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RESEARCH ARTICLE

Compatibility and efficacy of post-emergence herbicides tank mixed with zinc sulphate and urea for weed management in wheat

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ABSTRACT

A study was conducted to evaluate the compatibility and efficacy of post-emergence herbicides with zinc sulphate and urea (tank-mixed) in wheat during the year 2018–19, 2019–20 and 2020–21 at the research farm of CCSHAU Regional Research Station, Bawal, Haryana, India. The experiment was designed in a factorial randomized block design with three replications. The first factor included two treatments: with foliar spray of zinc sulphate plus urea and without the foliar spray of zinc sulphate plus urea, while the second factor comprised of seven weed control treatments: metsulfuron 4 g/ha, carfentrazone 20 g/ha, 2,4-D sodium salt 500 g/ha, 2,4-D ester salt 500 g/ha, metsulfuron + carfentrazone (RM) 24 g/ha, unweeded check, and weed-free. The herbicides tested were found compatible with zinc sulphate (0.5%) + urea (2.5%) when tank-mixed, as no phytotoxicity was observed on the crop at any stage. The application of zinc sulphate (0.5%) + urea (2.5%) was found to be compatible with different herbicides recommended for the post-emergence management of broad-leaved weeds and increased wheat grain yield by 4%. Among different herbicides, metsulfuron + carfentrazone (RM) 24 g/ha recorded the highest grain yield (6.06 t/ha) and achieved the maximum net returns (₹ 85,907/ha) with a benefit-cost (B:C) ratio of 2.78 over three seasons. The highest weed control efficiency was also observed with metsulfuron + carfentrazone (RM) 24 g/ha tank-mixed with zinc sulphate and urea. The various herbicides when tank mixed with zinc sulphate plus urea provided higher weed control efficiency than the herbicides used alone.

Keywords: Compatibility, Herbicides, Metsulfuron + carfentrazone, Weed control efficiency, Wheat, Zinc sulphate with urea

INTRODUCTION

Wheat is one of the major cereal crops globally, cultivated in an area of 219.5 million hectares, with a production of 808.4 million tonnes (Anonymous 2022a). India is the second largest wheat producer after China, contributing 13.3% of global production with 107.7 million tonnes in 2022, grown on 30.46 million hectares (13.9% of global wheat acreage) (Anonymous 2022b). By 2050, it is estimated that a sustainable increase in global food supply of 70–100% will be required to meet the demands of a population projected to reach 9 billion (Godfray *et al.* 2010). Given the limited scope for expanding cultivated areas, increasing crop productivity remains the only viable strategy to address the food security challenge. In arid and semi-arid regions, wheat yields are significantly limited by inadequate nutrient supply (Nagora *et al.* 2023). Weeds also pose a major constraint to wheat production, with the potential for the greatest losses among biotic factors, including pathogens, insects, and animals. In India, weeds result in an annual economic loss of over USD 11 billion (Gharde *et al.* 2018). They compete with crops for essential resources such as nutrients, moisture, light, and space, leading to yield losses ranging from 15 to 53% and in severe cases, complete crop failure (Jitender *et al.* 2021; Nibhoria *et al.* 2021, 2022; Malik and Singh 1995; Soni *et al.* 2023, 2024).

Among weed management methods, chemical control is considered the most efficient, cost-effective, and time-saving. Moreover, various herbicides have been recommended for different types of weed flora. Wheat in south western parts of Haryana state is mainly dominated by broad-leaved weeds. Nutrient management is another critical factor affecting yield and quality. Combined application of agrochemicals, such as herbicides and micronutrients, can address both weed management and nutrient deficiencies while reducing operational costs. However, herbicide performance can be

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influenced by co-applied agrochemicals, resulting in synergistic, antagonistic, or additive effects depending on their chemistry, application rates, formulations, spray volume, target weeds, and environmental conditions (Daramola *et al.* 2023). In Brazilian farms, approximately 97% of agrochemical users tank mix up to six or more products, applying them concomitantly, such as herbicides with insecticides and fungicides (Gazziero 2015). Such combinations can also create synergistic effects, enhancing weed control efficiency (Li *et al.* 2019). In maize, the addition of urea to herbicides increased both phytotoxicity and herbicide efficacy (Tahir *et al.* 2011). Similarly, in wheat, herbicide efficacy improved when combined with zinc (Jitender *et al.* 2022). Zinc (Zn) is a vital micronutrient for plants, contributing to enzymatic activities, crop yield, and quality (Sheoran *et al.* 2021). In India, nearly 49% of soils are deficient in micronutrients like Zn and Fe (Shukla *et al.* 2012). Deficiencies in plant-available zinc lead to lower zinc content in grains, which in turn exacerbates malnutrition in humans. Factors such as high soil pH, high calcium carbonate content, sandy soil texture, and low organic matter contribute to zinc deficiency in soils, despite its natural abundance. Mixing urea with zinc also enhances nutrient assimilation in crops and boosts herbicide performance. Foliar application of water-soluble fertilizers has emerged as an effective and economical method to enhance crop production under such conditions. Given the rising production costs and the overlapping timings for the application of post-emergence herbicides and micronutrient sprays, farmers could benefit from their concurrent use. This approach saves time, labour, and energy, while also reducing costs. However, limited research is available on the compatibility of herbicides with zinc sulphate and urea. Thus, this study was designed to determine the compatibility of herbicides with zinc sulphate and urea to provide valuable insights and practical solutions for wheat growers.

MATERIALS AND METHODS

The experiment was carried out in three consecutive seasons, *i.e.* 2018-19 to 2020-21 at CCS Haryana Agricultural University, Regional Research Station, Bawal (Rewari) Haryana, India (coordinates of 28º4' N latitude and 76º35' E longitude, an altitude of 266 m from mean sea level). Climate of Bawal (Rewari), India classified as tropical and semiarid with hot and dry winds in summer, severe cold in winter; and humid, warm weather during the rainy season. The average rainfall of the region is 350-550 mm. A total 34.3, 110.3 and 68.6 mm of rainfall was received during cropping seasons 2018-19, 2019-20 and 2020-21, respectively (**Figure 1, 2, 3**). The soil of the experimental field was loamy sand (typic ustochrept) in texture and slightly alkaline in reaction with pH 7.8, low in soil organic carbon (0.21%) and nitrogen (89 kg/ha); and medium in available phosphorus (10.8 kg/ha soil) and potash (166 kg/ha soil). Seeds of wheat crop variety WH 1105 were drilled manually with the help of hand plough into rows at 20 cm spacing on well-prepared seed bed. The crop was fertilized as per the recommended dose, i.e., 150 kg N, 60 kg P, and 30 kg K per hectare. Five irrigations were applied at 22, 45, 65, 85, and 105 days after sowing (DAS) in all seasons. Other agronomic operations were conducted according to the recommended packages of practices developed by the university.

Treatment details

The experiment was designed in a factorial randomized block design (RCBD) with three replications with gross plot size of 5m × 2.6m. The first factor included two treatments: with and without the spray of zinc sulphate (0.5%) + urea (2.5%), while the second factor comprised seven weed control treatments: post-emergence application (PoE) of metsulfuron 4 g/ha, carfentrazone 20 g/ha, 2,4-D sodium salt 500 g/ha, 2,4-D ester salt 500 g/ha, metsulfuron + carfentrazone - ready mix (RM) 24 g/ha, unweeded check (UWC), and weed-free check (WFC). Post-emergence application of herbicides was done at 35 days after sowing (DAS) of wheat using a knapsack sprayer with a flat fan nozzle calibrated to deliver 375 L water per ha. In weeds-free plots, weeds were removed manually as and when appeared; and no weeding was done in unweeded check treatment.

Observations on weeds

The data on weed density and total dry weight (weed biomasss) were recorded at 75 DAS using a quadrat of 0.5 x 0.5 m^2, placed randomly at 4 spots in each of the plot. The total weed counts were summed up to express weed density per meter square. All weeds were uprooted, and sundried followed by oven drying at 65±5 ^{0}C till a constant weight was achieved. The dried samples of weeds were weighed and the total weeds biomass was expressed as g/m^2. Weed control efficiency (WCE%) was calculated using following formula:

$$WCE = \frac{Wc - Wt}{Wc} \times 100$$

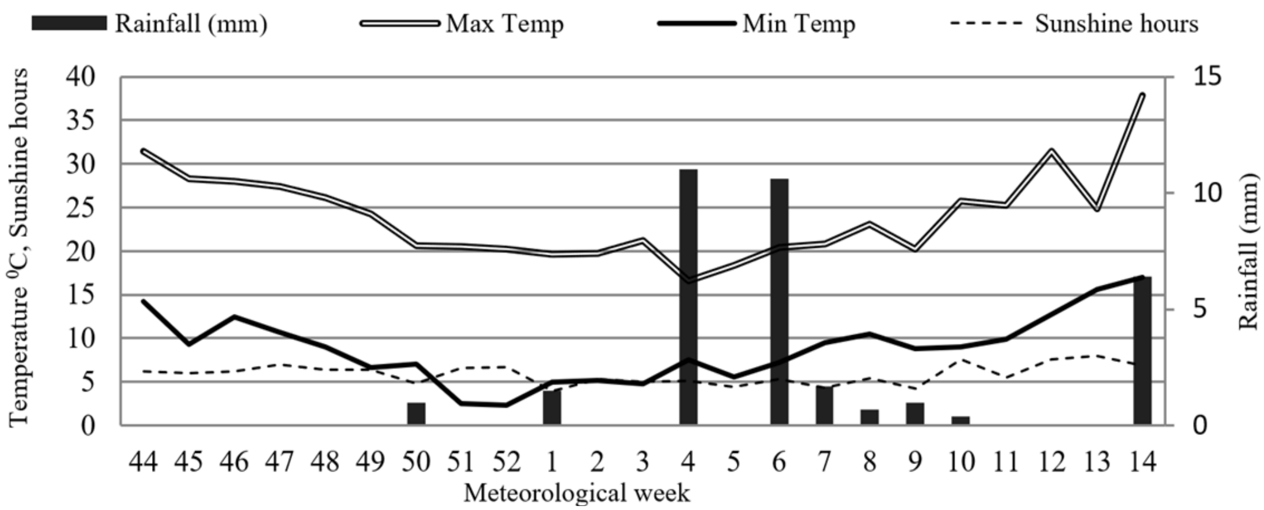

Figure 1. Weather data of crop season 2018-19

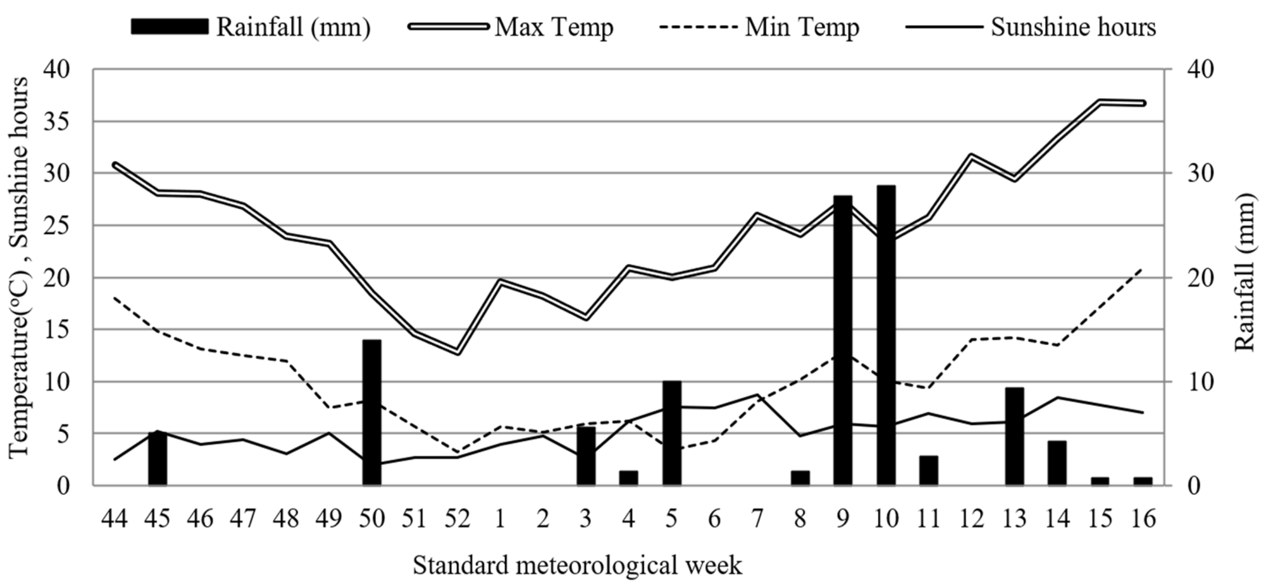

Figure 2. Weather data of crop season 2019-20

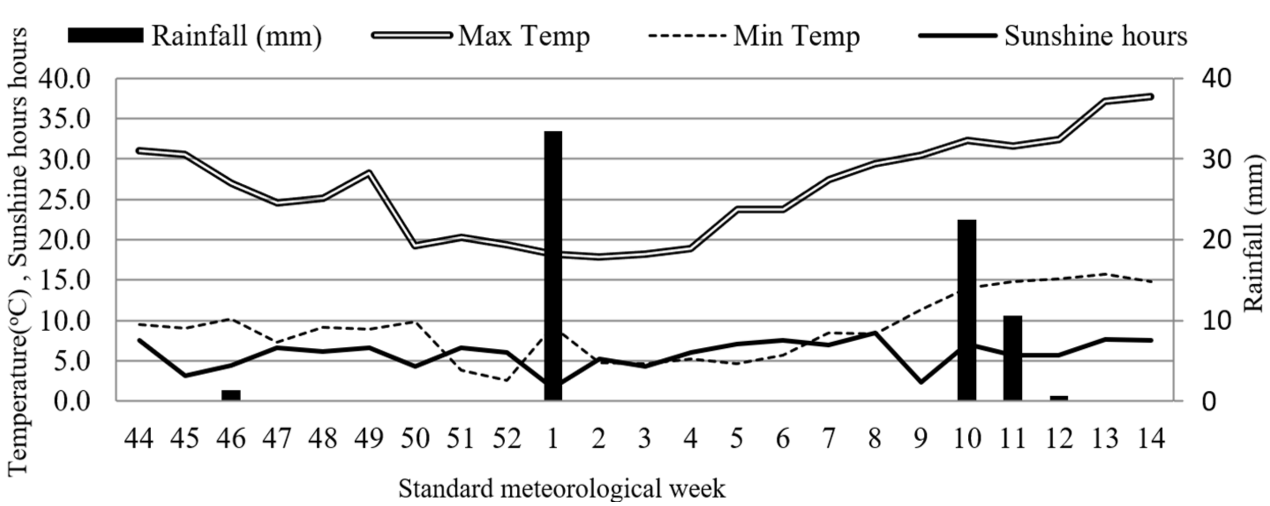

Figure 3. Weather data of crop season 2020-21

Where,

Wc = weeds biomass in weedy plot (g)

Wt = weeds biomass in treated plot (g)

Wheat yield attributes, including effective tillers (no./m²), grains per spike, and 1000-grain weight were recorded at harvest. Effective tillers were calculated by averaging counts from three random one-meter row lengths per plot and converting them to m² based on row spacing. Grains per spike were determined by threshing and counting grains from twenty randomly collected spikes per plot. The 1000-grain weight was measured by weighing thousand healthy grains from each plot using a digital balance. Wheat grain and straw yields (t/ha) were measured by threshing the sun-dried wheat harvested from the net plot area using a mini-plot thresher and weighing the produce with a digital balance.

Economics

The cost of cultivation was calculated based on the prevailing market rates for all operations and inputs. Gross returns were determined by multiplying wheat grain and straw yield with minimum support price of wheat and prevailing market rates of straw, respectively, in corresponding seasons. Net returns were the difference between gross returns and cost of cultivation per ha. Benefit- cost (B: C) ratio was calculated using the following formula:

B: C = Gross returns (Rs/ha) ÷ Gross cost (Rs/ha)

Statistical analysis

Statistical analysis was performed using STAR (Statistical Tools for Agricultural Researcher) software package (STAR version 2014). The significance of the treatment was determined by the F-test, and the difference between the means of treatments with factors having more than two levels, multiple comparisons were performed using Tukey HSD at 5% probability level. To homogenize the variance of weed density and biomass, square root ($\sqrt{x+1}$) transformation was performed. Additionally, correlation analysis was conducted to assess the relationships between key variables such as weed density, weed biomass, yield attributes, and yield. Regression analysis was performed to model the influence of independent variables (weed biomass (dry weight), weed density and WCE) on dependent variables (grain yield).

RESULTS AND DISCUSSION

The crop was mainly infested with broad-leaved weeds, *viz. Chenopodium album, Chenopodium murale, Anagallis arvensis, Corronopus didymus, Convolvulus arvensis* etc. The application of $ZnSO_4$ (0.5%) and urea (2.5%) with tested post-emergence herbicides significantly reduced weed density and biomass in comparison to weedy check (**Table 1**). The density of weeds significantly reduced with all weed control treatments in comparison to unweeded check that may be ascribed to the application of zinc sulphate + urea led to better crop growth and lesser competition between crop and weeds. Among various herbicidal treatments for weed management, metsulfuron + carfentrazone (RM) 24 g/ha recorded the least weed density as well as weeds biomass over a period of three seasons **(Table 1)**. The interaction was insignificant. These results are in agreement with Gandini *et al.* (2020).

Weed control efficiency (WCE)

Significantly highest WCE was achieved with metsulfuron + carfentrazone (RM) 24 g/ha in with and without combinations of zinc sulphate with urea **(Figure 4)**. However, the inclusion of zinc sulphate with urea consistently improved the WCE across all herbicide treatments. The combination of metsulfuron and carfentrazone offers superior weed control due to their complementary modes of action. Metsulfuron, a systemic ALS inhibitor, provides long-lasting control by targeting amino acid synthesis, while carfentrazone, a contact PPO inhibitor, delivers rapid knockdown by disrupting chlorophyll production. This synergy enhances overall efficacy compared to other herbicides like 2,4-D, offering both immediate and sustained weed suppression. Further, improvement with the addition of zinc sulphate with urea attributed to several synergistic effects. Zinc sulphate, as a micronutrient, enhances enzymatic activity and chlorophyll synthesis in crops, improving their vigour and enabling them to compete more effectively with weeds. Urea, on the other hand, can alter the pH of the spray solution, enhancing the absorption and translocation of systemic herbicides like metsulfuron and 2,4-D, while also improving the efficacy of contact herbicides such as carfentrazone. Additionally, the nutrient combination of zinc and urea may impose metabolic stress on weeds, making them more susceptible to herbicidal action. These combined effects likely contributed to the increased efficacy of herbicides in the presence of zinc sulphate and urea, leading to superior weed control and crop performance. The findings underscore the importance of integrating nutrient management with herbicide application to achieve enhanced weed suppression and sustainable crop production. Similar increase in WCE has been reported by Sabeti (2015) wherein about 10 per cent increase in herbicide efficacy was reported due to tank mixture of micronutrients and herbicides.

Crop yield attributes and yield

Mixture of $ZnSO_4$ and urea was compatible with various herbicides in tank mixing, leading to enhanced crop yield attributes. Foliar application of zinc sulfate combined with urea resulted in an improvement across all yield parameters, with a significant increase noted specifically in grains per spike. Various herbicidal treatments significantly increased tillers per meter square by 6-8 and grains per spike by 11-13 per cent over unweeded check (**Table 2**). Importantly, no phytotoxicity was observed from any herbicide application, whether zinc plus urea was included or not. Furthermore, the interaction between $ZnSO_4$ + urea and the applied herbicides was statistically insignificant. These results are consistent with findings reported by Jitender *et al.* (2023).

Grain yield

Spray of $ZnSO_4$ (0.5%) + urea (2.5 %) tank mixed with herbicides exerted significant effect (4% increase) on grain yield of wheat over three cropping seasons (**Table 3**). Similarly, Maurya *et al.* (2015) reported 26 % hike in grain yield of wheat with two foliar spray of $ZnSO_4$ (0.5%) + urea (2.0%) at 25 and

Table 1. Effect of zinc sulphate with urea and different weed control treatments on weed density and biomass in wheat at 75 DAS (Mean of 2018-19 to 2020-21)

Treatment	Weed density (no./m^2)	Weeds biomass (g/m^2)
Zinc sulphate with urea		
No spray of $ZnSO_4$ (0.5%) + urea (2.5%)	5.7^b (25.0)	4.4^b (15.4)
Spray of $ZnSO_4$ (0.5%) + urea (2.5%)	5.1^a (20.2)	3.8^a (13.4)
Herbicides		
Metsulfuron 4 g/ha PoE	4.7^b (20.1)	3.4^b (13.4)
Carfentrazone 20 g/ha PoE	4.4^a (20.1)	3.2^b (12.0)
2, 4-D Na salt 500 g/ha PoE	4.7^b (23.0)	3.4^b (12.0)
2, 4-D ester salt 500 g/ha PoE	4.9^b (18.4)	3.6^b (9.2)
Metsulfuron + carfentrazone (RM) 24 g/ha PoE	3.0^c (8.1)	1.8^a (3.8)
Unweeded check	15.1^d (134.9)	12.7^c (98.2)
Weed free check	1.0 (0)	1.0^d (0)
P-value at 5% level of significance		
Year	0.0000*	0.0003*
Zinc	0.0000*	0.0000*
Herbicide	0.0000*	0.0000*
Zinc × Herbicide	0.0665	0.1568
Year × Zinc	0.5500	0.6012
Year × Herbicide	0.0000*	0.0000*
Year × Zinc × Herbicide	0.1089	0.9244

Figures in parentheses are original values which were subjected square root transformation. RM: ready mix

The values in the table represent p-values, a p-value < 0.05 suggests a significant effect, while a p-value ≥ 0.05 indicates a non-significant effect.

Means marked with at least one common letter are not significantly different from each other under a particular factor (p<0.05). DAS = days after seeding; PoE = Post emergence application; RM = ready mix

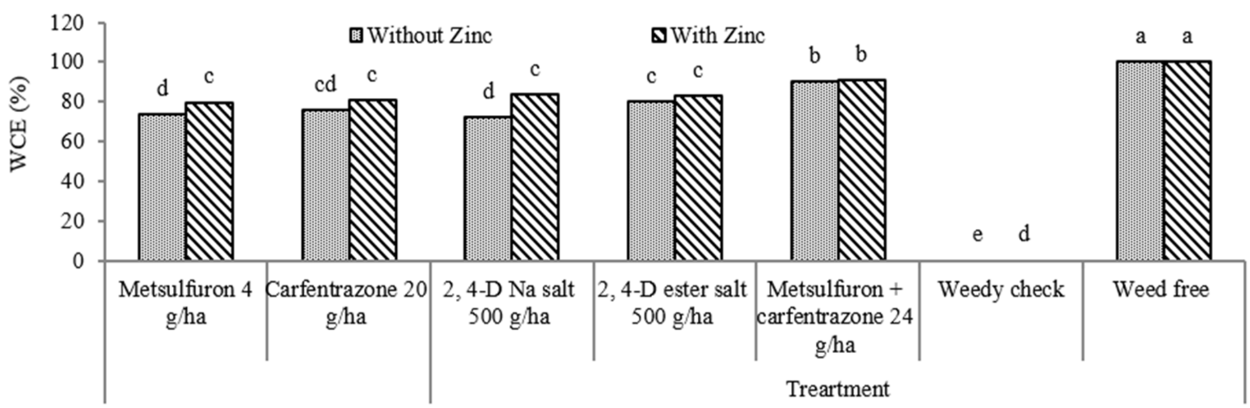

Figure 4. Weed control efficiency of different weed management treatments with and without tank mixing of zinc sulphate + urea at 75 DAS in wheat (mean of 2018-19 to 2020-21)

50 DAS. These results are further supported by Gao *et al.* (2024) who reported that increasing Zn supply via foliar spraying could effectively correct or prevent the symptomatic occurrence of Zn deficiency, ensure sufficient Zn uptake by wheat and improve grain yields. Among various weed control treatments, maximum increase in grain yield (33%) over unweeded check was recorded under metsulfuron + carfentrazone (RM) 24 g/ha and weed free check followed by 30% with carfentrazone 20g/ha. The mean grain yield of three years of study under all herbicidal treatments was significantly higher than

Table 2. Effect of application of zinc sulphate with urea and different weed control treatments on yield attributes of wheat (mean of 2018-19 to 2020-21)

Treatment	Tillers/m^2	Grains/spike	1000-grain wt. (g)
Zinc sulphate with urea			
No spray of $ZnSO_4$ (0.5%) + urea (2.5%)	348.3^{ns}	43.9^b	42.1^{ns}
Spray of $ZnSO_4$ (0.5%) + urea (2.5%)	350.8^{ns}	45.4^a	42.6^{ns}
Herbicides			
Metsulfuron 4 g/ha PoE	352.0^a	45.1^a	42.8^a
Carfentrazone 20 g/ha PoE	352.7^a	45.1^a	42.8^a
2, 4-D Na salt 500 g/ha PoE	350.2^a	44.9^a	42.9^a
2, 4-D ester salt 500 g/ha PoE	352.7^a	45.2^a	42.7^a
Metsulfuron + carfentrazone (RM) 24 g/ha PoE	356.2^a	45.7^a	43.5^a
Unweeded check	328.8^b	40.6^b	38.8^b
Weed free check	354.3^a	45.9^a	43.2^a
P-value at 5% level of significance			
Year	0.0000*	0.0000*	0.0003*
Zinc	0.0641	0.001*	0.1828
Herbicide	0.0000*	0.0000*	0.0000*
Zinc × Herbicide	0.9973	0.9256	0.9995
Year × Zinc	0.8605	0.3300	0.4698
Year × Herbicide	0.1680	0.9701	0.9996
Year × Zinc × Herbicide	0.9979	1.0000	0.9999

The values in the table represent p-values, a p-value < 0.05 suggests a significant effect, while a p-value ≥ 0.05 indicates a non-significant effect.

Means marked with at least one common letter are not significantly different from each other under a particular factor (p<0.05). PoE = Post emergence application; RM = ready mix

Table 3. Effect of application of sulphate with urea and different weed control treatments on grain and straw yield of wheat

Treatment	Grain yield (t/ha)				Straw yield (t/ha)			
	2018-19	2019-20	2020-21	Mean	2018-19	2019-20	2020-21	Mean
Zinc sulphate with urea								
No Spray of $ZnSO_4$ + urea	6.26^{ns}	5.33^b	5.37^b	5.65^b	9.46^{ns}	9.36^{ns}	9.98^b	9.54^b
Spray of $ZnSO_4$ + urea	6.30^{ns}	5.66^a	5.63^a	5.87^a	9.50^{ns}	9.82^{ns}	10.40^a	9.91^a
Herbicides								
Metsulfuron 4 g/ha PoE	6.42^a	5.59^a	5.62^a	5.90^a	9.69^a	9.75^a	10.24^a	9.89^a
Carfentrazone 20 g/ha PoE	6.53^a	5.72^a	5.71^a	5.95^a	9.64^a	9.95^a	10.48^a	10.03^a
2, 4-D Na salt 500 g/ha PoE	6.59^a	5.58^a	5.62^a	5.90^a	9.70^a	9.75^a	10.23^a	9.89^a
2, 4-D ester salt 500 g/ha PoE	6.46^a	5.61^a	5.64^a	5.90^a	9.67^a	9.82^a	10.32^a	9.94^a
Metsulfuron + carfentrazone (RM) 24 g/ha PoE	6.49^a	5.84^a	5.78^a	6.06^a	9.76^a	10.03^a	10.70^a	10.17^a
Unweeded check	4.98^b	4.37^b	4.35^b	4.56^b	8.11^b	7.84^b	8.25^b	8.07^b
Weed free check	6.51^a	5.77^a	5.78^a	6.05^a	9.81^a	9.99^a	10.50^a	10.10^a
P-value at 5% level of significance								
Year	--	--	--	0.000*	--	--	--	0.0003*
Zinc	0.7966	0.0079*	0.0021*	0.004*	0.7515	0.1915	0.0442*	0.0288*
Herbicide	0.000*	0.000*	0.000*	0.000*	0.000*	0.0244*	0.0126*	0.000*
Zinc × Herbicide	0.9804	0.9999	0.8929	0.9824	0.9999	1.0000	0.9999	0.9998
Year × Zinc	--	--	--	0.2329	--	--	--	0.3507
Year × Herbicide	--	--	--	0.9985	--	--	--	0.9998
Year × Zinc × Herbicide	--	--	--	0.9995	--	--	--	1.000

The values in the table represent p-values, a p-value < 0.05 suggests a significant effect, while a p-value ≥ 0.05 indicates a non-significant effect.

Means marked with at least one common letter are not significantly different from each other under a particular factor (p<0.05). PoE = Post emergence application; RM= ready mix unweeded check and statistically similar to that of weed free check treatment. The straw yield of wheat also followed almost similar trend over study period. The synergistic effect of tank mixed zinc and herbicide resulted in better translocation of photosynthates form source to sink and ultimately higher economic yield and thereby giving better returns. Furthermore, fertilizers enhance the plant´s adaptive potential by minimizing injury from herbicides (Machado *et al.* 2017). Foliar fertilizers and growth regulators can induce adaptive plant responses to harmful substances by acting to detoxify superoxide anions in them (Upreti and Sharma 2016). Ram *et al.* (2022) also reported 5.74% increased grain yield with foliar Zn + herbicide mixture than control.

Economics

Over three years, the application of $ZnSO_4$ + urea in wheat resulted in higher net returns and benefit-cost ratio (B:C). The tank mixing of $ZnSO_4$ (0.5%) + urea (2.5%) increased the net returns by Rs. 5116/ha and B: C from 2.53 to 2.60 over 3 seasons (**Table 4**). Similar outcomes of improvement in B: C with foliar spray of zinc sulphate mixed with urea was reported by Maurya *et al.* (2015). All weed management treatments fetched statistically similar gross returns, net returns and B: C except unweeded check which recorded significantly lower economic parameters in comparison to all other treatments. Among various weed management treatments, metsulfuron + carfentrazone (RM) 24 g/ha resulted in the highest net returns (Rs.85,907/ha) and B: C (2.78). Other herbicidal treatments also resulted in increase in net returns as well as B: C in comparison to unweeded check. Interestingly, weed-free plots recorded significantly lower net returns (Rs. 56,934/ha) and B:C (1.68) than herbicidal treatments. This could be attributed to the higher cost of labor involved in manual weed management. The improvement in economic parameters, such as net returns and B:C, was primarily due to enhanced grain and straw yield in wheat under treatments involving the foliar application of zinc and herbicides (Jitender *et al.* 2023). Daramola *et al.* (2023) also highlighted the benefits of co-application of agrochemicals, emphasizing advantages such as time efficiency, reduced field application trips, improved pest control, lower fuel consumption, and minimized environmental pollution.

Box plot analysis

The analysis of the box plot data reveals that the combined application of $ZnSO_4$ with urea significantly enhances wheat performance in terms of weed control efficiency (WCE), grain yield, and straw yield compared to herbicide alone under combined herbicide treatments in three seasons **(Figure 5)**. The mean WCE increased from 70.22% without $ZnSO_4$ + urea to 73.98% with $ZnSO_4$ + urea,

Table 4. Effect of application of zinc sulphate with urea and different weed control treatments on economics of wheat (mean of 2018-19 to 2020-21)

Treatment	Gross returns (Rs./ha)	Net returns (Rs./ha)	B: C
Zinc sulphate with urea			
No Spray of $ZnSO_4$ + urea	133715[b]	75038[b]	2.53[b]
Spray of $ZnSO_4$ + urea	138512[a]	80154[a]	2.60[a]
Herbicides			
Metsulfuron 4 g/ha PoE	138686[a]	82622[a]	2.74[a]
Carfentrazone 20 g/ha PoE	141185[a]	84720[a]	2.73[a]
2, 4-D Na salt 500 g/ha PoE	139674[a]	83455[a]	2.73[a]
2, 4-D ester salt 500 g/ha PoE	139355[a]	83058[a]	2.73[a]
Metsulfuron + carfentrazone (RM) 24 g/ha PoE	142514[a]	85907[a]	2.78[a]
Unweeded check	109388[b]	55964[c]	2.16[b]
Weed free check	141990[a]	74445[b]	2.19[b]
P-value at 5% level of significance			
Year	0.0031*	0.0000*	0.0000*
Zinc	0.0005*	0.0002*	0.0113*
Herbicide	0.0000*	0.0000*	0.0000*
Zinc × Herbicide	0.9751	0.9875	0.9772
Year × Zinc	0.0162	0.0705	0.5299
Year × Herbicide	0.9990	0.9993	0.0000*
Year × Zinc × Herbicide	0.9999	0.9997	0.9993

The values in the table represent p-values, a p-value < 0.05 suggests a significant effect, while a p-value ≥ 0.05 indicates a non-significant effect.

Means marked with at least one common letter are not significantly different from each other under a particular factor ($p<0.05$). PoE = Post emergence application; RM = ready mix with a more stable range (65.47 to 100% vs. 42.54 to 100%). This highlights the role of $ZnSO_4$ with urea in improving crop vigour, which indirectly suppresses weed growth through better competition via synergy with herbicides used in experiments. In terms of grain yield, the mean yield under the combined treatment of $ZnSO_4$ with urea was higher (5.9 t/ha) compared to herbicide alone (5.7 t/ha). Moreover, the range of grain yield shifted towards higher values (4.1 to 7.5 t/ha with $ZnSO_4$ with urea, compared to 3.9 to 7.4 t/ha without $ZnSO_4$ and urea), indicating consistent yield improvements driven by better nutrient uptake and utilization facilitated by zinc. The addition of $ZnSO_4$ with urea likely supported enzymatic activities and nutrient assimilation, directly enhancing grain development. Straw yield, an indicator of biomass production, also benefitted from the combined application of $ZnSO_4$ with urea. The mean straw yield increased from 9.5 t/ha with herbicide alone to 9.9 t/ha with $ZnSO_4$ and urea with herbicides, with an extended upper range (7.0 to 12.3 t/ha vs. 7.3 to 11.3 t/ha). This suggests that $ZnSO_4$ with urea enhances root and shoot development, leading to improved overall plant growth and higher biomass accumulation.

Regression studies

Wheat grain yield showed a strong negative linear relationship with weed density and biomass, and a positive linear relationship with WCE (**Figure 6**). The regression analysis highlights the impacts of weed biomass, density, and weed control efficiency (WCE) on wheat grain yield. For weed biomass , the equation y= -0.006x + 5.916 (R^2=0.279) indicates that a unit increase in weed biomass leads to a proportional reduction of 0.006 times in grain yield, explaining 27.9% of the yield variation. Similarly, for weed density, the equation y= -0.0047x+5.954 (R^2=0.364) shows a proportional reduction of 0.0047 times in grain yield per unit increase in weed density, accounting for 36.4% of the variation. In contrast, for WCE, the equation y=0.0148x+4.694 (R^2=0.420) suggests that a unit increase in WCE results in a proportional increase of 0.0148 times in grain yield, explaining 42.0% of the variation. These findings emphasize the critical role of managing weeds and improving WCE to enhance wheat grain yield.

Correlation studies

The correlation analysis among various yield parameters and weed-related traits with grain yield in

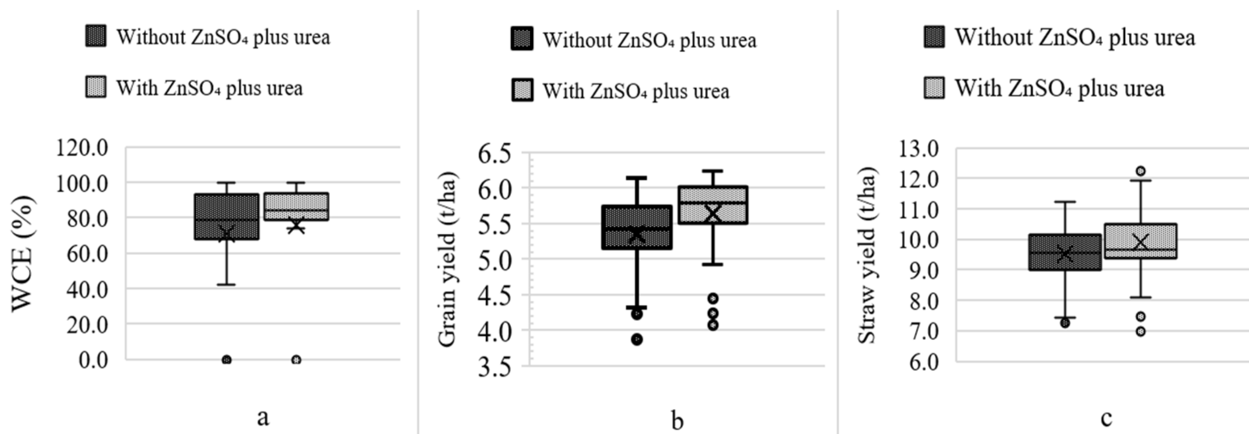

Figure 5. Effect of $ZnSO_4$ with urea on (a) Weed Control Efficiency, (b) Grain Yield, and (c) Straw Yield in Wheat (combined means of herbicides and seasons)

Table 5. Correlation of grain yield with yield parameters and weed parameters of wheat

Parameters*	Tillers/m^2	Grains per spike	1000 grain wt.	Grain yield	Harvest index	Weed density at 75 DAS	Weeds biomass at 75 DAS	WCE
Tillers/m^2	—							
Grains per spike	0.949**							
1000 grain wt.	0.987**	0.957**						
Grain yield	0.983**	0.963**	0.987**					
Harvest index	0.901**	0.873**	0.907**	0.948**				
Weed density 75 DAS	-0.972**	-0.924**	-0.964**	-0.955**	-0.883**			
Weed biomass at 75 DAS	-0.983**	-0.936**	-0.978**	-0.973**	-0.913**	0.994**		
WCE	0.977**	0.930**	0.972**	0.969**	0.913**	-0.993**	-0.999**	--

*DAS = days after seeding

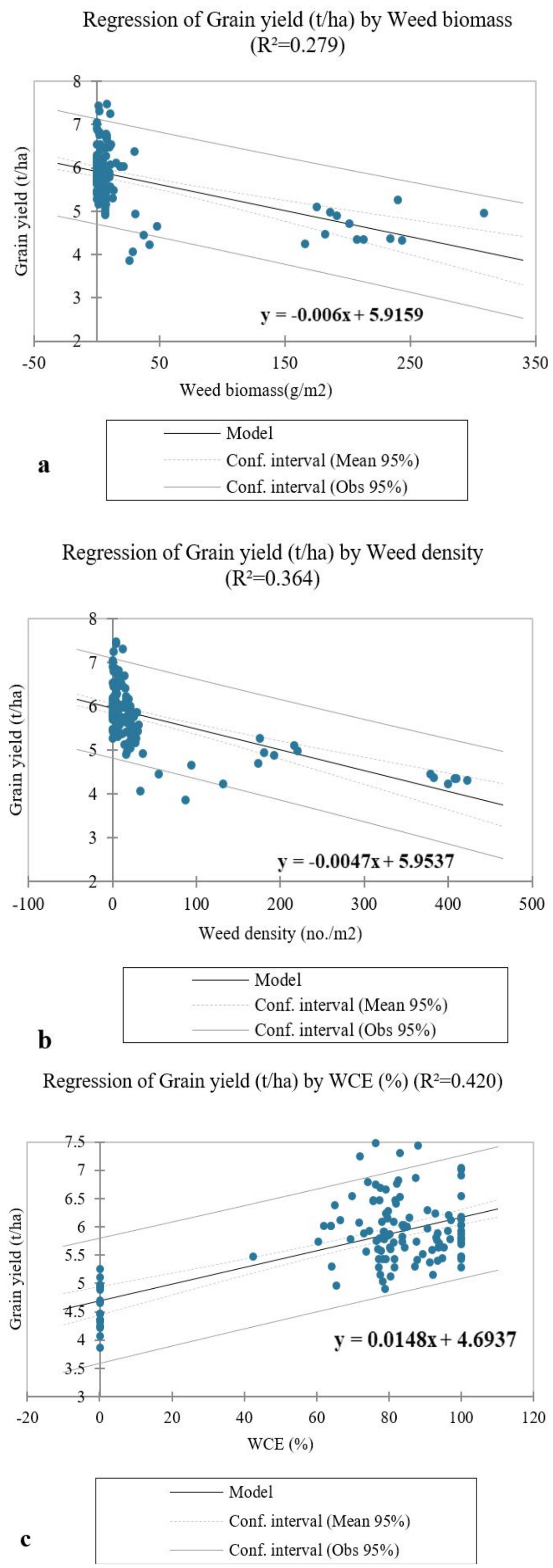

Figure 6. Relationship between wheat grain yield and weed parameters (pooled data of three seasons), (a) weed biomass, (b) weed density, (c) WCE

wheat was performed using Spearman's correlation coefficient (**Table 5**). The findings reveal critical insights into the relationships between yield determinants and weed attributes. Grain yield exhibited a highly significant and positive correlation with tillers/m² (0.983), grains per spike (0.963), and 1000-grain weight (0.987), indicating that these yield components are vital contributors to wheat productivity. These parameters enhance the plant's capacity to generate more grains and allocate resources efficiently, leading to higher yields. Similarly, harvest index showed a strong positive correlation with grain yield (0.948), reflecting its importance in determining the proportion of biological yield that is converted into economic yield.

Weed control efficiency (WCE) displayed a highly significant positive correlation with grain yield (0.969). This emphasizes that effective weed management is crucial for reducing competition between weeds and wheat, thus enhancing crop growth and productivity. On the contrary, weed density and the weeds biomass at 75 DAS showed highly significant and negative correlations with grain yield (-0.955 and -0.973, respectively). The negative correlations suggest that higher weed presence and biomass adversely impact yield attributes by competing for vital resources like nutrients, water, and light.

Conclusion

Application of $ZnSO_4$ (0.5%) with urea (2.5%) was found compatible when tank mixed with different post-emergence herbicides recommended for management for broad-leaved weeds. This combination resulted in a 4.7 % increase in wheat grain yield. Among different herbicides, metsulfuron + carfentrazone (RM) 24 g/ha recorded highest yield (6.06 t/ha) and achieved the maximum net returns (Rs. 85,907/ha) with a B: C ratio of 2.78 over three seasons. To enhance weed control efficiency, maximize yield, and improve economic returns, the co-application of zinc sulphate and urea with post-emergence herbicides is recommended. This integrated approach offers a practical and cost-effective strategy for efficient weed management in wheat cultivation.

REFERENCES

Anonymous. 2022a. FAOSTAT. Area, production and productivity of wheat in world (2022). Accessed on 20.12.2024 through link https://www.fao.org/faostat/en/#data/QCL.

Anonymous. 2022b. Agricultural Statistics at a Glance 2022. Department of Agriculture & Farmers Welfare, Government of India.

Daramola OS, MacDonald GE, Kanissery RG, and Devkota P. 2023. Effects of co-applied agrochemicals on herbicide performance: A review. *Crop Protection* **174**: 106396.

Gandini EMM, Costa ESP, dos Santos JB, Soares MA, Barroso GM, Corrêa JM, Carvalho AG and Zanuncio JC. 2020. Compatibility of pesticides and/or fertilizers in tank mixtures. *Journal of Cleaner Production* **268**: 122152. DOI: 10.1016/j.jclepro.2020.122152.

Gao X, Zhao Q, Yuan N, Li X, Zhang B, Zhu Y, Kong L, Wang Z and Xia H. 2024. Appropriate Soil fertilization or drone-based foliar Zn spraying can simultaneously improve yield and micronutrient (particularly for Zn) nutritional quality of wheat grains. *Agriculture* **14**(9): 1530.

Gazziero DLP. 2015. Misturas de agrotóxicos em tanque nas propriedades agrícolas do Brasil. *Planta Daninha* **33**(1): 83–92.

Gharde Y., Singh PK, Dubey RP and Gupta PK. 2018. Assessment of yield and economic losses in agriculture due to weeds in India. *Crop Protection* **107**: 12–18. doi:10.1016/j.cropro.2018.01.007

Godfray HCJ, Beddington JR, Crute IR, Haddad L, Lawrence L, Muir JF, Pretty J, Robinson S, Thomas SM and Toulmin C. 2010. Food Security: the challenge of feeding 9 billion people. *Science* **327:** 812–818.

Jitender, Amarjeet, Kumar P, Sandeep and Singh B. 2023. Effect of post-emergence herbicidal combinations tank mixed with zinc or/and iron sulphate on weed index and economics in wheat crop (*Triticum aestivum*). *Madras Agricultural Journal* **110**(1-3): 72–77.

Jitender, Amarjeet, Mal T, Akshit, Soni S, and Kumar P. 2022. Efficacy of herbicidal combinations tank mixed with zinc and iron sulphate against weeds in wheat (*Triticum aestivum*). *Indian Journal of Ecology*, **49**(2): 417–423.

Jitender, Amarjeet, Todar-Mal, Kumar P, Sandeep, Singh C. 2021. Effect of post emergence herbicidal combinations tank mixed with zinc or/and iron sulphate on yield attributes and grain yield of wheat crop (*Triticum aestivum* L.). *Agricultural Mechanization in Asia, Africa and Latin America* **51**(1): 775–783.

Li BX, Liu Y Zhang, P Li XX, Pang XY, Zhao YH, Li H, Liu F, Lin J and Mu W. 2019. Selection of organosilicone surfactants for tank-mixed pesticides considering the balance between synergistic effects on pests and environmental risks. *Chemosphere* **217:** 591–598.

Machado MS, Ferreira LR, Pereira GAM, Goncalves VA and Paixao GP. 2017. Protective effect on eucalyptus plants and signal grass control with a tank mixture of glyphosate and liquid fertilizer. *Planta Daninha* **35**: 1–8. DOI: 10.1590/s0100-83582017350100079.

Malik RK and Singh S. 1995. Littleseed canarygrass (*Phalaris minor* Retz.) resistant to isoproturon in India. *Weed Technology* **9**: 419–425.

Maurya, DP, Singla A and Negi S. 2015. An overview of key pretreatment processes for biological conversion of lignocellulosic biomass to bioethanol. *Biotechnolgy* **5**(5): 597–609.

Nagora M, Shweta, Sewhag M, Chaudhary K, Kumar L, Kumar S and Anjeeta. 2023. Potential role of wheat varieties in semi-arid areas of India with diverse mulch materials. *Biological Forum – An International Journal* **15**(4): 293-300.

Nibhoria A, Kumar J, Singh B, Satyajeet, Dehinwal AK and Kumar M. 2021. Relative performance of different methods of weed management in pearl millet (*Pennisetum glaucum*). *Forage Research* **47**(3): 334–339.

Nibhoria A, Singh B, Kumar J, Soni JK, Dehinwal AK. 2022. Mechanized weed management in chickpea (*Cicer arietinum* L.). *Agricultural Mechanization in Asia, Africa and Latin America* **53**(1): 5317–5327.

Ram H, Singh B, Kaur M, Gupta N, Kaur J and Singh A. 2022. Combined use of foliar zinc fertilisation, thiamethoxam and propiconazole does not reduce their effectiveness for enriching zinc in wheat grains and controlling insects and disease. *Crop and Pasture Science* **73**(5): 427–436.

Sabeti P. 2015. Evaluation of the effect of micronutrients on herbicide mixture 2,4-D + MCPA, Bromoxynil + MCPA and Tribenoron-methyl efficacy in wheat (*Triticum aestivum*). *Biological Forum – An International Journal* **7**: 1855–1858.

Sheoran P, Grewal S, Kumari S and Goel S. 2021. Enhancement of growth and yield, leaching reduction in wheat (*Triticum aestivum)* using biogenic synthesized zinc oxide nanofertilizer. *Biocatalysis and Agricultural Biotechnology* **32**: 101938. doi: 10.1016/J.Bcab.2021.101938 .

Shukla AK, SK Behera, YS Shivay, Singh P and Singh AK. 2012. Micronutrient and field crop production in India: A review. *Indian Journal of Agronomy* **57**(3rd IAC Special Issue): 123–130.

Soni JK, Nibhoria A, Punia SS and Hota S. 2024. Assessment of herbicide resistance in *Phalaris minor* and managing clodinafop-resistance with alternative herbicides. *Indian Journal of Weed Science*, **56**(2): 142–150.

Soni JK, Nibhoria A, Punia SS, *et al*. 2023. Herbicide resistant *Phalaris minor* in India—history of evolution, present status and its management. *Phytoparasitica* **51**: 353–378. https://doi.org/10.1007/s12600-022-01039-6.

STAR, version 2.0.1 2014 Biometrics and Breeding Informatics, PBGB Division, International Rice Research Institute, Los Baños, Laguna.

Tahir M, Nadeem MA, Tanveer A, Ayub M, Hussain A, Naeem M and Javeed HMR. 2011. The effect of urea as adjuvant on herbicide effectiveness, yield and weeds of maize with full and reduced doses of herbicide. *Pakistan Journal of Life and Social Sciences* **9**(1): 45–51.

Upreti KK and Sharma M. 2016. Role of plant growth regulators in abiotic stress tolerance. In: Abiotic Stress Physiology of Horticultural Crops (NK Sriniwasa Rao *et al.* Eds.). Springer, New Delhi, pp 19-46.