Journal of Scientific Research and Reports

Volume 30, Issue 11, Page 208-222, 2024; Article no.JSRR.124985
ISSN: 2320-0227

Optimizing Sorghum Yield and Quality: A Study on the Role of Plant Growth Regulators and Micronutrient Management Strategies

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/jsrr/2024/v30i112548

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/124985

Original Research Article

Received: 15/08/2024
Accepted: 17/10/2024
Published: 30/10/2024

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Cite as: *R, Zahida, R K Agarwal, Naveen K, B G Shekara, S Prasad, Sabina N, Shabeena M, F A Bahar, N S Khuroo, S Iqbal, T Ahnger, Raies A Bhat, Rakshanda A, Z A Dar, and Sabiya Bashir. 2024. "Optimizing Sorghum Yield and Quality: A Study on the Role of Plant Growth Regulators and Micronutrient Management Strategies". Journal of Scientific Research and Reports 30 (11):208-22. https://doi.org/10.9734/jsrr/2024/v30i112548.*

ABSTRACT

This study assessed the impact of plant growth regulators (PGRs) and micronutrients on sorghum (Sorghum bicolor L.) productivity in four locations viz., Palampur, Srinagar, Mandya, and Ayodhya during *Kharif* 2020-2021. Twelve treatments, combining PGRs and micronutrients, were evaluated. The best treatment (T_{10}), applying 5 kg Zn and 2 kg B per hectare with a triacontanol (10 ppm) foliar spray at 30 days after sowing, resulted in the highest green fodder yield (493.2 q/ha), dry matter yield (125.6 q/ha), and crude protein yield (10.80 q/ha). It also improved the leaf-stem ratio (0.63), ADF (42.34%), and NDF (63.03%). Economic analysis showed a gross return of Rs. 130,208/ha, net return of Rs. 81,717/ha, and B:C ratio of 2.56. These findings provide actionable insights for enhancing sorghum productivity in semi-arid regions through integrated nutrient management, improving both food security and farmer incomes in challenging agricultural environments.

Keywords: Sorghum; plant growth regulators; micronutrients; yield; nutrient management.

1. INTRODUCTION

In recent years, the agricultural sector has faced numerous challenges, including soil degradation, declining crop yields, and increased pest and disease pressures (Tudi et al. 2021). Traditional agricultural practices, heavily reliant on synthetic fertilizers and chemical pesticides, have raised concerns regarding their environmental impact, sustainability, and long-term viability. In response to these challenges, there has been a growing interest in sustainable agricultural practices that enhance crop productivity while minimizing environmental degradation (Gamage et al. 2023). Sorghum (*Sorghum bicolor* L.) is a vital cereal crop recognized for its resilience and adaptability, particularly in semi-arid regions of the world (Ananda et al. 2020). Sorghum is an essential dual-purpose crop and is recognized as the most drought-tolerant among the top five carbohydrate-rich crops globally, thriving from the equator to altitudes of 2,500 meters (Fadhil 2020). Its remarkable resilience to low-input conditions makes it a vital option for areas with limited rainfall. Given the increasing demand for scarce freshwater resources, the growing use of marginal lands, and shifting climatic patterns, sorghum has the potential to play a significant role in feeding the world's most vulnerable populations. These compelling characteristics make sorghum an ideal species for exploring evolutionary relationships among grass species and conducting various research studies under changing climate conditions to ensure food security. This research could lead to improved adaptation strategies for climatic variations, particularly regarding abiotic stresses such as water scarcity, high salinity, low-temperature tolerance, and nutrient efficiency. Such efforts are crucial, especially as global food production needs to increase by 70% in the face of declining arable land and water resources, compounded by frequent environmental extremes like floods and droughts. Sorghum's adaptability to diverse environments, particularly under water-limited conditions, further underscores its value as a crop suited for regions with erratic rainfall and high temperatures. This drought-resistant crop serves multiple purposes, including human food, fodder, animal feed, and fuel, with its seeds also used for making popcorn and various dishes. Its cultivation can be extended to moisture-deficient areas, given its ability to thrive with minimal inputs and care. In Bangladesh, sorghum is traditionally grown in regions such as Jamalpur, Sherpur, Meherpur, Kushtia, Pabna, Rajshahi, Bagerhat, and the Chittagong Hill Tracts, where approximately 3,200 metric tons of sorghum grain are produced annually from around 4,000 hectares of land, yielding an average of 3.6 metric tons per hectare. As the fifth most important cereal globally, sorghum serves multiple purposes, including food for humans, fodder for livestock, and a source of biofuel. Its ability to withstand drought, high temperatures, and poor soil conditions makes it a crucial crop for millions of people, especially in Africa and Asia, where it is a staple food for many communities (Tsygankova et al. 2023). Despite its importance, sorghum production is often hampered by several challenges, notably nutrient deficiencies and suboptimal agronomic practices. One of the primary nutrient deficiencies affecting sorghum is in zinc (Zn) and boron (B). Research indicates that approximately 43% of Indian soils are deficient in zinc, while around 18% are deficient in boron (Hadebe et al. 2021). Zinc plays a critical role in various physiological processes, including enzyme function, protein synthesis, and overall plant metabolism, which directly influences crop yield. Boron, on the other hand, is essential for cell wall formation and reproductive development; its deficiency can lead to impaired vegetative and reproductive growth, ultimately reducing yield and quality (Ahmed et al. 2014). In addition to addressing nutrient deficiencies, the application of plant growth regulators (PGRs) has emerged as a promising strategy to enhance sorghum productivity. PGRs such as salicylic acid and triacontanol have been shown to stimulate growth, improve nutrient uptake, and enhance stress tolerance in plants (Shah et al. 2023). These regulators can help mitigate the adverse effects of environmental stressors, thereby improving overall crop performance. For instance, studies have demonstrated that the application of triacontanol can lead to increased biomass accumulation and improved physiological responses under stress conditions (Islam 2020). The integration of PGRs and micronutrients in sorghum cultivation presents a unique opportunity to enhance productivity and sustainability. Previous research has indicated that the combined application of these treatments can lead to synergistic effects, resulting in improved growth metrics and higher yields (Lone et al. 2023). However, despite the potential benefits, the adoption of these practices remains limited due to factors such as inadequate access to quality seeds, declining soil fertility, and poor agronomic practices (Chang et al. 2024). This study aimed to assess the impact of PGRs and micronutrients on the growth, yield, and quality of sorghum. By conducting field experiments across multiple locations, the research evaluated various treatment combinations and their effects on key yield parameters, including green fodder yield, dry matter yield, and crude protein yield. The findings from this study provided valuable insights into effective strategies for enhancing sorghum productivity, ultimately contributing to improved food security and farmer livelihoods in regions facing agricultural challenges. Through a comprehensive understanding of the interactions between PGRs, micronutrients, and sorghum growth, this research sought to inform best practices that could be adopted by farmers and policymakers alike.

2. MATERIALS AND METHODS

2.1 Experimental Design and Location

A field experiment was conducted during the *Kharif* season of 2020-21 to assess the impact of plant growth regulators (PGRs) and micronutrients on the growth, yield, and quality of sorghum (*Sorghum bicolor* L.). Palampur and Srinagar experience moderate temperatures, with Palampur having a mean maximum of 26.5°C and Srinagar slightly cooler at 27.6°C, both showing a cooling trend in later weeks due to their higher elevation. Palampur is more humid (RH1: 86.2%, RH2: 75.2%) than Srinagar (RH1: 79.2%, RH2: 54.5%) and receives substantial rainfall (1920.8 mm), especially during weeks 26-32, while Srinagar is drier with fewer rainy days (33 total). Palampur also has more sunshine (5.3 hours/day) compared to Srinagar (4.4 hours/day). In contrast, Mandya and Ayodhya are warmer, with Ayodhya having a higher mean maximum temperature (33.1°C) than Mandya (29.9°C), which could lead to faster crop growth. Ayodhya is also more humid (RH1: 91.3%, RH2: 69.3%) than Mandya (RH1: 88.8%, RH2: 65.9%) and receives more rainfall, especially in weeks 29-33, favoring water-dependent crops like rice. Both regions have sufficient sunshine, though Mandya has slightly more (4.3 hours/day). The experimental design employed was a Randomized Complete Block Design (RCBD) with three replications. The study included a total of 12 treatments, which were as follows:T_1 (Tricontanol 10 ppm foliar spray at 30 days after sowing (DAS), T_2(Salicylic acid 100 ppm foliar spray at 30 DAS),T_3(5 kg Zn/ha soil application), T_4 (2 kg B/ha soil application), T_5, (5 kg Zn + 2 kg B/ha soil application), T_6(5 kg Zn/ha soil application + Tricontanol 10 ppm foliar spray at 30 DAS), T_7(5 kg Zn/ha soil application + Salicylic acid 100 ppm foliar spray at 30 DAS), T_8(2 kg B/ha) soil application + Tricontanol 10 ppm foliar spray at 30 DAS, T_9 (2 kg B/ha soil application + Salicylic acid 100 ppm foliar spray at 30 DAS), T_{10} (5 kg Zn + 2 kg B/ha soil application + Tricontanol 10 ppm foliar spray at 30 DAS), T_{11}(5 kg Zn + 2 kg B/ha soil application + Salicylic acid 100 ppm foliar spray at 30 DAS) and T_{12}(Water spray at the time of PGR application) (control). Zinc and boron were applied at the time of sowing in the soil, and the crop was raised following recommended agronomic practices with a plant to plant spacing of 30 cm. In treatments where zinc was not included, an equivalent amount of sulphur through gypsum was applied to compensate for the absence of sulphate supplied with the zinc sulphate. The field experiments were conducted at four different locations to ensure diverse environmental conditions and validate the findings across various agro-ecological zones. The locations included: Palampur, known for its temperate climate and suitable soil conditions for sorghum cultivation, Srinagar, characterized by its unique climatic conditions that influence crop growth, Mandya, Located in Karnataka, this region has a history of sorghum production and provides valuable insights into regional agronomic practices., Ayodhya, A location with varying soil types and climatic conditions, contributing to the comprehensive assessment of the treatments.Each site provided a distinct set of environmental factors, including soil type, temperature, and moisture availability, which are critical for evaluating the effectiveness of the applied treatments on sorghum productivity. The combination of these locations aimed to enhance the reliability and applicability of the research findings across different farming systems. Plant Height was measured from the base of the plant to the tip of the longest leaf. Biomass yield was determined by harvesting plants from a $1m^2$ areas in each plot, drying them to constant weight, and extrapolating to per hectare basis. The grain yield was measured after threshing and cleaning the harvested sorghum heads. The cost of inputs and the market value of the yield were used to calculate the net economic returns for each treatment.

2.2 Statistical Analysis

The data were subjected to statistical analysis using ANOVA to determine the significance of differences between treatments. Mean comparisons were performed using the Least Significant Difference (LSD) test at a 5% significance level. Additionally, economic analysis was conducted to assess the cost-effectiveness of each treatment combination.

3. RESULTS AND DISCUSSION

3.1 Growth Parameters of Sorghum

The impact of various treatments on the plant height of sorghum at harvest was assessed across four locations: Palampur, Srinagar, Ayodhya, and Mandya.The results (Table 1) demonstrated that the application of plant growth regulators (PGRs) and micronutrients significantly influenced the plant height of sorghum at harvest. Among the treatments, the combination of 5 kg Zn and 2 kg B per hectare with triacontanol (10 ppm) foliar spray at 30 days after sowing (DAS) (T_{10}) resulted in the highest average plant height of 215.1 cm at Palampur, 201.9 cm at Srinagar, 310.0 cm at Ayodhya, and 226.8 cm at Mandya, yielding a mean height of 238.5 cm. This treatment was significantly superior to all other treatments, indicating that the synergistic effects of zinc, boron, and triacontanol effectively enhanced plant growth. The findings align with previous research that highlights the positive effects of micronutrients and PGRs on plant growth (Abbas 2024). One study reported that the application of zinc and boron improved the growth parameters of sorghum, contributing to higher yields (Bhanse et al. 2022, Upadhyay et al. 2023). Similarly, the use of triacontanol has been shown to stimulate growth and enhance physiological responses under stress conditions (Abbas et al. 2024, Abbas et al. 2023). The treatments involving salicylic acid (T_2 and T_{11}) also demonstrated significant improvements in plant height compared to the control, indicating that salicylic acid can play a crucial role in enhancing plant growth by improving stress tolerance and metabolic efficiency. The results suggest that integrating PGRs and micronutrients into sorghum cultivation practices can lead to substantial improvements in crop performance, ultimately contributing to enhanced food security and farmer livelihoods in regions facing agricultural challenges (Abdulkadhim 2019).

The results indicated that the application of plant growth regulators (PGRs) and micronutrients significantly influenced the green fodder yield of sorghum (Table 2). The highest mean green fodder yield was observed in treatment T_{10}, which included the combination of 5 kg Zn + 2 kg B per hectare along with triacontanol (10 ppm) foliar spray at 30 days after sowing, yielding an impressive 493.2 q/ha. This treatment was significantly superior to all other treatments, indicating that the synergistic effects of zinc, boron, and triacontanol effectively enhanced the productivity of sorghum. The treatments involving salicylic acid (T_2 and T_{11}) also demonstrated strong performance, with mean yields of 404.9 q/ha and 485.9 q/ha, respectively (Ali et al. 2024) Similarly, the application of zinc and boron (T_5) resulted in a mean yield of 437.9 q/ha, further supporting the importance of these micronutrients in improving crop performance. Conversely, the control treatment (T_{12}), which involved only water spray, resulted in the lowest mean green fodder yield of 362.1 q/ha. This finding emphasizes the critical role of nutrient management in optimizing sorghum productivity. The results align with previous research indicating that the application of micronutrients can lead to significant increases in green fodder yield (Abdulkadhim 2019, Nandi et al. 2024).

3.2 Quality of Sorghum

The results indicated that the application of plant growth regulators (PGRs) and micronutrients influenced the leaf-stem ratio (Table 3) of sorghum. The combination of 5 kg Zn and 2 kg B per hectare with tricontanol (10 ppm) foliar spray at 30 days after sowing (DAS) (T_{10}) and the combination of 5 kg Zn and 2 kg B per hectare with salicylic acid (100 ppm) foliar spray at 30 DAS (T_{11}) resulted in the highest mean leaf-stem ratio of 0.63 at Palampur, Ayodhya, and Mandya. This indicates that these treatments effectively enhanced the leaf-to-stem ratio, which is an important factor in determining forage quality. The findings align with previous research that suggests the positive effects of micronutrients and PGRs on leaf-stem ratio in sorghum. The results observed by Kewan et al. 2021 reported that the leaf-stem ratio in sorghum ranged from 0.13 to 0.35, and by Hassanen and Abotaleb 2020 found that the leaf-stem ratio was significantly influenced by fertilizer treatments. The treatments involving salicylic acid (T_2 and T_{11}) and tricontanol (T_1 and T_8) also demonstrated improvements in leaf-stem ratio compared to the control, indicating their potential in enhancing forage quality. The results suggest that integrating PGRs and micronutrients into sorghum cultivation practices can lead to substantial improvements in forage quality, which is crucial for livestock production. However, it is important to note that the leaf-stem ratio is also influenced by factors such as genotype, environmental conditions, and management practices.

The results showed that the application of plant growth regulators (PGRs) and micronutrients significantly influenced the dry matter yield of sorghum. The highest mean dry matter yield was observed in treatment T_{10}, which combined 5 kg Zn + 2 kg B per hectare with triacontanol (10 ppm) foliar spray at 30 days after sowing, yielding an impressive 125.6 q/ha. This treatment was significantly superior to all other treatments, indicating that the synergistic effects of zinc, boron, and triacontanol, effectively enhanced the dry matter production of sorghum. The treatments involving salicylic acid (T_2 and T_{11}) also demonstrated strong performance, with mean yields of 102.1 q/ha and 126.3 q/ha, respectively. Salicylic acid is known to enhance stress tolerance and improve physiological processes, which can lead to higher yields (Maced 2021). Similarly, the application of zinc and boron (T_5) resulted in a mean yield of 112.1 q/ha, further supporting the importance of these micronutrients in improving crop performance. Conversely, the control treatment (T_{12}), which involved only water spray, recorded the lowest mean dry matter yield of 90.8 q/ha. This finding emphasizes the critical role of nutrient management in optimizing dry matter production. The results align with previous research indicating that the application of micronutrients can lead to significant increases in dry matter yield (Mthiyane et al. 2024, Abdulkadhim et al. 2023).

The results indicated that the application of plant growth regulators (PGRs) and micronutrients significantly influenced the crude protein content of sorghum. The highest mean crude protein content was observed in treatment T_{10}, which combined 5 kg Zn + 2 kg B per hectare with triacontanol (10 ppm) foliar spray at 30 days after sowing, yielding a mean crude protein content of 8.91%. This treatment was significantly superior to all other treatments, indicating that the synergistic effects of zinc, boron, and triacontanol, effectively enhanced the protein content of sorghum.The treatments involving salicylic acid (T_2 and T_{11}) also demonstrated notable performance, with mean crude protein contents of 7.99% and 8.79%, respectively. Salicylic acid is known to enhance stress tolerance and improve physiological processes, which can contribute to higher protein content in crops (Aires et al. 2022). Similarly, the application of zinc and boron (T_5) resulted in a mean crude protein content of 8.32%, further supporting the importance of these micronutrients in improving the nutritional quality of sorghum. Conversely, the control treatment (T_{12}), which involved only water spray, recorded the lowest mean crude protein content of 7.30%. This finding emphasizes the critical role of nutrient management in optimizing protein content. The results align with previous research indicating that the application of micronutrients can lead to significant increases in crude protein content (Prajapati et al. 2023). The crude protein content of sorghum is particularly important given its role as a forage crop for livestock. Higher protein levels can improve the nutritional value of the feed, leading to better animal performance. The findings suggest that integrating PGRs and micronutrients into sorghum cultivation practices can enhance the protein content, thereby improving the overall quality of the forage (Fadhil et al. 2020).

Table 1. Effect of PGRs and micronutrients on growth parameters of sorghum

Treatments	Plant Height (cm) at harvest				
	Palampur	**Srinagar**	**Ayodhya**	**Mandya**	**Mean**
T_1Tricontanol10ppmat30DAS	161.5	161.8	289.0	205.2	204.4
T_2Salicylicacid100 ppmat30DAS(foliarspray)	169.6	167.8	284.7	206.1	207.1
$T_3$5kgZn/hasoilapplication	161.3	156.5	286.8	213.9	204.6
$T_4$2 kgB/hasoilapplication	167.5	152.7	273.5	217.9	202.9
$T_5$5kgZn+2kgB/hasoilapplication	171.1	165.8	299.0	225.4	215.3
$T_6$5 kgZn/hasoilapplication+ triacontanol10ppmat30DASfoliarspray	187.5	170.1	301.0	218.5	219.3
$T_7$5 kg Zn/ha soil application + salicylic acid 100 ppm at 30DASfoliarspray	177.2	166.6	296.8	224.2	216.2
$T_8$2kgB/hasoilapplication+triacontanol10 ppmat30 DASfoliarspray	185.3	171.7	286.8	223.2	216.8
$T_9$2 kg B/ha soil application + salicylic acid 100 ppm at 30DASfoliarspray	186.7	168.8	285.8	220.2	215.4
T_{10}5 kg Zn + 2 kg B/ha soil application + triacontanol 10 ppmat30DASfoliar spray	215.1	201.9	310.0	226.8	238.5
T_{11}5 kgZn+ 2kgB/hasoilapplication+salicylicacid100ppmat30DASfoliar spray	212.4	196.0	302.9	227.9	234.8
T_{12}WatersprayatthetimeofPGRapplication	157.2	147.9	261.9	193.1	190.0
SE(m)±	**7.10**	**3.13**	**6.93**	**6.55**	**-**

Table 2. Effect ofPGRs and micronutrients on green fodder yield (q/ha) of sorghum

Treatments	Green fodder yield (q/ha)				
	Palampur	**Srinagar**	**Ayodhya**	**Mandya**	**Mean**
T_1Tricontanol10ppmat30DAS	383.5	363.9	536.9	339.8	406.0
T_2Salicylicacid100 ppmat30DA (foliarspray)	391.7	369.5	508.7	349.9	404.9
$T_3$5kgZn/has oil application	371.9	350.6	531.8	358.6	403.2
$T_4$2 kgB/has oil application	376.0	353.6	507.1	377.8	403.6
$T_5$5kgZn+2kgB/has oil application	386.2	369.2	546.5	449.5	437.9
$T_6$5kgZn/has oil application+triacontanol10ppmat30DAS foliar spray	423.3	419.5	555.3	425.8	456.0
$T_7$5kgZn/has oil application+salicylicacid100ppmat30DASfoliar spray	419.4	424.6	537.6	430.0	452.9
$T_8$2kgB/has oil application+triacontanol10ppmat30DAS foliar spray	427.2	425.4	518.6	431.1	450.6
$T_9$2kgB/has oil application+salicylicacid100ppmat30DAS foliar spray	433.9	427.4	512.0	435.2	452.1
T_{10}5kgZn+ 2 kgB/hasoilapplication+triacontanol10ppmat30DASfoliar spray	465.6	449.5	573.2	484.6	493.2
T_{11}5 kgZn+ 2kgB/has oil application+salicylic acid100ppmat 30DAS foliar spray	453.0	444.4	554.7	491.4	485.9

Treatments	Green fodder yield (q/ha)				
	Palampur	Srinagar	Ayodhya	Mandya	Mean
T_{12}Water spray atthetime of PGR application	349.2	315.2	472.6	311.3	362.1
SE(m)±	**21.4**	**4.5**	**15.3**	**22.5**	**-**
C.D.(P=0.05)	**63.3**	**13.1**	**44.8**	**65.9**	**-**

Table 3. Effect of PGRs and micro nutrients on quality of sorghum

Treatments	Leaf Stem Ratio				
	Palampur	Srinagar	Ayodhya	Mandya	Mean
T_1Tricontanol 10ppmat30DAS	0.65	0.63	0.71	0.30	0.57
T_2Salicylicacid100ppmat30DAS (foliarspray)	0.67	0.62	0.70	0.32	0.58
$T_3$5kgZn/has oil application	0.60	0.75	0.72	0.32	0.60
$T_4$2kgB/has oil application	0.68	0.73	0.70	0.33	0.61
$T_5$5kgZn+2kgB/has oil application	0.61	0.68	0.73	0.38	0.60
$T_6$5kgZn/has oi lapplication+Tricontanol 10pp mat 30DAS foliar spray	0.68	0.68	0.74	0.36	0.62
T_7 5kgZn/hasoilapplication+salicylicacid100 ppmat30DASfoliarspray	0.71	0.67	0.72	0.35	0.61
T_8 2 kg B/ha soil application + tri contanol 10 ppmat30DASfoliar spray	0.70	0.69	0.71	0.35	0.61
T_9 2kgB/has oil application+ salicylic acid100 ppmat30DASfoliarspray	0.69	0.67	0.70	0.37	0.61
T_{10}5kgZn+2kgB/hasoilapplication+tricontanol10 ppmat30DASfoliarspray	0.70	0.7	0.75	0.38	0.63
T_{11}5kgZn+2kgB/has oil application+salicylic Acid100ppmat30 DAS foliar spray	0.68	0.69	0.74	0.39	0.63
T_{12}WatersprayatthetimeofPGRapplication	0.72	0.73	0.70	0.29	0.61
S.Em±	**0.02**		**0.01**	**0.02**	**-**
C.D.(P=0.05)	**0.06**	**NS**	**NS**	**0.06**	**-**

Table 4. Effect of PGRs and micro nutrients on quality of sorghum

Treatments	ADFContent (%)				NDFContent (%)			
	Palampur	**Ayodha**	**Mandya**	**Mean**	**Palampur**	**Ayodhya**	**Mandya**	**Mean**
T_1Tricontanol10ppmat30DAS	46.2	40.2	43.2	43.19	64.8	62.9	63.2	63.63
T_2Salicylicacid100ppmat30DAS foli ar spray)	44.3	37.5	40.9	40.91	63.1	60.2	60.7	61.35
$T_3$5kgZn/has oil application	46.7	39.4	43.0	43.04	66.8	62.1	62.9	63.95
$T_4$2kgB/has oil application	46.1	37.6	41.9	41.85	67.2	60.7	61.8	63.22
$T_5$5kgZn+2kgB/has oil application	43.7	41.0	42.4	42.36	63.5	63.1	63.2	63.24
$T_6$5kgZn/has oil application+ Triacontanol10 pp mat 30DAS foli ar spray	43.8	41.4	42.6	42.59	62.0	63.4	63.2	62.88
$T_7$5 kg Zn/ha soil application +salicylicacid100 ppmat30DASfoliarspray	43.7	40.0	41.9	41.86	62.5	62.3	62.3	62.37
$T_8$2 kg B/ha soil application +triacontanol10 pp mat 30 DAS foliar spray	42.4	39.2	40.8	40.78	61.8	62.0	62.0	61.95
$T_9$2 kgB/has oila pplication+ salicylic acid 100pp mat 30DASfoliarspray	42.3	38.2	40.3	40.26	61.4	60.6	60.7	60.89
T_{10}5kgZn+2kgB/hasoil application + triacontanol 10 ppm at 30DASfoliarspray	43.0	41.7	42.3	42.34	60.9	64.4	63.8	63.03
T_{11}5 kg Zn + 2 kg B/ha soil application+salicylic acid100ppmat30DAS foli ar spray	43.7	41.4	42.6	42.56	61.8	63.5	63.3	62.86
T_{12}Water spray atthetime of PGR application	46.4	37.0	41.7	41.72	65.0	60.4	61.2	62.18
SE(m)±	**0.3**	**1.5**	**1.77**	**-**	**0.4**	**1.9**	**1.0**	
C.D.(P=0.05)	**1.0**	**NS**	**NS**	**-**	**1.3**	**NS**	**3.2**	

Table 5. Effect of PGRs and micronutrients on crude protein content(%)of sorghum

Treatments	Crude Protein (%)				
	Palampur	Srinagar	Ayodhya	Mandya	Mean
T_1Tricontanol10ppmat30DAS	9.07	8.70	7.28	7.37	8.19
T_2Salicylicacid100 ppmat 30DAS (foliarspray)	9.07	8.90	6.98	6.50	7.99
$T_3$5kgZn/has oil application	9.20	8.70	7.12	6.93	8.03
$T_4$2 kgB/has oil application	8.87	8.40	6.99	5.63	7.56
$T_5$5kgZn+2kgB/has oil application	9.00	8.60	7.29	6.50	8.32
$T_6$5kgZn/has oil application+triacontanol10 pp mat30 DAS foli ar spray	9.00	8.90	7.37	7.37	8.82
$T_7$5 kgZn/has oil application+ salicylicacid100 pp mat 30DAS foli ar spray	9.00	9.10	7.22	6.93	8.66
$T_8$2kgB/has oil application+triacontanol10ppmat30DASfoliarspray	9.20	9.40	7.12	6.50	8.69
$T_9$2 kg B/ha soil application + salicylic acid 100 ppmat30DASfoliar spray	9.07	8.80	6.99	6.93	8.56
T_{10}5 kgZn+ 2 kgB/has oil application+ triacontanol 10pp mat 30 DAS foli ar spray	9.00	9.00	7.58	9.07	9.85
T_{11}5 kg Zn+ 2kgB/has oil application+salicylic acid100pp mat 30 DAS foli ar spray	9.07	9.20	7.38	6.50	9.18
T_{12}Water spray at the time of PGR application	8.47	7.70	6.97	6.07	6.96
SE(m)±	**9.07**	**0.14**	**0.28**	**0.26**	**-**
C.D.(P=0.05)	**9.07**	**NS**	**NS**	**0.75**	**-**

Table 6. Effect of PGRs and micronutrients on economics of sorghum

Treatments	Gross return(Rs./ha)					Netreturns(Rs./ha)				
	Palampur	Srinagar	Ayodhya	Mandya	Mean	Palampur	Srinagar	Ayodhya	Mandya	Mean
T_1Tricontanol 10 ppm at 30DAS	134211	109170	118109	67968	107365	84042	60433	96409	35953	69209
T_2Salicylic acid100ppmat 30DAS (foliarspray)	137086	110850	111918	69986	107460	96441	71638	89718	37851	73912
$T_3$5kgZn/has oilapplication	130146	105180	116987	71720	106008	73067	62693	93987	36283	66508
$T_4$2kgB/has oilapplication	131598	106080	111551	75568	106199	79141	65337	88851	42993	69081
$T_5$5kgZn+2kgB/hasoil application	135183	110760	120226	89898	114017	67778	66517	95926	52841	70765
$T_6$5kgZn/has oil application+ triacontanol 10 ppm at 30DASfoliarspray	148146	125850	122168	85160	120331	81316	73613	99068	48663	75665
$T_7$5kgZn/has oilapplication+ salicylic acid 100 ppm at 30DASfoliarspray	146776	127380	118270	85994	119605	89472	84668	95070	49377	79647

Treatments	**Gross return(Rs./ha)**					**Netreturns(Rs./ha)**				
	Palampur	**Srinagar**	**Ayodhya**	**Mandya**	**Mean**	**Palampur**	**Srinagar**	**Ayodhya**	**Mandya**	**Mean**
T_8 2kgB/has oil application +tria contanol10ppmat30DAS foliar spray	149518	127620	114099	86220	119364	87311	77158	90799	52085	76838
$T_9$2kgB/has oil application+salicylic acid100ppmat30 DAS foliar spray	151850	128220	112638	87040	119937	99168	87252	89238	52785	82111
T_{10}5kgZn+2kgB/has oil application+ tria contanol 10Pp mat 30 DAS foliar spray	162961	134850	126108	96914	130208	85806	80857	101408	58797	81717
T_{11}5 kg Zn + 2 kg B/ha soil application+ salicylicacid100Ppm at 30 DASfolia rspray	158555	133320	122034	98272	128045	90925	88852	97034	60035	84212
T_{12}Watersprayatthetime of PGR application	122220	94560	103968	62268	95754	79051	52823	82418	30633	61231

Table 7. Effect of PGRs and micronutrients on B: C ratio of sorghum

Treatments	**B:C ratio**				
	Palampur	**Srinagar**	**Ayodhya**	**Mandya**	**Mean**
T_1Tricontanol10ppmat 30DAS	2.68	1.24	4.44	2.12	2.62
T_2Salicylicacid100ppmat 30DAS (foliar spray)	3.37	1.83	4.04	2.18	2.86
T_3 5kg Zn/has oil application	2.28	1.47	4.09	2.02	2.46
T_4 2kgB/has oil application	2.51	1.6	3.91	2.32	2.59
T_5 5kgZn+ 2kgB/has oil application	2.01	1.5	3.95	2.43	2.47
T_6 5kgZn/ha soilapplication+triacontanol10 ppmat30DASfoliar spray	2.22	1.41	4.29	2.33	2.56
$T_7$5kgZn/has oil application+salicylic acid 100ppmat30 DAS foliar spray	2.56	1.98	4.10	2.35	2.75
T_8 2kgB/ha soil application+ triacontanol10 ppmat30DASfoliar spray	2.4	1.53	3.90	2.53	2.59
$T_9$2kgB/ha soil application+salicylic acid 100ppmat30 DAS foliar spray	2.88	2.13	3.81	2.54	2.84
T_{10}5kgZn+ 2kg B/ha soil application+ Triacontanol10 ppmat30DAS foliar spray	2.11	1.5	4.11	2.54	2.56
T_{11}5kgZn+ 2kg B/ha soil application+ Salicylicacid100ppmat30DASfoliar spray	2.34	2	3.88	2.57	2.70
T_{12}Watersprayatthetime of PGR application	2.83	1.36	3.82	1.97	2.50

The results indicated that the application of plant growth regulators (PGRs) and micronutrients significantly influenced the ADF (acid detergent fiber) and NDF (neutral detergent fibre) content of sorghum (Table 4) The mean ADF content ranged from 40.26% to 46.7%, while the mean NDF content varied from 60.89% to 67.2%. Among the treatments, the application of 5 kg Zn + 2 kg B per hectare with triacontanol (T_{10}) resulted in a relatively lower ADF content of 42.34% and a mean NDF content of 63.03%, suggesting that this treatment improved the digestibility of the forage. Lower ADF and NDF levels are associated with better forage quality, as they enhance digestibility and nutrient intake in ruminants (Fadhil et al. 2020, Shi et al. 2023). The findings align with previous studies by Gao et al. 2022 that reported the impact of micronutrient applications on fiber content in forage crops indicated that the application of micronutrients can lead to reductions in fiber content, thus improving the overall quality of forage sorghum. Conversely, the highest ADF and NDF contents were observed in the control treatment (T_{12}), which had no PGR or micronutrient application. This finding emphasizes the importance of nutrient management in optimizing forage quality. The treatments involving salicylic acid (T_2 and T_{11}) and triacontanol (T_1 and T_8) also demonstrated significant improvements in fiber content compared to the control, indicating their potential in enhancing forage quality.

3.3 Economics

The results indicated that the application of plant growth regulators (PGRs) and micronutrients significantly influenced the gross returns from sorghum cultivation. The highest mean gross return was observed in the treatment combining 5 kg Zn + 2 kg B per hectare with triacontanol (T_{10}), yielding Rs. 130,208/ha. This was followed closely by the treatment with salicylic acid (T_{11}), which achieved Rs. 128,045/ha. In contrast, the control treatment (T_{12}) yielded the lowest gross return of Rs. 95,754/ha. Net Returns In terms of net returns, treatment T_{10} also resulted in the highest net return of Rs. 81,717/ha, indicating that the combination of zinc, boron, and triacontanol not only enhanced gross returns but also improved profitability. Treatment T_{11} produced a net return of Rs. 84,212/ha, demonstrating the economic viability of integrating PGRs and micronutrients into sorghum production. The control treatment (T_{12}) again showed the least profitability, with net returns of only Rs. 61,231/ha. Discussion The findings of this study highlight the economic benefits of applying PGRs and micronutrients in sorghum cultivation. The significant increase in both gross and net returns associated with treatments T_{10} and T_{11} underscores the importance of these inputs in enhancing crop productivity and profitability. The results are consistent with previous research that emphasizes the positive impact of micronutrients and PGRs on crop yields and economic returns. The application of zinc and boron improved both yield and profitability in sorghum production as noted by Fadhil (Fadhil 2020, Sabagh et al. 2021). Moreover, the observed improvements in economic returns can be attributed to the enhanced growth and quality of sorghum resulting from the synergistic effects of these treatments. The integration of PGRs and micronutrients not only boosts yield but also contributes to better forage quality, which is essential for livestock production and can lead to higher market prices.

The results indicate that the application of plant growth regulators (PGRs) and micronutrients improved the benefit-cost ratio of sorghum cultivation compared to the control treatment (T_{12}). The highest mean B:C ratio of 2.86 was observed in treatment T_2, which involved the foliar application of salicylic acid at 100 ppm. This was closely followed by treatment T_9 (2 kg B/ha soil application + salicylic acid 100 ppm foliar spray) with a mean B:C ratio of 2.84. Among the treatments combining micronutrients and PGRs, T_{11} (5 kg Zn + 2 kg B/ha soil application + salicylic acid 100 ppm foliar spray) achieved the highest mean B:C ratio of 2.70, indicating its economic viability. Treatment T_{10} (5 kg Zn + 2 kg B/ha soil application + triacontanol 10 ppm foliar spray) also demonstrated a favorable B:C ratio of 2.56. The results suggest that the application of PGRs, particularly salicylic acid, can significantly enhance the economic returns from sorghum cultivation. The integration of micronutrients, such as zinc and boron, further improves the profitability of sorghum production. These findings align with previous research that highlights the positive impact of PGRs and micronutrients on crop yields and economic returns (Fadhil 2020). It is important to note that the B:C ratio may vary depending on local market conditions, input costs, and other factors. However, the results of this study provide a strong indication of the economic benefits of adopting integrated nutrient management strategies involving PGRs and micronutrients in sorghum cultivation.

4. CONCLUSION

The study demonstrated that the application of plant growth regulators (PGRs) and micronutrients significantly enhanced the growth, yield, and quality of sorghum (*Sorghum bicolor* L.). Field experiments conducted during Kharif-2022 across multiple locations revealed that the treatment combining 5 kg of zinc (Zn) and 2 kg of boron (B) per hectare with triacontanol (10 ppm) foliar spray at 30 days after sowing (T_{10}) achieved the highest green fodder yield (493.2 q/ha), dry matter yield (125.6 q/ha), and crude protein yield (10.80 q/ha). These findings underscore the importance of integrated nutrient management strategies in optimizing sorghum productivity, particularly in semi-arid regions where nutrient deficiencies and suboptimal agronomic practices are prevalent. The results provide valuable insights for farmers and policymakers, highlighting effective strategies to improve food security and enhance farmer livelihoods.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:
The peer review history for this paper can be accessed here:
https://www.sdiarticle5.com/review-history/124985