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RESEARCH ARTICLE

Evaluating the effect of controlled-release atrazine formulations on weed suppression, crop growth and yield in Maize (*Zea Mays* L.)

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Abstract

Weed infestations significantly threaten agricultural productivity, particularly in maize cultivation. To enhance weed control efficiency through a sustainable approach, it was aimed to design a moisture-triggered herbicide release system using biodegradable polymers. Atrazine was used as a model herbicide in the protocol developed. The pot culture and field experiments were conducted, including nine treatments with three replications in a Completely Randomized Design (CRD) and Randomized Block Design (RBD) respectively. The treatments comprised three atrazine-loaded hydrogel formulations (A, B and C) at rates of 1.5 and 1.2 kg a.i. ha^{-1}(active ingredient per hectare), a commercial atrazine formulation, a weed-free check and an absolute control. The pot and field validation results revealed that atrazine formulations (C) at both rates exhibited higher weed control efficiency due to increased active ingredient concentration. The higher values of all growth and yield parameters were reported with application of formulation (C) @ 1.5 kg a.i. ha^{-1}. The higher grain and stover yields of 6444 and 14397 kg ha^{-1}, was reported with the application of formulation mix (C) @ 1.5 kg a.i. ha^{-1} among the herbicidal treatments. In contrast, the application of commercial atrazine resulted in lower weed control efficiency, growth and yield, likely attributed to leaching potential and pre-emergence-only application. The study highlights the potential benefits of atrazine-loaded formulations for efficient weed control in maize cultivation, contributing to sustainable agricultural practices and enhanced crop productivity.

Keywords

biodegradable polymers; entrapped atrazine; maize; weed control efficiency; yield

Introduction

Weed infestations have consistently threatened agricultural productivity, causing substantial economic loss of nearly $33 billion (1) and posing significant challenges to farmers across the globe (2). Among the various crops affected by weeds, maize (*Zea mays* L.) stands as a crucial staple crop, sustaining millions of people and serving as a fundamental source of animal feed and industrial raw material (3). The relentless competition between weeds and maize for vital resources such as water, nutrients and sunlight hampers crop growth and reduces overall yields, making effective weed management an indispensable aspect of modern agriculture (4).

Traditionally, farmers have relied on labour-intensive and time-consuming methods such as manual weeding and mechanical cultivation to control weed growth in maize fields (5). However, these conventional approaches often fall short in of managing the ever-increasing weed pressure efficiently. In recent decades, the use of herbicides has emerged as a powerful tool accounting for about 16 % in India and about 47.5 % worldwide to combat weed proliferation and enhance crop productivity (6). Among these chemical solutions, atrazine, a widely used triazine class herbicide has gained widespread popularity due to its broad-spectrum weed control capabilities (7).

Atrazine's effectiveness lies in its ability to inhibit photosynthesis in susceptible plants, leading to their eventual demise (8). Despite its proven efficacy, conventional atrazine application also raises concerns related to environmental contamination (9) and the development of herbicide-resistant weed species. These challenges highlight the need for innovative and sustainable weed control strategies to ensure long-term agricultural sustainability while safe guarding environmental health.

In response to these concerns, researchers and agricultural scientists have begun exploring alternative approaches, that have paved the way for us in the development of herbicide-loaded formulations, to enhance weed control efficiency in agricultural crops. These formulations aim to optimize herbicide delivery, ensuring better weed suppression while minimizing off-target effects and environmental impacts.

Primary aim of this research is to investigate and evaluate the potential benefits of atrazine-loaded formulations in improving weed control efficiency in maize fields thereby achieving improved crop growth and yield. By comparing the performance of these formulations to conventional atrazine application, we seek to determine whether they offer advantages in terms of weed control effectiveness, reduced environmental impact and overall crop yield enhancement.

With the ever-increasing global population and the mounting pressure to enhance food production (10), maize plays a vital role in ensuring food security (11). However, weed infestations hinder the realization of its full yield potential, making it imperative to develop effective and eco-friendly weed management strategies (12). Present research on atrazine-loaded formulations shows promise as a viable remedy for these issues, providing the possibility of increasing maize yields while reducing harmful environmental effects.

The effectiveness of atrazine-loaded formulations in weed management is evaluated in this paper through pot and field validation trials. We intend to clarify the potential of these formulations as an effective and sustainable method of weed control in maize agriculture through the results of our study. We hope to assist agricultural practices that advance global food security and environmental sustainability by advancing knowledge about cutting-edge weed control methods.

Materials and Methods

Designing of moisture triggered controlled release system

A laboratory experiment was carried out by us at Department of Agronomy, Tamil Nadu Agricultural University, Coimbatore, India to design moisture triggered controlled release system. The atrazine-loaded guar gum and nanocellulose hydrogel composite was prepared and the established protocol was submitted to the Indian Patenting Office and was published in the Indian patent search website with application number 202341057368 (13). About twenty-five such formulation mixes with different concentrations of various components used in the protocol were prepared by the crosslinking method, from which the best forming three formulation mixes were chosen for the pot and field validation trails based on the screening trials for weed control efficiency and other characterization results. The three formulation mixes were designated as Formulation mix A, B and C, respectively in the present experiment. The concentration of atrazine in the three formulation mixes were 8, 7 and 21 % respectively. The commercial atrazine used in the experiment was Atrataf 50 % WP.

Pot culture experiment

A pot culture experiment was conducted to assess the phytotoxicity of encapsulated formulation on plant growth and its effectiveness in controlling weeds in maize. The experiment consisted of nine different treatments (as mentioned in main field experiment section), each replicated three times and was arranged in CRD. In each pot, five maize seeds of variety COH (M) 6 were sown and the treatments were imposed on the same day of sowing, followed by the initial watering of the pots four days after sowing and treatment application.

Main field experiment

Field experiment was conducted at Eastern Block Farm, during summer season of 2023, with the maize variety COH (M) 6. The crop was sown on 20th March 2023 with a spacing of 60 cm×20 cm. The treatments included three atrazine-loaded hydrogel formulations labelled as A, B and C, each applied at rates of 1.5 and 1.2 kilograms of active ingredient per hectare, a commercial atrazine formulation, a weed-free check and absolute control (the treatments employed were same for both pot culture and field experiments). All the crop management practices, excluding weed management strategies, were implemented based on the guidelines outlined in the Crop Production Guide (2020) from Tamil Nadu Agricultural University, Coimbatore (14). Under weed management practices, different doses of atrazine-loaded hydrogel formulations were utilized in a pre-emergence application, following the prescribed treatment schedule. The encapsulated hydrogel formulations were mixed with sand at a rate of 50 kgha^{-1} and evenly spread across the respective plots. Similarly, a commercial formulation was applied as a pre-emergence treatment using a knapsack sprayer, with a spray volume of 500 liters per hectare. On the day of treatment application, the soil was kept dry and irrigation was initiated one week later to evaluate the effectiveness of the encapsulated formulations in minimizing volatilization losses. Regular weeding was conducted to maintain a weed-free environment in the designated plots. Unweeded and undisturbed plots were maintained as control groups. After the critical period of crop-weed competition, the entire plot was manually weeded once.

Weed parameters

Weed density : The observations on weed density were recorded at 15, 30 and 45 days after initial irrigation (DAI). For each observation, a quadrat measuring 0.25 m^2 (0.5 m × 0.5m) was randomly placed at four locations within each plot to record the weed density and expressed in number m^2 (15).

Weed control efficiency : Weed control efficiency refers to how effective a weed management strategy or treatment in reducing or suppressing weed populations. Weed control efficiency usually compares different treatments of weed control based on their effect on weed density. It was calculated by the formula given below and is expressed in percentage (16).

Weed control efficiency (%) =

$$\frac{(\text{weed density in control plot- weed density in treated plot})}{(\text{weed density in control plot})} \times 100$$

Weed index : Weed index is a measure of the increase in crop yield resulting from weed control, expressed as a percentage of the yield obtained from a plot that is completely free of weeds. This calculation is done using the formula (17),

Weed index =

$$\frac{\text{Crop yield from weed free plot (kg ha}^{-1}\text{) - crop yield in treated plot (kg ha}^{-1}\text{)}}{\text{Crop yield in weed free plot (kg ha}^{-1}\text{)}}$$

Maize growth parameters : The maize plant height, number of functional leaves, leaf area index, ear height and dry matter per plant were recorded. All the growth parameters, i.e., plant height, number of functional leaves, Leaf Area Index (LAI) and dry matter per plant were recorded at 30^{th}, 60^{th} and 90^{th} days after first irrigation, whereas ear height was recorded at the maturity stage of maize. The plant height was measured from the base of the plant i.e., ground level to the base of the last fully opened leaf up to the tassel emergence and from ground level to the base of the tassel after emergence of the five randomly selected plants in each net plot. The number of green leaves per plant provides insight into the overall vigor of the plant. To assess this, the count of fully opened green leaves was conducted on five randomly selected plants. The average number of fully opened green leaves was recorded for each observation period. For leaf area measurements, the fourth leaf counting from the top was selected. LAI was calculated using the given formula (18).

$$\text{LAI} = \frac{\text{Leaf length X Breadth X 0.75 X No. of leaves}}{\text{Area occupied by the plant}}$$

Ear height : During the maturity stage, measurements were taken by recording the distance from the soil surface to the node that carried the uppermost ear. This measurement was carried out on five selected plants and the average value was calculated based on these observations.

Dry matter per plant : To determine the dry matter per plant, one representative plant sample was uprooted from each gross plot. The plant material was then chopped into smaller pieces and subjected to air drying initially. Subsequently, the samples were placed in an oven at 60 ± 2 °C until a constant weight was achieved. After weighing the material, the dry matter of each plant was recorded and expressed in $kgha^{-1}$.

Yield attributes and yield : Five observational plants from each net plot were used to record and report the yield-contributing characteristics on a periodic basis. By determining the average value, the number of ears on observational plants was counted and expressed as the number of ears per plant. For each treatment, the length of the ear from base to tip was measured and expressed in centimeters. The total number of grain rows in each ear was determined by counting the rows from five observed plants. The average number of grain rows was calculated for each ear based on these observations. A random sample of hundred kernels from the produce of each treatment was taken by quadrant method for recording hundred grain weight per treatment. The plants were harvested and sun dried until their weight remained constant. Each net plot's dry biomass weight was measured.

Grain yield ($kgha^{-1}$) : Ears were exposed to the sun to dry after harvest and a hand maize sheller was used to remove the grains. Grain yield per hectare was computed using grain weight per net plot.

Results

Assessment of phytotoxicity of atrazine formulation in pot culture assay

No phytotoxicity symptoms were observed from both commercial and atrazine-loaded hydrogel formulation applied pots. The pots without any weed control measures had the highest weed density with 139.62 weeds per pot. The lowest weed density of 0.71 weeds per pot was achieved in pots that were kept weed-free. Applying a pre-emergence atrazine formulation at a rate of 1.5 kg a.i. ha^{-1} resulted in a weed count of 5.05 weeds per pot, which was similar to the application of the same formulation at a lower rate of 1.2 kg a.i. ha^{-1}. Using a commercial atrazine product led to a weed count of 9.95 weeds per pot (Table 1).

A higher weed control efficiency of 100 % was observed from the weed free check pots. Among the herbicide treatments, a higher weed control efficiency of 81.95 % was noted with pre-emergence application of atrazine formulation (C) 1.5 kg a.i. ha^{-1} followed by same formulation @ 1.2 kg a.i. ha^{-1} (74.31 %). Commercial formulation applied pots have registered a weed control efficiency of 29.32 %. Absolute control pots have registered the lowest weed control efficiency (Table 1).

Effect of atrazine formulations on weed control under field experiment

The lower number of total weed counts (9.5 m^{-2}) was observed

Table 1. Effect of different formulations and rates of atrazine-loaded guar gum and nanocellulose hydrogel composite on weed density and weed control efficiency in pot culture experiment

Treatments	Weed density (No. pot^{-1})	Weed control efficiency (%)
T$_1$: Pre-emergence application of atrazine formulation (A) @ 1.5 kg a.i.ha^{-1}	6.15 (37.46)	72.94
T$_2$: Pre-emergence application of atrazine formulation (A) @ 1.2 kg a.i.ha^{-1}	9.15 (83.33)	40.37
T$_3$: Pre-emergence application of atrazine formulation (B) @ 1.5 kg a.i.ha^{-1}	8.40 (70.24)	49.26
T$_4$: Pre-emergence application of atrazine formulation (B) @ 1.2 kg a.i.ha^{-1}	9.53 (90.48)	34.81
T$_5$: Pre-emergence application of atrazine formulation (C) @ 1.5 kg a.i.ha^{-1}	5.05 (25.04)	81.95
T$_6$: Pre-emergence application of atrazine formulation (C) @ 1.2 kg a.i.ha^{-1}	6.03 (35.94)	74.31
T$_7$: Pre-emergence application of commercial atrazine @ 1.5 kg a.i.ha^{-1}	9.95 (98.67)	29.32
T$_8$: Weed free check	0.71 (0.00)	100.00
T$_9$: Absolute control	11.83 (139.62)	0.00
SEd	0.35	-
CD (P=0.05)	1.03	-

** Original data subjected to square root transformation ($\sqrt{x + 0.5}$) The data given in the parenthesis are the actual mean values*

with the application of atrazine formulation (A) at the rate of 1.5 kg a.i. ha^{-1} followed by the treatment T$_8$ (0.71 m^{-2}). The treatments T$_1$ and T$_3$ have been found to be statistically on par with respect to weed count on 15 days of first irrigation. The next lowest total weed counts were observed with the treatments T$_2$ and T$_4$ (11.1 and 11.9 No. m^{-2} respectively). Pre-emergence spray of commercial atrazine had a total weed count of 12.4 no. m^{-2} (Table 2).

A similar trend on total weed density was observed at 30 days of first irrigation as that of weed counts recorded during 15 days after first irrigation. Among the other herbicidal treatments, the lowest weed density of 9.3 no. m^{-2} was observed with the application of atrazine formulation (C) @ 1.5 kg a.i. ha^{-1}. Control plots without any measures for the removal of weeds were found to have the highest weed density of 16.9 Nos. m^{-2}, followed with pre-emergence application of commercial atrazine @ 1.5 kg a.i. ha^{-1} (12 Nos. m^{-2}).

The lowest total weed count of 8.9 Nos. m^{-2} was registered in plots with pre-emergence application of formulation mix No C @ 1.5 kg a.i.ha^{-1} excluding weed-free check plots. A significantly highest weed population was observed with pre-emergence application of commercial atrazine (T$_7$) @ 12.6 Nos. m^{-2} (Table 2).

The efficiency of weed control was higher at 15 days after initial irrigation compared to 30 and 45 days after initial irrigation (Fig. 1). The pre-emergence application of atrazine formulation (A) @ 1.5 kg a.i. ha^{-1} showed the highest weed control efficiency of 80.12 % The pre-emergence application of atrazine formulation (C) at 1.5 kg a.i. ha^{-1} demonstrated highest weed control efficiency of 68 % and 64 % respectively during 30 and 45 days of first irrigation.

The reduction of grain yield of plots with different herbicidal treatments are compared to that of weed-free plot was compared to assessing the efficacy of herbicidal treatments. The extent of yield reduction caused by weeds was compared to that of weed free plots to assess the weed control efficiency of herbicides. Weed index acts as an indicator of effectiveness of different treatments in controlling weeds. Pre-

Table 2. Effect of different formulations and rates of atrazine-loaded guar gum and nanocellulose hydrogel composite on total weed density in maize field experiment

Treatments	Total weed density (m^{-2})		
	15 DAI	**30 DAI**	**45 DAI**
T$_1$: Pre-emergence application of atrazine formulation (A) @ 1.5 kg a.i.ha^{-1}	9.52 (91.67)	10.91 (120. 67)	10. 24 (104.67)
T$_2$: Pre-emergence application of atrazine formulation (A) @ 1.2 kg a.i.ha^{-1}	11.12 (127. 00)	11.44 (131. 67)	11. 64 (135.33)
T$_3$: Pre-emergence application of atrazine formulation (B) @ 1.5 kg a.i.ha^{-1}	9.76 (98.33)	11.23 (128. 67)	11. 02 (121.33)
T$_4$: Pre-emergence application of atrazine formulation (B) @ 1.2 kg a.i.ha^{-1}	11.86 (141. 33)	11.53 (132. 67)	11. 94 (142.33)
T$_5$: Pre-emergence application of atrazine formulation (C) @ 1.5 kg a.i.ha^{-1}	10.20 (107. 33)	9.28 (92. 00)	8.92 (79.33)
T$_6$: Pre-emergence application of atrazine formulation (C) @ 1.2 kg a.i.ha^{-1}	10.32 (109. 00)	10.80 (116. 67)	9.77 (95.33)
T$_7$: Pre-emergence application of commercial atrazine @ 1.5 kg a.i.ha^{-1}	12.37 (155. 00)	11.98 (147. 00)	12. 63 (159.33)
T$_8$: Weed free check	0.71 (0.00)	0.71 (0.00)	0.71 (0. 00)
T$_9$: Absolute control	21.35 (461. 00)	16.92 (289. 00)	14.89 (222.00)
SEd	1.54	1.32	0.54
CD (P=0.05)	3.28	2.81	1.15

***** Original data subjected to square root transformation ($\sqrt{x + 0.5}$) data given within parenthesis are mean of original values emergence application of commercial atrazine registered higher weed index of 0.44 indicating yield reduction of 44 % due to weeds compared to weed free plots. The application of formulation mix (B) @ 1.2 kg a.i.ha^{-1} registered 40 % yield reduction of treatments. Pre emergence application of atrazine formulation mix (C) at the rate of 1.5 kg a.i.ha^{-1} recorded lowest weed index of 0.13 among herbicidal treatments. Fig. 1 confirms that encapsulated formulations outperformed commercial atrazine in weed control leading to an increase in yield.

Effect of application of atrazine-loaded guar gum and nanocellulose hydrogel composite on growth of maize

Plant height plays a significant role in determining a plant's ability to overcome weeds. Taller crops have an advantage in exploring light competition, shading out weeds and limiting weeds to access the sunlight. Effective weed management aims to reduce weed competition, while higher plant height of crops experiencing higher weed infestations are considered.

In the present trial, the highest plant heights were documented in plants of weed-free check plots consistently had highest plant heights of 41 and 196 cm, on 15 and 30 days of first irrigation respectively. Plant height of 220 cm was registered at 45 days of irrigation. However, the use of encapsulated atrazine had a significant impact on plant height (Table 3).

The application of atrazine formulation mix (C) at 1.5 kg a.i. ha^{-1} resulted in higher plant heights of 39.7 and 182.9 cm at 15 and 30 days of initial irrigation respectively. The application of atrazine formulation mix (A) and (B) at a rate of 1.5 kg a.i. ha^{-1} and formulation (C) at 1.5 and 1.2 kg a.i. ha^{-1} showed higher plant heights during 60 and 90th day of initial irrigation. However, significantly lower plant heights were observed in the absolute control plots at 30, 60 and 90 days after initial irrigation respectively.

The number of functional leaves directly has a relationship with the crop's competitive ability against weeds. Weed-free check plots consistently have a higher count of functional leaves. There was a notable surge in the number of functional leaves between 30 and 60 days after initial irrigation (DAI), followed by a marginal increase in functional leaves from 60 to 90 days after initial irrigation. Herbicide applied plots are reported to have a similar number of leaves to that of weed-free maintained plot 30 days after first irrigation, whereas the number of functional leaves in plots applied with formulation mix (A) and (C) were statistically on par with weed-free check plots at 60th days of initial irrigation (Table 3).

In maize, a higher LAI indicates a denser canopy of leaves, causing shade out of competing weeds. In the present experiment, the rate of increase in leaf area index was higher between 30 days and 60 days of initial irrigation. However, during the later stage of the experiment, the increase in LAI was relatively less in maize (Table 3).

The application of different herbicidal treatments had a significant influence on the LAI at all the observed stages of crop growth. The highest leaf area index of 1.2, 5.4 were registered from the weed-free plots on 30 and 60 days of irrigation. Among the herbicidal treatments, higher leaf area index was observed with the application of atrazine formulation mix (C) @ 1.5 kg a.i. ha^{-1} followed by the application of the same formulation @ 1.2 kg a.i. ha^{-1}. LAI of weed-free check plots and plots with application of atrazine formulation mix (C) @ 1.5 kg a.i.ha^{-1} remained on par with each other at 60 and 90 days of irrigation.

Dry matter represents the total plant biomass, which is a direct indicator of plant growth and development. A higher

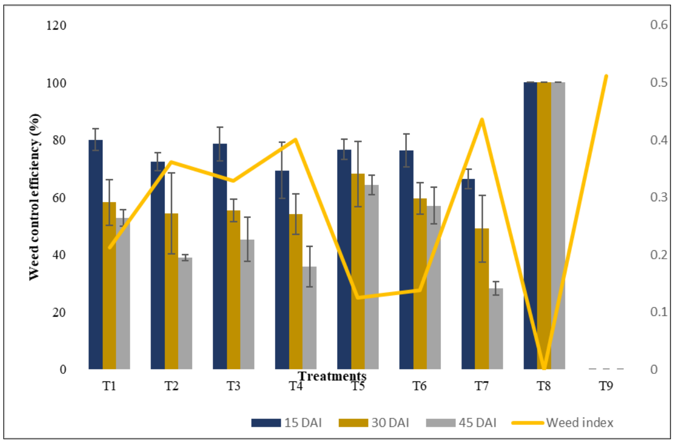

Fig. 1. Impact of herbicide formulations on weed management.

Table 3. Effect of different formulations and rates of atrazine loaded guar gum and nanocellulose hydrogel composite on growth parameters in maize

Treatments	Plant height (cm)			No. of functional leaves			Leaf Area Index			Ear height (cm)
	30 DAI	60 DAI	90 DAI	30 DAI	60 DAI	90 DAI	30 DAI	60 DAI	90 DAI	
T_1: Pre-emergence application of atrazine formulation (A) @ 1.5 kg a.i.ha^{-1}	38.71	182.07	201.23	8.67	12.60	12.81	0.69	4.13	3.71	74.62
T_2: Pre-emergence application of atrazine formulation (A) @ 1.2 kg a.i.ha^{-1}	36.73	177.93	183.56	8.60	12.40	12.63	0.62	3.76	3.50	68.02
T_3: Pre-emergence application of atrazine formulation (B) @ 1.5 kg a.i.ha^{-1}	38.38	180.40	192.28	8.60	12.53	12.78	0.63	4.08	3.62	72.42
T_4: Pre-emergence application of atrazine formulation (B) @ 1.2 kg a.i.ha^{-1}	36.31	177.53	180.34	8.40	12.20	12.31	0.44	3.42	3.11	65.41
T_5: Pre-emergence application of atrazine formulation (C) @ 1.5 kg a.i.ha^{-1}	39.67	182.93	211.64	8.73	12.87	13.10	0.92	4.84	4.50	76.14
T_6: Pre-emergence application of atrazine formulation (C) @ 1.2 kg a.i.ha^{-1}	39.30	182.53	209.21	8.73	12.60	12.81	0.89	4.67	4.27	75.21
T_7: Pre-emergence application of commercial atrazine @ 1.5 kg a.i.ha^{-1}	35.10	175.87	181.25	8.07	12.13	12.24	0.27	2.96	2.58	65.11
T_8: Weed free check	41.03	196.13	220.24	9.13	13.40	13.68	1.21	5.40	5.02	77.23
T_9: Absolute control	34.73	167.13	173.27	7.20	11.47	11.69	0.24	2.08	1.77	62.35
SEd	2.52	8.50	15.77	0.41	0.39	1.03	0.05	0.30	0.29	5.93
CD (P=0.05)	5.34	18.03	33.45	0.86	0.83	NS	0.11	0.64	0.62	12.60

dry matter indicates better plant health and growth and higher yield potential. The effect on plant dry matter due to the application of commercial atrazine and atrazine loaded hydrogels are depicted in Fig. 2.

Weed-free plots recorded significantly higher dry matter in all stages of crop growth, while the application of atrazine formulation mix (C) at 1.5 kg a.iha^{-1} recorded highest dry matter of 909 and 7302 while application of formulation mix (C) @ 1.5 kg a.iha^{-1} registered 11554 kg$ha^{-1}$of dry matter production on 90 days after first irrigation. Dry matter production in plots with application of formulation mix (C) at 1.5 kg a.iha^{-1} was found to be statistically on par with weed-free check plots at 60 and 90 days after initial irrigation.

The height at which the ears are positioned on the maize plants influences the yield potential of crops. Higher ear placement is generally associated with better access to sunlight and improved photosynthesis, contributing to higher grain production. The main ears grew at the lowest position (62.35 cm) in absolute control plots followed by the application of commercial atrazine formulation at 1.5 kg a.i. ha^{-1} (65.11 cm). The higher position of main ears was observed from the weed-free check plots (77.23 cm), whereas plots with application of atrazine formulation mix (C) at 1.5 kg a.i. ha^{-1} recorded the ear height of 76.14 cm (Table 3).

Effect of application of atrazine loaded guar gum and nanocellulose hydrogel composite on yield of maize

Effective weed management aims to maximize crop yield and minimize weed competition. Measuring yield attributes provides a clear and practical indicator of the success of weed control strategies. The data on yield attributes namely, number of ears per plant, ear length, ear girth, number of grain rows per ear, number of grains per ear, grain weight per ear and seed index are presented in Table 4.

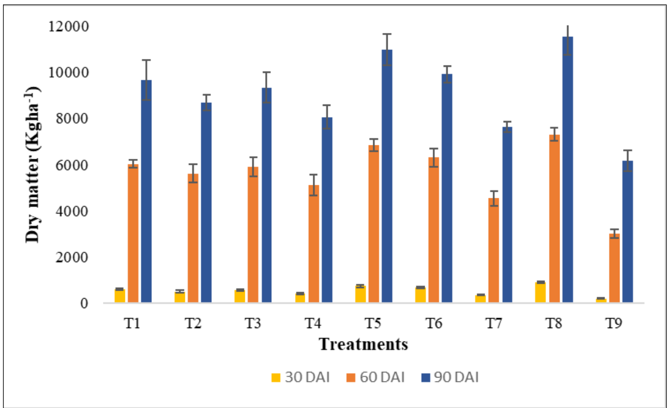

Fig. 2. Impact of different herbicidal treatments on dry matter of maize.

The herbicidal treatments did not exert a significant influence on a number of ears per plant. However, the highest number of ears (1.27) was observed in plots with application of atrazine formulation mix (C) at 1.5 kg a.i.ha^{-1}, followed by the application of atrazine formulation mix (A) @ 1.2 kg a.i. ha^{-1} and formulation mix (B) at 1.5 kg a.i. ha^{-1}. On the other hand, lower number of ears (1.07) was noticed in plots with the application of commercial atrazine.

Generally, weed management practices affect the ear length of corn plants. Longer ear length was observed in plots of weed-free check, followed by the treatment with atrazine formulation mix (C) at 1.5 kg a.i. ha^{-1} and 1.2 kg a.i. ha^{-1}. However, all the plots treated with encapsulated atrazine formulations had uniform ear lengths, which were comparable to the highest values of ear length observed in weed-free checks. The plots treated with commercial atrazine had lowest ear length of 16.5 cm.

Girth of the ear was higher in weed-free check plots. Similarly, the application of atrazine formulation mix (C) @ 1.5 kg a.i.ha^{-1} and 1.2 kg a.i.ha^{-1}registered ear girths of 13.82 and 13.57 cm respectively. Ear girths of maize ears were statistically on par with herbicide treated plots and weed-free check. Commercial atrazine applied plots reported the ear girth of 12.28 cm.

Herbicide treatments influenced the number of rows per each ear. However, all the ears observed had the same number of grain rows (14.0) in all plots except plants in absolute which had lower number of grain rows (12.7) per ear.

Weed free check plots recorded higher grain count per ear, averaging 505 grains in a ear. The application of atrazine formulation (C) at 1.5 kg a.i.ha^{-1} resulted in similar grain count in the ear as observed in the weed-free check. All plots treated with encapsulated formulations were comparable to the weed-free check in terms of the number of grains per ear except the maize plants applied with pre-emergence application of atrazine formulation (B) at the rate of 1.2 kg a.i. ha^{-1}, which had a lower grain count of 416 grains per ear.

Table 4. Effect of different formulations and rates of atrazine-loaded guar gum and nanocellulose hydrogel composite on yield attributes of maize

Treatments	No. of ears plant^{-1}	Ear length (cm)	Ear girth (cm)	No. of grain rows ear^{-1}	No. of grains ear^{-1}	Grain weight ear^{-1} (g)	Seed index (g)
T_1: Pre-emergence application of atrazine formulation (A) @ 1.5 kg a.i.ha^{-1}	1.07	18.54	13.62	14.00	474	116.92	23.65
T_2: Pre-emergence application of atrazine formulation (A) @ 1.2 kg a.i.ha^{-1}	1.20	17.44	12.54	14.00	439	100.66	22.87
T_3: Pre-emergence application of atrazine formulation (B) @ 1.5 kg a.i.ha^{-1}	1.20	17.86	13.21	14.00	456	103.85	23.27
T_4: Pre-emergence application of atrazine formulation (B) @ 1.2 kg a.i.ha^{-1}	1.07	17.00	13.14	14.00	416	95.95	22.34
T_5: Pre-emergence application of atrazine formulation (C) @ 1.5 kg a.i.ha^{-1}	1.27	19.50	13.82	14.00	502	126.67	24.26
T_6: Pre-emergence application of atrazine formulation (C) @ 1.2 kg a.i.ha^{-1}	1.07	19.00	13.57	14.00	498	125.82	23.86
T_7: Pre-emergence application of commercial atrazine @ 1.5 kg a.i.ha^{-1}	1.07	16.50	12.28	14.00	393	92.26	20.58
T_8: Weed free check	1.13	20.04	14.29	14.00	505	129.00	25.11
T_9: Absolute control	1.13	15.50	11.76	12.67	367	84.13	19.73
SEd	0.13	1.48	1.07	0.28	36.80	8.83	2.07
CD (P=0.05)	NS	3.14	2.27	0.60	78.07	18.74	NS

However, the plots treated with commercial atrazine formulation and the absolute control showed the lowest number of grains per ear, with 393 and 367 respectively.

The highest grain weight per ear, measuring 129 g, was recorded in weed-free checks. The pre-emergence application of atrazine formulation (C) at 1.5 kg a.i.ha^{-1}, resulted in a grain weight of 126.67 g ear^{-1} The application of formulation No V (A) at 1.5 kg a.i.ha^{-1} and formulations (C) at both 1.5 and 1.2 kg a.i.ha^{-1} respectively showed comparable grain weights to the highest grain weight observed in weed free checks. Among the herbicidal treatments, plants with application of commercial atrazine had the lowest grain weight per ear measuring 92.3 g, followed by the application of atrazine formulation (B) at 1.2 kg a.i.ha^{-1} which yielded 95.25 g.

The seed index refers to the hundred grain weight, which was higher in weed-free check treatment, measuring 25.11 g. Similarly plants with application of atrazine formulation (C) at a rate of 1.5 kg a.i. ha^{-1}and 1.2 kg a.i.ha^{-1} registered 24.26 and 23.86 g respectively. However, lower seed index was reported in the absolute control plots, measuring 19.73 g.

Effect of application of atrazine-loaded guar gum and nanocellulose hydrogel composite on yield of maize

The main objective of weed management is to mitigate the adverse effects of weeds that they have on crop yield. Evaluating grain yields serves as a direct way to assess the effectiveness of various weed management approaches in achieving this objective.

Grain yield obtained from weed-free check plot (7399 kgha^{-1}) was statistically superior over the rest of the treatments. Pre-emergence application of atrazine formulation (C) at 1.5 kg a.i. ha^{-1}reported to have a higher grain yield (6444 kgha^{-1}) followed by application of same formulation at 1.2 kg a.i. ha^{-1} (6379 kgha^{-1}) which were remaining on par with each other. Application of commercial formulation of atrazine produced a lower grain yield of 4150 kgha^{-1} among the herbicide treatments. Absolute control plots registered the least grain yield of 3608 kgha^{-1} (Fig. 3).

Weed-free check plots produced the highest stover yield of 14652 kgha^{-1}. Among the herbicide treatments, the pre -emergence application of atrazine formulation (C) at 1.5 kg a.i.ha^{-1} resulted in a higher stover yield of 14397 kgha^{-1}, followed by the plot with the application of the same formulation at 1.2 kg a.i.ha^{-1}. These two treatments showed similar results to the highest yield. The plot treated with commercial atrazine had a stover yield of approximately 10136 kgha^{-1}. On the other hand the absolute control plots yielded the lowest stover yield (Fig. 3).

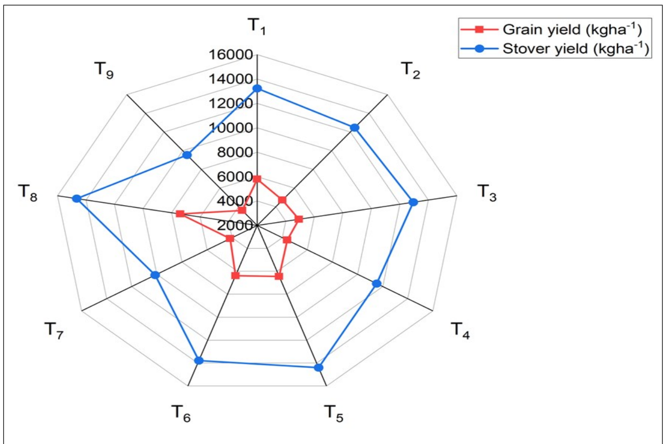

Fig. 3. Impact of different herbicidal treatments on yield (kg ha^{-1}) of maize.

Discussion

Generally, chemical weed management is again an effective strategy for controlling weeds in rainfed agriculture. However, soil active herbicides require optimum soil moisture for facilitating the diffusion of herbicides into sub soil areas to inhibit the germinating weeds. However, rainfall is a truly random event, which makes chemical weed management challenging in the rainfed crops. The absence of rainfall during the application of herbicides triggers the volatilization of active herbicide molecules, while multiple rainfall events also cause leaching out of herbicides. These situations limit herbicide availability in the target sites resulting in low weed control efficiency in the rainfed crop production systems. To test verify the efficacy of entrapped atrazine in rainfed settings and, both seeding of maize and application of atrazine were carried out on the same day and left for seven days without irrigation. Other agronomic practices were carried out according to the recommendations of the crop production guide.

The effectiveness of soil-applied herbicides primarily relies on the accessibility of the herbicides to the roots of growing weeds. However, soil moisture plays a vital role in dissolving atrazine and facilitates the movement of atrazine along the soil solution to make it available for the uptake of weed roots. Similarly, less affinity of atrazine for the adsorption in soil often leads to leaching, thus contaminating groundwater (9). The leaching and other degradation routes of atrazine contribute to the occurrence of higher weed density in plots with application of commercial atrazine formulations. However, when atrazine is loaded or encapsulated composite hydrogel, gets protected in the rigid polymer matrix, preventing the loss of atrazine through leaching and achieved prolonged release of atrazine into the environment. A timeline (Fig. 4) vividly illustrates reduced weed density at different stages of crop growth with entrapped atrazine formulation compared to commercial atrazine. The Fig. 4 clearly depicts that the active molecules of atrazine, when encapsulated within the polymer matrix, achieves sustained release of atrazine where polymer composite gradually releases the active ingredient in response to moisture up to approximately 45 days. The controlled release of atrazine ensured effective weed control for prolonged period. On the other hand, the conventional formulation, atrazine may have leached or lost through photo degradation and volatilization routes which reduce the amount of herbicide available in the soil. Consequently, the weed density was found to be more in lot with application of commercial formulation of atrazine.

The prolonged and sustained release of atrazine from hydrogel composite is found to be advantageous in agricultural systems for season long weed control in the field settings. Additionally, the reduced leaching potential of encapsulated atrazine minimizes the quantum of herbicides that leached into groundwater. The data on weed density

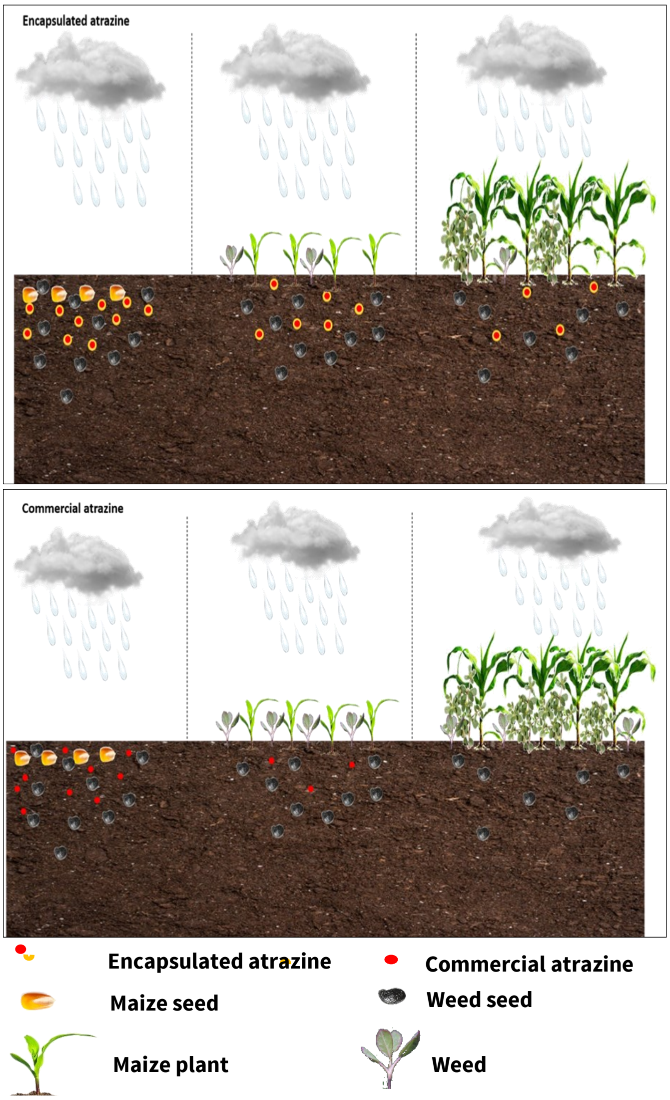

Fig. 4. Timeline figure depicting the working mechanism of encapsulated and commercial atrazine for weed control.

revealed that the plots applied with entrapped atrazine formulations at 1.5 and 1.2 kg a.i. ha^{-1} reduced the weed emergence at 15 DAI (Days After Initial Irrigation). Similar, trend on weed density during 30 and 45 days of first irrigation was also observed with application of atrazine through hydrogel composite formulations. The application of encapsulated formulation of atrazine in dry soil reduced the total weed density compared to that of commercial atrazine. The controlled release mechanism of the encapsulated formulation ensured prolonged availability of atrazine in the soil for controlling weeds (Plate 01-07)|.

Weed infestation was found to gradually decreased with 1.5 kg a.i. ha^{-1} with entrapped atrazine formulation compared to that of 1.2 kg a.i. ha^{-1}. As the concentration of atrazine increased, there was a noticeable decline in the weed population (19, 20). When a higher dose of atrazine was applied using encapsulated formulations at 1.5 kg a.i. ha^{-1}, there was a notable reduction in the overall weed density in the plots. Among hydrogel composite formulations, the application of atrazine formulation (C) at 1.5 kg a.i. ha^{-1} on the day of sowing was found to be the most promising treatment for achieving prolonged weed control in maize crops.

The rapid degradation of commercial atrazine reduced effectiveness of the product for controlling weeds compared to that of encapsulated formulation. Similarly, the hydrogel composite (Plate 02) with gradual increase in swelling capacity demonstrated improved weed control efficiency. Conversely, formulation mixes with lower amounts of atrazine exhibited reduced weed control efficiency. However, formulation mixes with lower atrazine amounts with higher entrapment efficiency showed higher weed control efficiency. When atrazine was added in excessive amounts, surpassing saturation levels, results in the decline of entrapment efficiency and weed control efficiency. The findings suggest that the controlled release formulations with gradual swelling and optimal loading of atrazine results in effective weed control.

The formulation mix (A) was found to be effective for controlling weeds during the initial days, attributed to a burst release effect of hydrogel composite (Plate 02). However, the efficiency of formulation (A) was found to be less in later stages of crop growth due to the depletion of atrazine within the

Plate 02. Effective weed control in maize with pre-emergence application of formulation (A) @ 1.5 kg a.i.ha^{-1} at 7 DAI.

Plate 01. Pots showing the weed density on application of [a] atrazine formulation (C) @ 1.5 kg a.i. ha^{-1} (30 days after application) [b] Commercial atrazine [c] Absolute control.

hydrogel. The formulation (A) and (B) displayed higher weed control efficiency than formulation (C) during the first 15 days of irrigation due to the initial burst release. Higher content of guar gum and lower amount of nanocellulose in the formulations (A) and (B) facilitate the burst release of atrazine. Subsequently, formulation (C) at 30 (Plate 07) and 45 days recorded the highest weed control efficiency due to the ability of the gradual release of atrazine over extended periods.

The extended release of atrazine was observed in the hydrogel composite intercalated with higher concentration of nanocellulose and higher (optimized) loading of atrazine. The interaction zones develop between polymer chains of guar gum and the surface of nanocellulose, altering the barrier property of hydrogel composite. Hence the release of atrazine is not immediate, where atrazine molecules follow a tortuous path avoiding interaction zones to move the polymer matrix. The phenomenon delays and sustains the release of active molecules form the polymer matrix. Moreover, polymer chains make strong bonds with nanoparticles through inter-atomic and inter-molecular forces that result in the formation of high bond dissociation energy between nanoparticles and polymer chains with forming new immobilized polymer interfaces.

Application of formulation (B) did not improve weed control efficiency for the prolonged period of 30 to 45 days. The minimum weed control efficiency in the formulation may be due to the loading of lower amount of polymer and higher concentration of nanocellulose in the formulation, causing inadequate swelling and deswelling to release and maintain atrazine at the lethal concentration for prolonged period. However, all three formulations A, B and C exerted better weed control compared to that of commercial atrazine formulation (21-23). The lower efficiency of commercial formulation of atrazine on weed control efficiency is due to the loss of atrazine molecule on exposure to various environmental factors like light and temperature during the period between the application of herbicide and first irrigation to the crop.

The weed index compares the yield reduction due to weed infestation with the yield of weed-free plots. The higher the weed index indicates lesser the effectiveness of treatment over the control of weeds. The plots treated with a commercial formulation of atrazine at 1.5 kg a.i.ha^{-1} were with higher weed index due to the inadequate control of weeds (Fig. 1). However, the application of encapsulated atrazine formulations at 1.5 kg a.i.ha^{-1}, were resulted in the lower weed index. The reduced weed index with encapsulated formulation was attributed to the persistence of herbicidal activity, which led to better weed control over time.

The interaction of various crop growth factors, including plant height, number of leaves, leaf area index and dry matter production is instrumental in the efficient harnessing of resources. Weeds are an important biotic constraint affecting crop yields. The absence of weed competition during the critical stages of crop growth allows the crop to express their potential in the given environment. The efficacy of weed control treatments reflects the difference in the quantifiable traits of maize with respect to growth and yield attributes.

Plant height, number of leaves and LAI are vital growth factors which are directly associated with grain yield. The positive impact of encapsulated formulations on growth

Plate 03. Effective weed control in maize with pre-emergence application of formulation (C) @ 1.5 kg a.i.ha^{-1} at 7 DAI.

Plate 04. Weed growth in maize with pre-emergence application of commercial atrazine @ 1.5 kg a.i.ha^{-1} at 7 DAI.

Plate 05. Effective weed control in maize with pre-emergence application of formulation C @ 1.5 kg a.i.ha^{-1} at 15 DAI.

Plate 06. Weed growth in maize with pre-emergence application of commercial atrazine @ 1.5 kg a.i.ha^{-1} at 15 DAI.

Plate 07. Weed control in maize with pre-emergence application of formulation C @ 1.5 kg a.i.ha^{-1} at 30 DAI.

Plate 08. Weed growth in maize with pre-emergence application of commercial atrazine @ 1.5 kg a.i.ha^{-1} at 30 DAI.

attributes is likely due to improved weed control achieved through the formulations. Effective weed control allowed the crop to grow with less weed competition for essential resources, which enhanced growth attributes of the maize crop. In absolute control plots, the presence of severe weed competition significantly hindered nutrient and water uptake, access to light and space for rooting resulted in reduced plant height and LAI (24-26).

The higher biomass of plants is due to higher leaf area index, which provides more leaf area for carrying photosynthesis resulting in higher food reserve in plants which directly influences the amount of dry matter accumulated in the plant. Indeed, the dry matter production in plants depends on the carbon assimilation rate through photosynthesis and subsequent transformation into plant biomass. The amount of radiation absorbed through the canopy of plant also influences the dry matter accumulation. Increased plant height and leaf area index due to reduced weed competition improved efficiency in capturing and utilizing solar radiation and partitioning of assimilate (27-29), improved the dry matter accumulation with the application of atrazine formulation mix (C) at 1.5 kg a.i. ha^{-1}.

Weed compete with crops for essential resources where severe infestation of weeds have negative impact on the overall growth and development of crops, leading to decline in crop yields. Various herbicidal treatments exhibited significant differences in weed control efficiency and, crop growth and yield attributes. Weed-free plots and encapsulated herbicide applied plots created a favorable environment for maize during the critical stages of crop growth. Less weed density in plots applied with encapsulated formulations makes maize crop to utilize available resources more efficiently for enhanced growth and higher grain yield.

The observed improvement in yield-contributing characteristics of crops attributed to the efficient utilization of resources under weed-free conditions. The translocation of photosynthates (products of photosynthesis) from the source to the sink may be efficient with reduced weed competition (30 -33). The absolute control plots, which had high weed density, resulted in the lowest number of grains per cob and grain weight per cob. Similarly, lower grain and stover yield were recorded in unweeded plots due to heavy weed infestation. The reduction of 51 and 35 % in grain and stover yield respectively were observed in unweeded plots with that of weed-free check plots. The presence of weeds during the critical growth phase of crop exerts pressure on the crop to obtain resources leading to a decline in growth attributes and yield-related characteristics, such as the number of kernels per ear and kernel weight per cob.

The notable increase in the yield indicates the weed control efficiency of the formulation for 45 days of first irrigation in maize which corresponds to the critical period of crop weed competition. The application of atrazine formulation mix (C) at 1.5 kg a.i.ha^{-1} led to a substantial increase of 36 and 30 % of grain and stover yield respectively to that of plots with the application of commercial atrazine. Furthermore, lower application rate of 1.2 kg a.i.ha^{-1}, through the formulation mix (C) reflected yield advantage with application of commercial atrazine application. The observed improvement in yield with application of encapsulated atrazine are due to the prolonged availability of atrazine in the soil through the protection of atrazine molecules from leaching and volatilization.

Conclusion

In conclusion, this study focused on addressing weed-related challenges in rainfed agriculture through encapsulating atrazine in a polymeric system composed of guar gum and cellulose nanoparticles. This method aims to achieve controlled herbicide releasse triggered by moisture, offering sustainable weed management. Laboratory experiments identified three optimal formulation mixes (A, B and C) with high atrazine entrapment efficiencies and effective weed control. Further, among the three formulation mixes, formulation A with better weed control in the initial stages and formulation C with better weed control at later stages was reported from the field trials which have led to improved crop growth and yield. The findings support the notion that optimizing atrazine delivery through appropriate formulations can contribute to improved weed suppression and higher crop yields. Furthermore, the research highlights the importance of carefully selecting different doses and application rates of these formulation mixes to maximize weed control without compromising environmental sustainability.

Future line of work

Future research should focus on evaluating the environmental impact of encapsulated atrazine, including its degradation, residual effects and influence on soil microbial activity. Long-term studies are needed to assess its potential risks to soil health and groundwater contamination. Additionally, investigating the role of soil properties and moisture variability in herbicide release dynamics could optimize formulation performance. Comparative studies on volatilization, leaching and degradation pathways between commercial and encapsulated atrazine would provide insights into their efficiency and safety. Further research should also examine whether sustained-release formulations influence herbicide resistance in weed populations and explore their adaptability to different cropping systems to enhance sustainable weed management strategies.

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Authors' contributions

JP developed the protocol for formulations and conducted pot and field trials and prepared the original draft, MS gave the concept and validated the experiment, GG helped with the methodology and formal analysis, PC have carried out data curation, SRN and PP providing funding for publication of manuscript, USN and SSY has reviewed and edited the manuscript (original draft).

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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