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Enhancing productivity and profitability of spring maize (*Zea mays*) in Uttarakhand's Tarai region through effective weed management practices and irrigation scheduling

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ABSTRACT

A field experiment was conducted during the spring seasons of 2022 and 2023 at Norman E Borlaug Crop Research Centre, Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, Uttarakhand to enhance maize yield and profitability. The experiment was conducted a split-plot design (SPD) with two irrigation scheduling treatments, viz. irrigation applied at an IW/CPE ratio of 0.8 (I_1); and 1.2 (I_2) in main plot and 8 weed management treatments, viz. W_1, atrazine 1000 g/ha; W_2, tembotrione 120 g/ha; W_3, topramezone 25.2 g/ha; W_4, atrazine 1000 g/ha followed by hand-weeding at 35 DAS (days after sowing); W_5, atrazine 1000 g/ha followed by tembotrione 120 g/ha; W_6, atrazine 1000 g/ha followed by topramezone 25.2 g/ha; W_7, weed-free; and W_8, weedy check in sub-plots. Irrigation applied at IW/CPE ratio of 1.2 significantly improved the maize productivity and profitability, yielding higher net returns (₹66,206.9/ha) and grain yield (6.1 t/ha). Among the herbicidal treatments, atrazine 1000 g/ha followed by topramezone 25.2 g/ha recorded the highest weed control efficiency (80%) and maize grain yield (6.3 t/ha). The percentage net monetary return was in the following sequence: W_6 (100%) > W_7 (92.4%) > W_5 (91.8%) > W_4 (89.6%) > W_3 (81.5%) > W_2 (78.2%) > W_1 (67.6%) > W_8 (46.4%). The percentage gain in grain yield was recorded in the following sequence: W_7 (100%) > W_6 (91.4%) > W_5 (87.4%) > W_4 (86.4%) > W_3 (84.1%) > W_2 (81.1%) > W_1 (71.5%) > W_8 (52.5%). In conclusion, optimizing irrigation to IW/CPE ratio of 1.2 and employing weed management practice atrazine (1000 g/ha) followed by topramezone (25.2 g/ha) application, can significantly enhance spring maize yield, weed control efficiency and economic returns in Uttarakhand's Tarai region.

Keywords: Atrazine, IW/CPE ratio, Maize, Tembotrione, Topramezone, Weed

Globally, maize (*Zea mays* L.) is the third most significant cereal crop, known for its high productivity and adaptability. In India, maize follows rice and wheat as a major cereal, covering 9.89 million hectares and yielding 31.65 million tonnes, contributing about 9% to the national food supply (IIMR 2021). However, maize production faces challenges, including annual yield losses of 25–30% due to drought and waterlogging (Zaidi *et al.* 2010). India's maize yields are below the global average, impacted by various biotic and abiotic stresses (Yadav *et al.* 2016). Understanding the impact of climate change on maize is vital, as global demand is projected to double by 2050 (Tilman *et al.* 2011). As a C_4 plant, maize has complex responses to environmental stress, which can be either reversible (elastic) or irreversible (plastic) (Salika and Riffat 2021). Changing climatic conditions increase yield variability, highlighting the need to refine agricultural practices.

Optimizing irrigation by aligning it with crop needs can improve maize grain yield by reducing water loss and matching irrigation with evapotranspiration levels (Kumar *et al.* 2024). This is particularly beneficial for spring-planted maize, which often faces moisture limitations, affecting crop performance and herbicide efficacy. Weed competition also poses a significant challenge, as maize's slow initial growth and wide spacing make it vulnerable to weeds, which can cause yield losses of 28–100% (Dass *et al.* 2012). Manual weeding is labour-intensive and often impractical, while biological methods have limited success (Rao and Chauhan 2015). Sequential herbicide application strategies involving pre-emergent and post-emergent herbicides have been recommended to suppress weed growth during critical maize stages (Rao and Chauhan 2015, Shukla *et al.* 2023). Therefore, the present study aimed to sustain maize productivity by optimizing irrigation and weed management strategies. The findings offer valuable insights for refining

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agricultural practices to meet the growing demand for maize amid changing climate conditions.

MATERIALS AND METHODS

The field experiment was conducted during the spring seasons of 2022 and 2023 at Norman E Borlaug Crop Research Centre, Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, Uttarakhand. Soil of the experimental field was sandy loam, neutral (*p*H 6.75), high in organic carbon content (0.72%), available nitrogen (282.1 kg/ha), phosphorus (25 kg/ha) and potassium (184.0 kg/ha). The mean maximum temperatures were 34.6°C and 33.6°C, while the mean minimum temperatures were 21.4°C and 17.5°C during 2022 and 2023, respectively. The bulk density and infiltration rate were 1.49 g/cc and 6.1 mm/h, respectively. The moisture content at the field capacity and permanent wilting point were 18.7% and 6.8% (gravimetric water content), respectively. The experiment was conducted in a split-plot design (SPD) comprised of two irrigation scheduling treatments, viz. irrigation applied at an IW/CPE ratio of 0.8 (I_1); and 1.2 (I_2) in main plot and 8 weed management treatments, viz. W_1, atrazine 1000 g/ha; W_2, tembotrione 120 g/ha; W_3, topramezone 25.2 g/ha; W_4, atrazine 1000 g/ha followed by hand-weeding at 35 DAS (days after sowing); W_5, atrazine 25.2 g/ha followed by tembotrione 120 g/ha; W_6, atrazine 1000 g/ha followed by topramezone 25.2 g/ha; W_7, weed-free; and W_8, weedy check in sub-plot, replicated thrice. Spring maize cv. P-1899 was sown on 16th February and harvested on 19th June during 2022 while during 2023, it was sown on 28th February and harvested on 23rd June respectively at spacing of 60 cm × 20 cm with seed rate of 20 kg/ha. Grain moisture was determined using a grain moisture meter, and the grain yields of maize were adjusted to 14% moisture content. Crop was fertilized with a dose of 120:26.2:33.33 N, P and K kg/ha. Daily pan evaporation and rainfall data were collected from the meteorological observatory located at the research farm of Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, to calculate the CPE values. A total of 74.5 mm of rainfall was received during the 2022 maize crop season, while 225.6 mm of rainfall was received during the 2023 maize crop season, along with 486.4 mm and 668.4 mm of pan evaporation during the respective years. Pre-emergence (PE) application of herbicides was done using a knapsack sprayer (flat-fan nozzle with triple boom) with 600 litres/ha of water at one day after sowing, whereas post-emergence (PoE) application was done using a knapsack sprayer (flat-fan nozzle) with 500 litre/ha of water at 25 DAS. Under the weed-free treatment, manual weeding was performed five times to control weeds. Weed density was recorded at 30 DAS and 45 DAS using a quadrat of 50 cm × 50 cm (0.25 m^2) size from the centre of the plot. The entire weeds inside the quadrat were uprooted, cut close to the transition of root and shoot in each plot, and then shade dried for 2–3 days. Afterward, they were dried in a hot air oven at 65±5°C until a constant weight was achieved for dry matter accumulation (biomass). The dried samples were weighed and expressed as biomass (g/m^2). The data on weeds, including weed density and their dry weight, were normalized by square root transformation with an additional factor of 0.5. Weed control efficiency (WCE) was calculated using the formula suggested by Mani *et al.* (1973). Data on growth, yield, and economics were statistically analysed as per standard procedures (Gomez and Gomez 1984).

RESULTS AND DISCUSSION

Weed flora: Among the weeds; grasses and sedges weeds were dominant in the experimental site as compared to the broad-leaf weeds. *Digitaria sanguinalis* (L.), *Sorghum halepense* (L.) and *Eleusine indica* (L.) were the major grassy weeds and *Cyperus rotundus* (L.) was the dominant sedge weed. *Alternanthera sessilis* (L.) was the major broad-leaf weed species during both the years of study.

Weed density: Different weed management options significantly affected weed density in maize at 30 and 45 DAS. Atrazine 1000 g/ha PE followed by (*fb*) topramezone 25.2 g/ha PoE had the lowest weed density at 30 DAS, comparable to atrazine 1000 g/ha PE *fb* tembotrione 120 g/ha PoE (Table 1). Tembotrione 120 g/ha PoE and topramezone 25.2 g/ha PoE applied alone at 25 DAS were the next best treatments. Consecutive applications of atrazine 1000 g/ha PE *fb* topramezone 25.2 g/ha PoE at 25 DAS reduced the densities of *Digitaria sanguinalis* by 78%, *Sorghum halepense* by 52.8%, *Eleusine indica* by 74%, *Cyperus rotundus* by 53.5%, and *Alternanthera sessilis* by 84.1% compared to the weedy check.

At 45 DAS, the lowest overall weed density (82.4%) was observed with atrazine 1000 g/ha PE *fb* hand-weeding at 35 DAS. This was similar to atrazine 1000 g/ha PE *fb* topramezone 25.2 g/ha and tembotrione 120 g/ha PoE. Compared to the weedy check, atrazine 1000 g/ha PE *fb* hand-weeding at 35 DAS reduced the density of *Digitaria sanguinalis* by 90.7%, *Sorghum halepense* by 78.4%, *Eleusine indica* by 82.8%, *Cyperus rotundus* by 73.9%, and *Alternanthera sessilis* by 90.2% (Table 1). Initially managed by atrazine, subsequent weed flushes were controlled by topramezone and tembotrione applications. This sequential herbicide application targets a broad spectrum of weeds, enhancing control through different modes of action. The co-application of HPPD- and PS II-inhibitors enhances weed control by increasing the PS II-inhibitor's binding efficiency to the D1 protein and elevating ROS levels due to the shortage of α-tocopherols, β-tocopherols, plastoquinone, and carotenoids, which normally quench ROS. Consequently, this process leads to the photooxidative destruction of chlorophyll and photosynthetic membranes, resulting in the characteristic white bleaching or chlorosis of young plant tissue followed by necrosis (Willemse *et al.* 2021). Hand-weeding at 35 DAS further reduced crop-weed competition during crucial growth stages.

Weed biomass and weed control efficiency: Pooled data analysis revealed that despite increased herbicide efficiency in 2022, no substantial variation in weed biomass

Table 1 Effect of irrigation levels and weed management practices on weed density in spring-planted maize (pooled mean)

Treatment	*Digitaria sanguinalis*		*Sorghum halepense*		*Eleusine indica*		*Cyperus rotundus*		*Alternanthera sessilis*		Total weed density	
	30 DAS	45 DAS	30 DAS	45 DAS	30 DAS	45 DAS	30 DAS	45 DAS	30 DAS	45 DAS	30 DAS	45 DAS
Irrigation level												
I_1	2.8 (8.6)	3.4 (14.6)	2.8 (8)	3.5 (13.4)	2.5 (6.6)	3.0 (10)	4.8 (25.2)	6.6 (50.4)	3.1 (10.1)	3.3 (13.2)	7.7 (67.2)	9.6 (112.2)
I_2	2.7 (8.3)	3.3 (13.8)	2.6 (7.1)	3.1 (10.6)	2.4 (5.8)	2.9 (9.6)	4.9 (26.5)	6.6 (49.2)	2.9 (9.5)	3.1 (12.4)	7.5 (64.7)	9.3 (105.2)
SEm±	0.01	0.13	0.03	0.04	0.03	0.04	0.04	0.09	0.03	0.04	0.03	0.09
LSD (*P*=0.05)	NS	NS	NS	0.23	NS	NS	NS	NS	NS	NS	NS	NS
Weed management												
W_1	3.1 (8.9)	4.5 (19.9)	3.3 (10.4)	4.3 (18.4)	2.7 (6.6)	3.8 (13.8)	5.7 (32.2)	9.1 (82.7)	3.5 (12)	4.6 (20.5)	9.1 (82.7)	12.4 (155.0)
W_2	2.7 (6.7)	3.3 (10.6)	2.8 (7.9)	3.8 (13.8)	2.4 (5.1)	3.1 (9.1)	5.2 (26.8)	7.4 (54.4)	3 (8.5)	3.1 (9.2)	7.9 (61.5)	10.3 (106.5)
W_3	2.6 (6.4)	3.2 (9.9)	2.8 (7.4)	3.6 (12.7)	2.3 (4.9)	3.1 (8.8)	5.2 (26.3)	7.3 (52.5)	2.9 (7.7)	3.0 (8.5)	7.7 (59.3)	10.1 (101.5)
W_4	3.1 (9.3)	2.4 (5.1)	3.3 (10.5)	2.5 (5.8)	2.7 (6.9)	2.4 (5.3)	5.8 (33.3)	5.3 (27.6)	3.6 (12.5)	2.3 (4.7)	9.2 (84.3)	7.4 (54.0)
W_5	2.5 (5.8)	2.7 (6.9)	2.6 (6.4)	3.1 (9.4)	2.3 (4.7)	2.6 (6)	4.7 (21.8)	6.2 (38.3)	2.3 (5)	2.6 (6.1)	7.1 (49.8)	8.7 (74.3)
W_6	2.4 (5.5)	2.6 (6.5)	2.5 (5.8)	3.1 (8.9)	2.2 (4.5)	2.5 (5.6)	4.7 (21.2)	6.1 (37)	2.2 (4.5)	2.5 (5.6)	6.9 (47.0)	8.5 (71.7)
W_7	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)
W_8	5.0 (25)	7.4 (54.9)	3.6 (12.3)	5.2 (26.9)	4.2 (17.3)	5.5 (30.1)	6.8 (45.6)	10.8 (105.9)	5.3 (28.3)	7 (47.9)	12 (142.5)	17.5 (306.5)
SEm±	0.03	0.05	0.04	0.07	0.04	0.03	0.11	0.16	0.04	0.04	0.08	0.24
LSD (*P*=0.05)	0.08	0.14	0.13	0.20	0.12	0.10	0.31	0.47	0.12	0.12	0.23	0.69

DAS, Days after sowing. Treatment details are given under Materials and Methods.

was observed at 30 and 45 DAS. In spring 2023, heavy rainfall likely reduced soil-applied herbicide efficacy due to leaching and runoff, and foliar-applied herbicides were washed off or diluted, leading to increased weed biomass (Table 2). In 2022, well-distributed rainfall and irrigation (IW: CPE 1.2) improved herbicide absorption, translocation, and metabolism. Corroborating these data, Jain *et al.* (2014) found that herbicide effectiveness in reducing weed density and dry weight was lower under water deficit conditions (80% ASM) compared to well-watered conditions (100% ASM).

At 30 and 45 DAS, the highest total weed dry matter under weedy check and the lowest under weed-free treatment were noted (Table 2). A significantly decreased weed dry matter was seen for atrazine 1000 g/ha PE followed by (*fb*) topramezone 25.2 g/ha PoE among the herbicide treatments in 30 DAS; this result was statistically comparable to atrazine 1000 g/ha PE *fb* tembotrione 120 g/ha PoE, whereas at 45 DAS, atrazine 1000 g/ha PE *fb* hand weeding at 35 DAS resulted in lowest weed biomass. Although the pre-emergence application of atrazine was ineffective 45 days after sowing, hand-weeding at 35 DAS and applications of post-emergence herbicides sequentially reduced the overall biomass of weeds at 30 and 45 DAS. Weed control efficiency did not differ due to varying irrigation levels during both the years (Table 3). Among the herbicidal treatments, weed control efficiency at 45 DAS was significantly higher under atrazine 1000 g/ha PE *fb* hand-weeding at 35 DAS (84.7%) and it was closely followed by atrazine 1000 g/ha PE *fb* topramezone 25.2 g/ha PoE (80%) and atrazine 1000 g/ha PE *fb* tembotrione 120 g/ha PoE (77.9%) (Table 3). This effectiveness was also documented by Triveni *et al.* (2017) and Shukla *et al.* (2023).

Growth: With irrigation at IW/CPE 1.2, plant height (153.2 cm), cob length (19.3 cm), and cob diameter (16.1 cm) were significantly higher than IW/CPE 0.8 (Table 3). The higher irrigation frequency ensures consistent soil moisture, extending the growing period, enhancing vegetative growth, root development, and nutrient uptake. This leads to taller plants, increased cob length, and diameter, supported by efficient gas exchange and hormone synthesis. These results align with the findings of Sampathkumar *et al.* (2014), Dutta *et al.* (2015), Kaur and Vashist (2016) and Ahirwar *et al.* (2023). Conversely, moisture stress at IW/CPE 0.8

Table 2 Effect of irrigation levels and weed management practices on weed dry weight in spring-planted maize (pooled mean)

Treatment	*Digitaria sanguinalis*		*Sorghum halepense*		*Eleusine indica*		*Cyperus rotundus*		*Alternanthera sessilis*		Total weed density	
	30 DAS	45 DAS	30 DAS	45 DAS	30 DAS	45 DAS	30 DAS	45 DAS	30 DAS	45 DAS	30 DAS	45 DAS
Irrigation level												
I_1	2.6 (7.9)	4.7 (26.7)	2.4 (5.8)	3.5 (13.7)	1.8 (3.3)	2.6 (7.2)	2.6 (7.1)	3.5 (15.1)	2.8 (9.1)	4.5 (24.2)	5.8 (40.1)	8.8 (97.4)
I_2	2.5 (7.4)	4.7 (27)	2.3 (5.5)	3.4 (13.3)	1.7 (2.9)	2.4 (6.6)	2.6 (7.3)	3.4 (14.2)	2.8 (9.2)	4.3 (22.2)	5.7 (38.6)	8.7 (95.7)
SEm±	0.02	0.02	0.03	0.02	0.01	0.02	0.01	0.03	0.03	0.05	0.05	0.05
LSD (*P*=0.05)	NS	NS	NS	NS	0.06	0.10	NS	NS	NS	NS	NS	NS
Weed management												
W_1	2.7 (7.0)	5.9 (34.8)	2.8 (7.3)	4.8 (22)	2.1 (4.0)	3.0 (8.5)	3 (8.4)	4.7 (21.4)	3.3 (10.1)	6 (35.3)	6.8 (45.4)	11.7 (137.4)
W_2	2.4 (5.5)	5.1 (25.2)	2.4 (5.2)	4.0 (15.5)	1.5 (1.7)	2.7 (6.9)	2.5 (5.7)	3.6 (12.5)	2.8 (7.1)	4.3 (18.2)	5.7 (31.6)	9.4 (87.9)
W_3	2.3 (4.7)	5.0 (24.8)	2.3 (5.0)	3.9 (14.8)	1.4 (1.4)	2.6 (6.2)	2.4 (5.3)	3.6 (12.1)	2.6 (6.4)	4 (15.7)	5.5 (30.0)	9.1 (82.8)
W_4	2.8 (7.2)	3.6 (12.2)	2.8 (7.4)	2.4 (5.5)	2.1 (4.0)	1.4 (1.6)	3 (8.4)	2.2 (4.5)	3.3 (10.2)	3.6 (12.7)	6.8 (45.3)	6.5 (42.3)
W_5	2.3 (4.9)	3.9 (15.0)	2.2 (4.3)	3.0 (8.5)	1.3 (1.1)	2.3 (5)	2.3 (4.8)	2.7 (7.0)	2.0 (3.5)	3.7 (13.2)	5 (24.4)	7.5 (55.5)
W_6	2.1 (4.1)	3.9 (14.8)	2.1 (3.8)	3 (8.2)	1.2 (1.0)	2.2 (4.5)	2.3 (4.6)	2.6 (6.5)	2.0 (3.3)	3.6 (12.8)	4.7 (21.9)	7.4 (53.7)
W_7	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)
W_8	5.3 (27.9)	9.4 (88.1)	3.6 (12.4)	5.8 (33.4)	3.5 (11.7)	4.8 (22.5)	4.6 (20.5)	7.3 (53.2)	5.8 (32.6)	8.8 (77.7)	10.8 (116)	17.7 (312.8)
SEm±	0.04	0.06	0.04	0.06	0.02	0.03	0.02	0.08	0.05	0.09	0.08	0.06
LSD (*P*=0.05)	0.12	0.18	0.10	0.18	0.05	0.09	0.07	0.22	0.15	0.25	0.23	0.19

DAS, Days after sowing. Treatment details are given under Materials and Methods.

inhibits growth, leading to shorter plants with reduced leaf area and stem diameter. Water-stressed plants show lower evapotranspiration and symptoms like leaf wilting and stunted growth, as noted by Kaur *et al.* (2021), reducing dry matter production and photosynthate translocation to grains.

Weed management treatments significantly enhanced maize growth and yield attributes compared to the weedy check (Table 3). Plant height (153.9 cm), cob length (19.2 cm) and cob diameter (15.5 cm) were highest under weed-free conditions, closely followed by atrazine 1000 g/ha PE *fb* topramezone 25.2 g/ha PoE and atrazine 1000 g/ha PE *fb* tembotrione 120 g/ha PoE. Effective season-long weed control was achieved by combining pre- and post-emergence herbicides with diverse modes of action, targeting weeds throughout the growing season. Atrazine prevents weed seed germination, reducing early weed pressure, while topramezone and tembotrione control emerged weeds, including those that survive atrazine application. Sequential herbicide application provides comprehensive weed control, reducing weed competition, increasing solar radiation penetration, and enhancing photosynthesis, which facilitates greater translocation of photosynthates from source to sink (Shekhar *et al.* 2014).

Interactions: Critical assessment of data revealed that interaction effect (I × W) between irrigation levels and weed management on grain yield was found to be significant (Supplementary Table 1). The grain yield recorded significantly highest in combination of atrazine 1000 g/ha *fb* topramezone 25.2 g/ha (6.3 t/ha) with irrigation scheduling at IW/CPE 1.2 over all other treatment combinations, which was statistically at par with atrazine 1000 g/ha *fb* tembotrione 120 g/ha (6.1 t/ha) under similar irrigation level. However, treatment combination at IW/CPE 0.8 intervals; atrazine 1000 g/ha *fb* tembotrione 120 g/ha (5.75 t/ha) coupled with IW/CPE 0.8 and atrazine 1000 g/ha *fb* topramezone 25.2 g/ha (5.74 t/ha) with IW/CPE 0.8 being at par with each other and found to be significantly higher over rest of treatment combinations.

Productivity: A notably greater yield of maize grain (6.1 t/ha) was obtained by applying irrigations at intervals of IW/CPE 1.2 over an irrigation level of IW/CPE 0.8 (Table 3). Based on two years pooled data, a similar trend in stover yield was seen for the two irrigation levels. The stover yield that was significantly highest (8 t/ha) was obtained when

Table 3 Effect of irrigation levels and weed management practices on growth, yield attributes and yield of spring planted maize (pooled mean)

Treatment	Plant height (cm)	Cob length (cm)	Cob diameter (cm)	Grain yield (t/ha)	Stover yield (t/ha)	Weed control efficiency (%)	Net returns ($\times 10^3$ ₹/ha)
Irrigation level							
I_1	136.5	16.5	13.9	5.27	7.3	67.2	49.78
I_2	153.2	19.3	16.1	6.04	8.0	68.4	66.21
SEm±	2.26	0.22	0.23	0.05	0.07	1.86	-
LSD (*P*=0.05)	8.41	0.84	0.81	0.17	0.27	NS	-
Weed management							
W_1	141.9	17.4	13.52	4.94	5.7	55.3	48.41
W_2	145.6	17.2	14.55	5.60	7.7	71.6	56.03
W_3	146.8	18.3	14.33	5.81	8.0	73.1	58.39
W_4	148.9	18.4	14.96	5.97	8.4	84.7	64.18
W_5	147.7	18.4	15.15	6.04	8.5	77.8	65.77
W_6	148.5	19.0	15.24	6.32	8.6	80	71.66
W_7	153.9	19.2	15.45	6.91	9.3	100	66.23
W_8	126	15.4	16.59	3.63	5.2	0	33.27
SEm±	3.05	1.16	0.36	0.12	0.13	1.51	-
LSD (*P*=0.05)	8.62	0.41	1.11	0.35	0.36	4.27	-

Treatment details are given under Materials and Methods.

irrigation was applied at an IW/CPE 1.2 level than IW/CPE 0.8. Higher rates of lipid peroxidation and ROS generation under water stress circumstances affected photosynthetic efficiency and limited maize growth (Hussain *et al.* 2023). This led to a reduction in yield attributing characteristics and ultimately a reduced yield in IW/CPE 0.8. Grain yield (6.9 t/ha) and stover yield (9.3 t/ha) were higher under weed-free treatment which was found to be statistically at par with atrazine 1000 g/ha PE *fb* topramezone 25.2 g/ha PoE and atrazine 1000 g/ha PE *fb* tembotrione 120 g/ha PoE but was significantly higher than weedy check plot (Table 3). The reduction of the weed seed bank and subsequent pressure, coupled with the disruption of weed growth processes and increased weed mortality, significantly reduces crop-weed competition during critical growth stages. This allows the maize crop to grow more vigorously, directing more resources toward biomass accumulation, development and yield production. Reddy *et al.* (2022) also observed that yields under weed-free conditions and sequential application of pre- and post-emergence herbicides were comparable.

Profitability: Higher irrigation at IW/CPE 1.2 significantly increased net monetary returns (₹66,206.9/ha) compared to IW/CPE 0.8 (₹49,779.7/ha), despite the higher costs (Table 3). Atrazine 1000 g/ha PE followed by (*fb*) topramezone 25.2 g/ha PoE yielded the highest net return (₹71,660.6/ha) due to effective weed control and increased crop yield, outperforming other treatments (Table 3). The next best treatments were atrazine 1000 g/ha PE *fb* tembotrione 120 g/ha PoE and weed-free, which were statistically at par with each other. The weedy check plot had the lowest net return due to high weed pressure.

The two-year study concluded that the optimal strategy for effective weed control, higher maize productivity, and maximum net returns in the Tarai region of Uttarakhand is a pre-emergence application of atrazine 1000 g/ha followed by post-emergence topramezone 25.2 g/ha, combined with irrigation at IW/CPE 1.2. Integrating resistant cultivars with optimized weed management and irrigation practices enhances maize resilience to changing environmental conditions, ensuring sustainable yields and economic viability.

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