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Effects of Atonic Concentration and Application Stage on Grain Yield and Yield Components of *Sorghum bicolor* (L.) Moench

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ABSTRACT

Background: Improving grain yield and its components is a major objective in sorghum production, particularly under arid and semi-arid conditions where crop productivity is frequently constrained. The application of plant growth regulators such as Atonic can promote plant development and productivity through their positive effects on plant physiological functions. This study evaluated the effects of different Atonic concentrations and application stages on grain yield and yield components of sorghum.

Methods: Field experiments were conducted during the spring and autumn growing seasons of 2021 at the University of Anbar, Iraq. Treatments consisted of four Atonic concentrations (0, 2.5, 5.0- and 7.5-mL L^{-1}) applied at three growth stages (end of vegetative growth, booting and 50% flowering) using a split-plot arrangement within a randomized complete block design with three replications. Data were collected on grain-filling duration, 1000-grain weight, grain number per head, grain yield and harvest index.

Results: Atonic concentration significantly affected grain-filling duration, 1000-grain weight, grain number per head, grain yield and harvest index in both growing seasons. The highest values for most yield traits were obtained at 5.0- and 7.5-mL L^{-1}. Spraying at the end of vegetative growth and booting stages generally produced superior results compared with spraying at 50% flowering. Significant interaction effects between Atonic concentration and application stage were observed for several measured traits. Foliar application of Atonic, particularly at 5.0-7.5 mL L^{-1} during the end of vegetative growth stage, improved grain yield and most yield components of sorghum under the environmental conditions of western Iraq.

Key words: Atonic, Biostimulants, Foliar application, Grain yield, Sorghum.

INTRODUCTION

Sorghum [*Sorghum bicolor* (L.) Moench] is one of the most important cereal crops worldwide due to its adaptability to diverse environmental conditions and withstand drought and saline stress. It ranks among the major cereal crops in global production and plays an important role in food, feed and biofuel systems (Abbas and Hassan, 2016; Chavan *et al.*, 2018). In Iraq, sorghum is cultivated mainly for grain and forage production because of its high adaptability to local climatic conditions and its importance as an alternative crop under water-limited environments (Prakash *et al.*, 2010; Karthika *et al.*, 2024).

Sorghum grains are used as human food in many developing countries and may be incorporated with wheat flour for bread production. The grain provides significant amounts of carbohydrates, protein, vitamins and additional nutritional constituents, making it an important source of food and feed resources (Khatik *et al.*, 2020; Mahmood *et al.*, 2025). In Iraq, sorghum cultivation is distributed in several regions, particularly in the southern provinces, where production levels vary according to cultivar performance, environmental conditions and agricultural practices (COSIT, 2017).

Despite its importance, sorghum productivity remains below its potential in many regions due to the use of low-yielding cultivars, unsuitable management practices and environmental stresses. Previous studies conducted in Iraq have focused on improving grain and forage production through comparative analysis of genotypes, nutrient management and agronomic practices (Al-Mozani and Al-Tai, 2014) (Khudhair *et al.*, 2024) (Abood and Salh, 2018). However, further studies are still required to identify effective and environmentally suitable approaches for improving sorghum productivity.

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Plant growth regulators and biostimulants have recently received increasing attention as promising tools for improving crop growth and yield. Several studies have demonstrated that foliar application of growth-promoting substances, micronutrients and commercial biostimulants can enhance plant physiological processes and improve productivity in different crops (Ali *et al*., 2022) (Ahmad *et al*., 2022). These substances may stimulate important metabolic pathways, including photosynthesis, enzyme activity, nutrient uptake and the synthesis of growth-related compounds (Bhutta *et al*., 2023) (Goher *et al*., 2022).

Atonic is a nitrophenolate-based plant biostimulant that has been reported to enhance plant growth and productivity by improving physiological activity, chlorophyll retention and assimilate production. The effectiveness of growth regulators depends not only on concentration but also on the developmental stage at which they are applied. Appropriate stage of application during critical growth stages may improve reproductive development and increase grain formation.

One of the main reasons for reduced crop productivity is suboptimal management during critical growth phases, which prevents plants from attaining their maximum genetic and physiological capacity. Therefore, applying appropriate agricultural practices and growth-promoting substances at suitable growth stages may enhance crop performance and yield formation (Abood *et al*., 2021; Abood, 2017).

Although previous studies have investigated the effects of Atonic and other growth regulators in several crops, limited information is available concerning the optimum concentration and application stage of Atonic for improving yield traits of sorghum under Iraqi environmental conditions. Therefore, this study was conducted to evaluate the effects of different Atonic concentrations and spraying stages on grain yield and yield components of sorghum.

MATERIALS AND METHODS

In 2021, field experiments were performed at Al-Hamdiya Research Station, College of Agriculture, University of Anbar, Iraq, in both spring and autumn seasons. The objective was to investigate how different concentrations and stages of Atonic foliar application affected yield traits and yield components of sorghum [*Sorghum bicolor* (L.) Moench] cultivar 'Inkath'. The experiment followed a split-plot RCBD with three replications.

Atonic (Atonik) is a plant biostimulants belonging to the nitrophenolate group. It contains active aromatic nitro compounds, including sodium para-nitrophenolate, sodium ortho-nitrophenolate and sodium 5-nitroguaiacolate, which have been reported to stimulate several physiological processes in plants. These compounds enhance plant metabolic activity, promote cell division, improve chlorophyll retention, increase photosynthetic efficiency and support nutrient utilization and assimilate translocation. Therefore, Atonic has been widely used as a growth-promoting substance to advance plant growth and productivity with different environmental conditions.

Atonic concentrations were assigned to the main plots and included 0 mL L^{-1} (control), 2.5 mL L^{-1}, 5.0 mL L^{-1} and 7.5 mL L^{-1}. Spraying stages were assigned to the subplots and included S1: the end of the vegetative growth stage (flag leaf emergence), S2: booting stage and S3: 50% flowering stage. Atonic solutions were prepared in line with the required concentrations and applied as foliar sprays using a hand sprayer during the early morning hours with a suitable surfactant to ensure uniform coverage of plant leaves.

The experimental field was prepared by plowing and levelling before sowing. The land was divided into experimental plots measuring 2 × 4 m. Each plot consisted of four rows spaced 50 cm apart, with a 4 m row length and 25 cm spacing between plants, resulting in a plant density of approximately 80,000 plants ha^{-1}. Soil samples were randomly collected from the 0-30 cm soil depth before planting to determine the physical and chemical characteristics of the experimental soil, including soil texture, pH, electrical conductivity, organic matter content and available nutrient concentrations (Table 1).

Sorghum seeds were sown on 1 April 2021 for the spring season and on 1 July 2021 for the autumn season. Phosphorus fertilizer was applied before planting at a rate of 100 kg P_2O_5 ha^{-1} using triple superphosphate fertilizer (45% P_2O_5) and incorporated into the soil. Nitrogen fertilizer was applied at a total rate of 100 kg N ha^{-1} in two equal applications; The first application was made at 2 weeks after emergence and the second followed approximately 4 weeks later. Crop management practices were carried out according to local recommendations. The corn stalk borer was controlled using diazinon insecticide (10% active ingredient) twice, first at the 4-5 leaf stage and again two weeks later. After pollination, the middle plants were covered with velvet bags to protect the heads from bird damage.

Measured parameters included grain-filling period, 1000-grain weight, number of grains per head, grain yield and harvest index. The grain-filling period was calculated as days from complete flowering to physiological maturity.

Table 1: Soil physical and chemical properties of the experimental site.

Soil properties and unit	
Ec dS m^{-1}	2.32
pH Soil	7.6
N mg kg^{-1}	20
Phosphor mg kg^{-1}	12.13
Potassium mg kg^{-1}	103
Organic g kg^{-1}	9.3
Sand (%)	185
Silt (%)	480
Clay (%)	335

At maturity, five heads per plot were randomly selected, harvested, threshed and used to obtain grain weight per head. 1000-grain weight was determined from a random seed subsample per plot. Grain yield was calculated based on grain weight per plant and plant density and expressed as t ha^{-1}. Harvest index was calculated according to the following equation:

$$\text{Harvest index (\%)} = \frac{\text{Grain yield}}{\text{Biological yield}} \times 100$$

Data were analyzed statistically according to the analysis of variance. L.S.D 5% (Steel and Torrie, 1960). GenStat software was used for statistical analysis The assumptions of normality and homogeneity of variance were checked before conducting ANOVA. Treatment means were separated using Fisher's Least Significant Difference (LSD) test at $P \leq 0.05$. All statistical analyses were performed using GenStat.

RESULTS AND DISCUSSION

Grain-filling duration

Atonic concentration significantly affected grain-filling duration during both growing seasons (Table 2). Increasing the concentration of Atonic progressively prolonged the grain-filling period, with the highest values recorded at 7.5 mL L^{-1}, whereas the control treatment showed the shortest duration. Grain filling lasted longer during the autumn season than during the spring season.

No significant influence of spraying stage alone was observed on grain-filling duration. However, the interaction between Atonic concentration and application stage was significant. The combination of 7.5 mL L^{-1} applied at the end of vegetative growth (S1) and booting stage (S2) produced the longest grain-filling period, while the control treatment sprayed at 50% flowering resulted in the shortest duration.

Thousand-grain weight

Thousand-grain weight increased significantly with increasing Atonic concentration in both seasons (Table 3). Plants treated with 7.5 mL L^{-1} produced the heaviest grains, whereas untreated plants produced the lowest grain weight. Application stage significantly influenced this trait. Foliar sprays applied at the end of vegetative growth (S1) and at the booting stage (S2) produced higher 1000-grain weight compared to application at 50% flowering (S3). There was no significant interaction between concentration and spraying stage.

Number of grains per head

Atonic application significantly increased the number of grains per head (Table 4). The highest values were obtained with 7.5 mL L^{-1}, while the control treatment consistently produced the lowest grain number.

Spraying at S1 and S2 resulted in significantly more grains than spraying at S3. A significant interaction between concentration and spraying stage was observed only during the autumn season, where the combination of 7.5 mL L^{-1} and S1 produced the highest grain number.

Grain yield

Grain yield increased significantly with increasing Atonic concentration during both growing seasons (Table 5). The highest grain yield was obtained with 7.5 mL L^{-1}, although it was statistically comparable with 5.0 mL L^{-1} during the spring season. Untreated plants consistently produced the lowest grain yield.

Although spraying stage alone had no significant effect on grain yield, earlier applications tended to produce greater yields than spraying at 50% flowering. The interaction between Atonic concentration and spraying stage indicated that the combination of 7.5 mL L^{-1} and S1 produced the maximum grain yield.

Table 2: The effect of atonic concentrations and the stages of its spraying on the number of days required to fill the grain (day) for the spring and autumn seasons of 2021.

Stages of atonic spraying	Atonic concentrations, ml. L^{-1}				Averages
	0	2.5	5	7.5	
			Spring season 2021		
S1	27.9	30.8	32.8	33.0	31.13
S2	28.0	29.7	31.2	31.9	30.2
S3	28.0	29.7	32.0	31.7	30.35
L.S.D			3.1		N.S
Averages	27.97	30.17	32	32.2	
L.S.D			2.2		
			Fall season 2021		
S1	32.57	33.95	34.67	34.67	34.47
S2	30.90	34.00	35.34	35.34	34.36
S3	30.77	34.73	36.76	36.76	35.45
L.S.D			2.7		N.S
Averages	31.41	34.23	35.59	36.80	
L.S.D			0.83		

Harvest index

Harvest index was significantly influenced by Atonic concentration in both seasons (Table 6). The highest harvest index was obtained with 5.0 mL L^{-1}, although it did not differ significantly from 7.5 mL L^{-1}.

Spraying stage significantly affected harvest index during the autumn season only, with S1 producing higher values than S3.

A significant interaction between concentration and spraying stage was detected in both seasons, indicating that treatment response depended on the combination of concentration and application timing.

This study demonstrates that foliar application of Atonic significantly improves the yield components and grain productivity of *Sorghum bicolor* under ambient conditions. The response of sorghum plants varied according to both Atonic concentration and application stage, indicating that the effectiveness of plant growth regulators depends on the applied dose and the physiological status of the plant at the time of treatment.

The increase in grain-filling duration observed with increasing Atonic concentration may be associated with improved photosynthetic activity and delayed degradation of chlorophyll during the reproductive stage. Nitrophenolate-based biostimulants have been reported to stimulate physiological processes related to chlorophyll maintenance, carbon assimilation and metabolic activity, which may prolong the period of assimilate production and

Table 3: The effect of atonic concentrations and spraying stages on the average weight of thousand grains (g) for the spring and autumn seasons of 2021.

Stages of atonic spraying	Atonic concentrations, ml. L^{-1}				Averages
	0	2.5	5	7.5	
			Spring season 2021		
S1	28.38	30.89	31.56	32.00	30.72
S2	29.55	31.49	31.43	32.17	31.16
S3	28.47	30.82	31.31	30.57	30.30
L.S.D			NS		0.78
Averages	28.98	31.07	31.43	31.58	
L.S.D			1.04		
			Fall season 2021		
S1	30.44	32.81	32.84	33.61	32.43
S2	30.25	32.58	32.87	32.68	32.09
S3	30.12	31.66	31.72	31.62	31.28
L.S.D			N.S		0.59
	30.27	32.35	32.48	32.64	
L.S.D			0.70		

Table 4: Effect of atonic concentrations and spraying stages on the average number of grains per head (grain $head^{-1}$) for the spring and autumn seasons 2021.

Stages of atonic spraying	Atonic concentrations, ml. L^{-1}				Averages
	0	2.5	5	7.5	
			Spring season 2021		
S1	842.0	907.5	1101.0	1282.0	1033.13
S2	827.7	932.6	1288.3	1361.0	1102.4
S3	852.7	905.2	1084.3	1070.7	969.23
L.S.D			N.S		108.8
Averages	840.8	915.1	1145.87	1237.9	
L.S.D			165.7		
			Fall season 2021		
S1	1182	1242	1598	1824	1461.5
S2	1122	1337	1641	1764	1466
S3	1110	1233	1375	1462	1295
L.S.D			254.1		99.6
Averages	1038	1270.7	1538	1683.3	
L.S.D			130.4		

enhance grain development (Przybysz *et al.*, 2014). In addition, the role of growth regulators in maintaining chlorophyll content and improving enzymatic activity during late plant development has been reported in cereal and field crops (Djanaguiraman *et al.*, 2005). Therefore, the extended grain-filling period observed in Atonic-treated plants may have resulted from prolonged leaf activity and improved assimilate supply to developing grains.

The longer grain-filling duration recorded during the autumn season compared with the spring season may be related to differences in environmental conditions, particularly temperature during the grain development period. High temperatures during reproductive growth accelerate respiration, reduce photosynthetic efficiency and shorten the duration of effective grain filling, consequently limiting dry matter accumulation in grains (Tashiro and Wardlaw, 1990). The environmental variation between seasons may therefore explain the differences observed in grain-filling duration between the two experiments.

The increase in 1000-grain weight following Atonic application indicates improved grain filling and greater accumulation of dry matter in kernels. This improvement may be attributed to enhanced source–sink relationships, where increased photosynthetic production in vegetative organs contributes to greater translocation of assimilates toward reproductive organs. Similar effects of plant growth regulators and biostimulants on improving grain weight have been reported in cereal crops through enhanced physiological activity and assimilate partitioning (Mazban, 2017) (Kocira *et al.*, 2015) (Al-Mafarji *et al.*, 2026a).

Table 5: The effect of atonic concentrations and spraying stages on the average grain yield, ton.ha^{-1}, for the spring and autumn seasons of 2021.

Stages of atonic spraying	Atonic concentrations, ml. L^{-1}				Averages
	0	2.5	5	7.5	
			Spring season 2021		
S1	2.084	3.100	3.437	3.704	3.081
S2	2.035	2.968	3.648	3.560	3.052
S3	2.092	2.984	3.389	3.379	2.961
L.S.D					N.S
Averages	2.070	3.017	3.491	3.548	
L.S.D					
			Fall season 2021		
S1	3.128	3.581	5.104	5.693	4.376
S2	2.949	3.749	4.779	5.168	4.161
S3	3.091	3.824	4.429	4.771	4.028
L.S.D		1.042			N.S
	3.056	3.718	4.771	5.211	
L.S.D			0.614		

Table 6: The effect of Atonic concentrations and spraying stages on the average harvest index (%) for the spring and autumn seasons 2021.

Stages of atonic spraying	Atonic concentrations, ml. L^{-1}				Averages
	0	2.5	5	7.5	
			Spring season 2021		
S1	15.94	15.61	19.06	17.74	17.09
S2	14.96	16.63	18.88	17.07	16.89
S3	15.75	15.96	18.33	17.59	16.91
L.S.D			2.4		NS
Averages	15.55	16.07	18.76	17.47	
L.S.D			1.48		
			Fall season 2021		
S1	16.66	19.17	22.86	21.78	20.12
S2	16.32	19.28	19.93	18.03	18.39
S3	15.39	17.88	18.78	18.23	17.57
L.S.D			2.8		1.32
Averages	16.12	18.78	20.52	19.53	
L.S.D			1.62		

The increase in grain number per head under higher Atonic concentrations may be explained by improved plant vigor, reproductive development and enhanced availability of assimilates during the flowering and grain-setting periods. Adequate assimilate supply during reproductive growth increases pollen viability, fertilization efficiency and grain establishment. Similar improvements in grain number following application of growth regulators have been reported in maize and other field crops (Księżak, 2008) (Hasan *et al*., 2026).

The significant improvement in grain yield resulting from Atonic application was mainly associated with the combined increase in grain number per head and 1000-grain weight. Grain yield represents the final outcome of interactions among genetic potential, environmental conditions and crop management practices. Any treatment that improves photosynthesis, nutrient utilization and assimilate movement toward grains can contribute to increased final yield (Elsahookie, 2002). Previous studies have also demonstrated positive effects of Atonic and other growth regulators on grain productivity of cereal crops, including wheat, maize and sorghum (Al-Issawi, 2022; Farahat, 2002; Al-Mafarji *et al*., 2026b).

The superior performance of plants treated with 5.0- and 7.5-mL L^{-1} Atonic suggests that these concentrations provided adequate stimulation of physiological processes without causing excessive hormonal effects. Although the highest concentration produced the greatest values for several traits, the similarity between 5.0- and 7.5-mL L^{-1} for some parameters indicates that the intermediate concentration may provide an economically suitable option for practical production systems.

The effect of application stage demonstrated that spraying during the end of vegetative growth and booting stages generally resulted in better performance compared with spraying at 50% flowering. This response may be attributed to the importance of these stages in determining plant biomass production, reproductive structure development and grain potential. Late application at flowering may be less effective because several yield-determining processes, such as spikelet formation and grain establishment, have already occurred.

The significant interaction between Atonic concentration and application stage indicates that the effectiveness of Atonic depends on the synchronization between concentration and plant developmental stage. Similar interactions between growth regulator concentration and application timing have been reported in field crops, confirming that optimum responses require appropriate management of both factors (Al-Issawi, 2022; Ali *et al*., 2022).

Harvest index increased following Atonic application, particularly at 5.0- and 7.5- mL L^{-1}. This indicates that Atonic improved the efficiency of dry matter partitioning toward grain production rather than only increasing vegetative biomass. Harvest index reflects the ability of plants to allocate photosynthetic products to economically important organs and increases in this parameter indicate improved crop productivity (Elsahookie, 2002). Similar increases in harvest index following application of growth regulators and biostimulants have been reported in field crops (Al-Issawi, 2022) (Hamdan, 2006).

Findings indicate that Atonic application increased sorghum productivity by improving physiological performance, grain formation and assimilate partitioning. However, since the experimental was conducted at a single site over two growing seasons, additional studies across multiple environments and years are needed to verify the consistency of these responses and to identify the most economically optimal application rate.

CONCLUSION

It can be concluded that foliar application of Atonic significantly enhanced grain yield and most yield components of *Sorghum bicolor* under the environmental conditions of western Iraq. Concentrations of 5.0- and 7.5-mL L^{-1} consistently produced superior performance compared with the untreated control. Application at the end of vegetative growth proved more effective than late application at 50% flowering. These findings suggest that Atonic can be incorporated into sorghum production programs to improve productivity under arid and semi-arid environments. However, further multi-location and multi-year studies, together with economic evaluation, are recommended before large-scale field adoption.

Conflict of interest

The authors declare that they have no conflict of interest.

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