.0229 A
Interaction (H × N)				
H_{pr} × $NOCU_{75\%}$	10.90 a	21.42 a	51.81	0.0252 a
H_{wc} × $NOCU_{100\%}$	7.90 l	15.35 i	42.78	0.0185 l

For each parameter, means within a factor followed by different letters are significantly different ($p<0.05$). For interaction, only the highest and lowest values are shown for brevity, with their respective significance letters.

4. Discussion

The findings from this study have shown that the combined management of herbicide timing and nitrogen form can greatly improve the efficacy of autumn maize by overcoming the combined limitations of weed interference and inefficient N use. The effectiveness of the pre-emergence herbicide (Hpr) treatment over the post-emergence (Hpo) and weedy check (Hwc) treatments in weed control is an important finding. The pre-emergence application of s-metolachlor herbicide ensured early-season weed control, which prevented the establishment of weeds and thus reduced weed competition during the early growth stages of maize. This is supported by the findings of Sarangi and Jhala (2018), who found that pre-emergence herbicides are highly effective in reducing weed density and biomass. The result of reduced weed pressure in the Hpr treatment plots enabled maize plants to make better use of available resources, resulting in significantly higher plant height, stem diameter, yield attributes, and ultimately, a 28% increase in grain yield compared to the weedy check.

Nitrogen fertilizer formulation and dose also played a significant role in influencing weed population and crop yield. The use of conventional urea fertilizer, particularly at the 100% recommended dose (SU100%), promoted the highest weed growth. This can be attributed to the high availability of N from urea fertilizer, which acts as a readily available resource for fast-growing weeds, thus increasing competition for the crop (Rajcan and Swanton, 2001). On the other hand, the neem oil-coated urea fertilizer (NOCU), particularly at the reduced rate of 75% RDN, promoted lower weed growth. The nitrification inhibitor in neem oil ensures a slow and gradual release of N, which matches well with the crop's demand pattern (Prasad, 2009). This slow release reduces the peak availability of N that weeds can utilize, thus providing the crop with a competitive advantage (Simić et al., 2020).

The most interesting finding emerging from this study is the better performance of the reduced rate NOCU treatment (NOCU75%). This treatment not only recorded the highest grain yield (9.72 Mg ha-1) among the N main effects but also outperformed the full rate standard urea treatment (SU100%) by 2.5%. This suggests that using 25% less nitrogen in the form of NOCU can be more productive than using the full recommended rate of conventional urea. This increased productivity is a direct consequence of the higher nitrogen use efficiency, as the NOCU75% treatment recorded the highest Agronomic N Efficiency (ANUE). The slow release nature of NOCU ensures that there is minimal loss of N to the environment and that maximum N is utilized by the crop, resulting in improved growth, biomass production, and grain filling (Ali et al., 2020; Ghafoor et al., 2021).

The important interaction between herbicide timing and form of N application highlights the need for an integrated approach. The interaction of pre-emergence herbicide and 75% NOCU (Hpr × NOCU75%) always proved to be the best treatment, and it produced maximum grain yield (10.90 Mg ha-1). This can be attributed to the complementary effects of both practices. The pre-emergence herbicide ensured a low-competition environment right from the beginning, and the slow-release NOCU ensured a constant supply of nutrients to the maize crop, which could then fully exploit the weed-free environment. This integrated approach successfully tackles the two major issues associated with autumn maize production, proving that the optimal management of resource supply (N) and reduction of competitive stress (weeds) together results in productivity gains that are greater than the sum of individual contributions.

5. Conclusion

The results of this study support the conclusion that the integrated management approach is very effective in enhancing the performance of autumn-sown maize. The pre-emergence herbicide approach using s-metolachlor was found to be more effective than the post-emergence approach, ensuring a conducive environment for the growth of the crop by reducing competition during the early stages. Additionally, the application of neem oil-coated urea (NOCU) at a lower rate of 75% of the recommended N dose was not only comparable but also superior to the 100% dose of standard urea in terms of grain yield and nitrogen use efficiency. The synergistic interaction between pre-emergence weed control and the application of 75% RDN as NOCU resulted in the highest grain yield and biomass. Therefore, it can be concluded that this integrated approach is an agronomically sound, efficient, and potentially more economical and environmentally sustainable strategy for closing the yield gap and enhancing the productivity of autumn maize in regions with similar agro-climatic challenges.

Conflict of Interest

The authors showed no conflict of interest.

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