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# Physiological and Morphological Responses of Wheat (Triticum aestivum L.) and Tomato (Solanum lycopersicum L.) to Seed Priming with Indole Acetic Acid as Plant **Growth Regulator**

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# ABSTRACT

**Article History** The use of plant growth hormones has become increasingly important in agriculture as they have Article # 24-583 Received: 16-Apr-24 the potential to improve plant growth, act as slow-release fertilizers, and facilitate targeted delivery of agrochemicals for sustainable crop production. In our study, we aimed to investigate Revised: 29-Apr-24 the effects of different concentrations of Indole acetic acid (IAA) on the growth rate and Accepted: 04-Mav-24 antioxidant enzyme activities of wheat and tomato plants. Different concentrations of IAA (control, Online First: 18-May-24 0.1, 1, 2.5, 5, 10, and 20mmol.L<sup>-1</sup>) were applied for 24 hours using seed priming techniques for wheat and tomato seeds. Our results showed that the application of IAA resulted in enhanced plant height, shoot and root biomass, and leaf area. Chlorophyll (a, b) and total chlorophyll contents were also promoted in wheat and tomato with varying responses. The highest growth level in wheat was recorded at 2.5mmol.L-1 treatment, whereas in tomato, it was recorded at 5mmol.L<sup>-1</sup> followed by 10mmol.L<sup>-1</sup> treatment. Moreover, the application of IAA significantly increased antioxidant enzyme activities such as Glutathione, Nitric Oxide, and malondialdehyde. These results suggest that IAA has a different effect on wheat and tomato seed priming, indicating that it may increase plant growth and development in different responses.

Keywords: Growth regulators; Antioxidant Enzymes; Growth Rate; Chlorophyll content

# INTRODUCTION

Indole acetic acid (IAA) which is known as a plant growth regulator (PGR) is essential for controlling several physiological functions in plants, including growth, development, and stress reactions. Plant growth regulators (PGRs) are commonly utilized in horticulture to improve plant growth and yield by enhancing fruit number and size (Serrani et al., 2007; Batlang, 2008). The application of PGRs has shown significant improvement in the production of tomatoes, wheat, and other vegetables, leading to better growth and quality (Saha et al., 2009; Nawaz et al., 2023). In crops like tomatoes, pepper and others, the application of PGRs can induce artificial parthenocarpy, enabling fertilization-independent fruit development and reducing yield fluctuation (Heuvelink & Körner, 2001; Saeed et al., 2023; Zafar et al., 2023). Synthetic gibberellins and auxins are frequently employed to enhance fruit setting in various fruit and vegetable cultivation, such as citrus and tomatoes. This is due to their recognized influence on parthenocarpy, fruit setting, and fruit size. By using PGRs, yields can be dramatically increased, up to four times in some cases.

As natural auxin moves from the stem to the roots, it prompts the overall growth of the root system. This leads to the formation of longer and more branched roots, which enhances the absorption of nutrients from the soil. Consequently, these nutrients are stored in the plant's storage organs, resulting in increased yield (Wang et al., 2005; Anwar et al., 2023). When the source of IAA is eliminated, root stimulation decreases accordingly. IAA is essential for fruit growth and development, retards fruit aging, and plays a minor role in the initiation of flowering and the development of reproductive structures (Asahira, 1967; Ahmed et al., 2023).

IAA plays a major role in regulating various aspects of plant growth, including the elongation of cells, apical dominance, and the formation of vascular tissue (Wang et al., 2021). The process known as lipid peroxidation (LPO) is

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happened when lipids are oxidized by reactive oxygen species (ROS), which damages cell membranes. Cell damage and eventually cell death may result from this (Celik & Tuluce, 2006; Ali et al., 2023). Depending on the IAA concentration and the plant species, IAA treatment can raise LPO levels in plant tissues (Yemelyanov et al., 2020; Zafar et al., 2022). Furthermore, by scavenging ROS and shielding cell membranes from LPO, IAA has been demonstrated to have antioxidant gualities and may aid in the reduction of oxidative stress in plants. This implies that IAA might shield plants from oxidative damage (Das Roychoudhury, 2014; Rehman et al., 2023). 8 Furthermore, IAA and NO are significant signaling molecules in tomatoes that are crucial for controlling a range of physiological processes, such as defense mechanisms, growth and development regulation, seed germination, root development, and reaction to biotic and abiotic stimuli. Nevertheless, the buildup of ROS may have numerous detrimental effects, such as color bleaching, LPO, and protein degradation (Ali et al., 2023; Singh et al., 2024).

Three amino acids make up the tripeptide molecule glutathione (GSH): glutamic acid, glycine, and cysteine. It is a potent antioxidant that aids in shielding plant cells from synthetic phytohormones, and oxidative stress brought on by pollution (Banerjee & Roychoudhury, 2019; Hossain et al., 2022). In addition, GSH helps detoxify toxic compounds and controls the growth and development of plants. Although the exact nature of the relationship between IAA and GSH in plants is unknown, research has indicated that IAA production and metabolism-related enzyme activity can be influenced by GSH levels (Jozefczak et al., 2012; Hasanuzzaman et al., 2017). By raising the activity of SOD in wheat, exogenous administration of phytohormones is one of the greatest ways to reduce oxidative stress (Guerreiro et al., 2013; Muhammad et al., 2016).

Our study aimed to evaluate the different responses in productivity of two important crops tomatoes and wheat due to treatment by different concentrations of IAA (control, 0.1, 1, 2.5, 5, 10, and 20mmol.L<sup>-1</sup>) using seed priming technique, by measuring the change in the morphological and physiological characteristics as the germination percentage, root length, shoot length, fresh weight, dry weight, and measuring some antioxidant activities.

# MATERIALS & METHODS

The research was performed to study the morphological and physiological response of wheat and tomato plant growth to Indole acetic acid as a growth hormone treatment. Wheat accession ID number (181) with local name Baldy Burr, tomato accession ID number (548). The seeds were collected from the National Gene Bank, Agricultural Research Center (ARC), Minister of Environment, Water and Agriculture, Riyadh, Kingdom of Saudi Arabia. Pre-sterilized seeds of the under-study plants were sown in different concentrations of IAA (Control, 0.1, 1, 2.5, 5, 10, and 20mmol.L<sup>-1</sup>) for 24H, treated seeds were washed in distilled water and then placed in petri dishes,

followed by three layers of filter paper that were moistened with distilled water. The control treatment was distilled water. After one week, the germinated seedlings were transferred to plastic pots of 30cm length containing 8kg of clayed soil. The sandy loam soil composition consisted of around 60% sand, 10% clay, and 30% silt particles. Organic manure was incorporated into the soil at a 1:1 ratio; synthetic fertilizers were not applied, and no signs of disease were detected throughout the experimental duration.

A completely randomized design with three replications was used. To assess the possible impacts of various concentrations of IAA on wheat and tomato growth attributes, plant height (cm), shoot fresh and dry mass (g), root length (cm), and root fresh and dry masses (g) were recorded. The leaf area was recorded with a leaf area meter (CI-202 Portable Laser Leaf Area Meter) after four weeks, six weeks, and eight weeks from selected plants of each treatment.

Physiological attributes, such as chlorophyll contents (chlorophyll a, chlorophyll b, and total chlorophyll), were measured by following protocol of Arnon (1949) and antioxidant enzyme activities (GSH, GST, GPX, and MDA) were also analyzed.

#### **Antioxidant Enzyme Activities Determination**

Ten mL of 100mM phosphate buffer was used to grind 0.5g of wheatgrass and tomato seeds, which were then submerged in an ice bath to estimate MDA, NO, GSH, and their corresponding enzymes (glutathione peroxidase, GPx and glutathione-S-transferase, GST). The homogenate was centrifuged for 20min at 4°C at 5000rpm. The various parameters were conducted using the supernatant. The biodiagnostic kit's brochure states that the method, which is based on the determination of thiobarbituric acid reactive substance (TBARS) as a product of lipid peroxidation (LPO), can be modified slightly and is described as follows: thiobarbituric acid reacts with malondialdehyde (MAD) in an acidic medium at 95°C for 30min to form TBARS; the absorbance of this pink product can be measured at 534nm (Buege & Aust, 1978). With a few minor adjustments, the nitric oxide assay was measured using Montgomery and Dymock's (1962) method. With a few minor adjustments, the procedure was reported by Beutler et al. (1963) for the interaction of GSH with 5, 5-dithiobis-2-nitrobenzoic acid, DTNB, to get a yellow color (Beutler et al., 1963). According to the biodiagnostic kit's brochure, the decreased chromogen's absorbance can be evaluated at 450 nm, with a direct correlation to the GSH concentration. Glutathione peroxidase activity is measured using the Paglia and Valentine (1967) method. With very few adjustments, the Habig et al. (1974) approach was applied, and it is reliant on quantifying the conjugation of reduced glutathione with 1-chloro-2,4dinitrobenzene (CDNB) to estimate the activity of GST. At 340nm, absorbance increases in tandem with conjugation (Habig et al., 1974). The rate of rise is directly correlated with the sample's GST activity as per the biodiagnostic kit's booklet.

#### **Statistical Analysis**

For this study, all experiments were conducted in triplicates. The mean and SD of the results were calculated. The investigated parameters were calculated by comparing the different gradual concentrations of Indole acetic acid (IAA) groups, 0.1, 1, 2.5, 5, 10, and 20mmol.L<sup>-1</sup> to the control group. The ANOVA test was performed, and the data are presented as mean $\pm$ SE from three independent biological replicates. Mean values with distinct letters indicate significant differences as determined by Tukey's multiple range test (P $\leq$ 0.05).

#### RESULTS

# Impact of IAA on Morphological Characteristics of Wheat and Tomato

The experiment aimed to assess the impact of various concentrations of IAA on the growth of wheat and tomato plants after 24-hour seed priming. Pre-sterilized seeds of the wheat variety and tomato variety were subjected to various IAA concentrations (Control, 0.1, 1, 2.5, 5, 10, and 20mmol.L<sup>-1</sup>) and then germinated using the seed priming technique. The plants were later transplanted to clay soil-filled pots. and data regarding growth parameters (plant heights) were collected and presented in Table 1 and Table 2 and illustrated in Fig. 1 and Fig. 2 for wheat and tomato plants, respectively.

#### Impact of IAA on Morphological Characteristics of Wheat

The measured growth parameters of wheat were collected and presented in Table 1. The data in Table 1 exhibited that the highest root fresh weight  $(1.98\pm0.66)$ ) was recorded with 2.5mmol.L<sup>-1</sup> IAA treatment, followed by 5mmol.L<sup>-1</sup> treatment which was  $1.66\pm0.72$  compared to the control ( $1.56\pm0.83$ ). The application of IAA also significantly boosted shoot fresh weight with the same concentrations of IAA. The highest shoot fresh weight ( $2.53\pm0.73$ ) was recorded with 2.5mmol.L<sup>-1</sup> IAA treatment, followed by 5mmol.L<sup>-1</sup> which was ( $2.41\pm0.66$ ) compared to the control ( $2.11\pm0.93$ ). After one month of germination, the highest shoot length was recorded with  $2.5mmol.L^{-1}$  IAA treatment followed by 1mmol.L<sup>-1</sup> IAA treatment compared to the control Table 1.

The maximum dry mass of the shoot was recorded  $(0.91\pm0.20g)$  with 2.5mmol.L<sup>-1</sup> IAA treatment, followed by 5mmol.L<sup>-1</sup> which was  $(0.82\pm0.09g)$  compared to the control  $(0.66\pm0.09g)$ . The minimum dry mass of the shoot was recorded with 20 5mmol.L<sup>-1</sup> IAA treatment  $(0.31\pm0.05g)$ . The highest root length after one month of germination was recorded with 2.5mmol.L<sup>-1</sup> IAA treatment, followed by 5mmol.L-1 compared to the control. The maximum root fresh weight  $(1.98\pm0.66g)$  was recorded with 2.5mmol.L<sup>-1</sup> IAA treatment, followed by 5mmol.L-1 ( $1.66\pm0.72g$ ) compared to the control. The minimum root fresh weight was recorded with 20mmol.L<sup>-1</sup> IAA treatment. Similarly, the maximum root dry weight was recorded with the same treatment concentrations of 2.5mmol.L<sup>-1</sup> and 5mmol.L<sup>-1</sup> as shown in Table 1.

Plant shoot height was monitored during the growth period for two, three, four, and eight weeks to evaluate the effectiveness of the different concentrations of IAA, these results are presented in Table 2 and illustrated in Fig. 1. After two weeks of germination, the induced growth effect was regarded only with 2.5mmol.L<sup>-1</sup> treatment with plant height was 20.4cm compared with the height of the control treatment which was 18.26cm. Although the other treatments had plant lengths less than the control where the lowest plant height was recorded with 20mmol.L<sup>-1</sup>. After three, four, and eight weeks of germination, the highest plant height was recorded with 2.5 followed by 5mmol.L<sup>-1</sup> treatment, and the lowest plant height was recorded with 20mmol.L<sup>-1</sup> treatment. Fig. 2 shows the difference in wheat growth rate due to the application of different concentrations of IAA.

The leaf area was also observed during the growth periods for four, six, and eight weeks and the results are presented in Table 3 and illustrated in Fig. 3. The highest leaf area was recorded with 2.5 followed by 5mmol.L<sup>-1</sup> treatment compared with control.

Information regarding the influence of IAA on wheat chlorophyll content is provided in Table 4. The findings reveal significant discrepancies among different treatments. The highest values for chlorophyll a, b, and total chlorophyll were recorded with 2.5mmol.L<sup>-1</sup> treatment followed by 5mmol.L<sup>-1</sup> treatment. Similarly, minimum chlorophyll contents' were obtained with 20mmol.L<sup>-1</sup> treatment, as compared with the control.

Table 1: Effect of different treatments of Indole acetic acid (IAA) on morphological attributes of wheat

Table 1: Effect of different treatments of indole acetic acid (IAA) on morphological attributes of wheat									
IAA Treatment	Root length	Root fresh weight	Root dry weight	Shoot length	Shoot fresh weight	Shoot dry weight			
Control	11.24±2.78a	1.56±0.83ab	0.26±0.27b	28.33±2.35a	2.11±0.93ab	0.66±0.09ab			
0.1	9.56±2.34b	1.29±0.56b	0.20±0.29b	30.06±2.2a	2.29±0.08ab	0.61± 0.13ab			
1	12.23±3.12ab	1.31±0.79b	0.24±0.18b	26.43±3.93b	1.63±0.05b	0.55±0.18b			
2.5	15.33±3.84a	1.98±0.66a	0.35±0.22a	32.26±3.44a	2.53±0.73a	0.91±0.20a			
5	13.3±2.95a	1.66±0.72ab	0.29±0.09b	27.43±1.23b	2.41±0.66a	0.82±0.09a			
10	8.32±1.24b	0.96±0.05c	0.19±0.04b	26.89±3.67b	1.34±0.87b	0.57±0.07b			
20	7.34±1.08b	0.35±0.08c	0.13±0.09b	25.06±0.736ab	0.97±0.06c	0.31±0.05c			

The data are presented as mean $\pm$ SE from three independent biological replicates. Mean representative values with different letters are significantly different according to Tukey's multiple range test (P $\leq$ 0.05).

Table 2: Plant height of wheat monitoring for 2	2, 3, 4, and 8 weeks after IAA treatment

Experimental weeks	5						
	Control	0.1	1	5	10	20	
2	18.26±1.01ab	17.16±0.78ab	17.26±1.38ab	20.40±2.84a	16.16±1.13ab	17.33±2.16ab	12.6±074c
3	24.50±0.4ab	25.33±2.05a	22.90±2.9c	26.33±3.06a	25.63±1.06a	23.26±3.56ab	20.1±2.02ab
4	28.33±2.35ab	30.06±2.2ab	26.43±3.93ab	32.26±3.44a	27.43±1.23ab	26.89±3.67ab	25.06±0.736c
8	47.00±4.78ab	44.66±6.34ab	43.33±4.18ab	53.33±7.34a	49.30±3.85a	37.30±6.34c	35.33±4.98c

The data are presented as mean $\pm$ SE from three independent biological replicates. Mean representative values with different letters are significantly different according to Tukey's multiple range test (P $\leq$ 0.05).



**Fig. 1:** Shows the different responses in plant heights of (A) wheat and (B) tomato after 2, 3, 4, and 8 weeks of treatment with different concentrations of Indole acetic acid (IAA).



Fig. 2: Show the difference in growth rate response for A-wheat and B-tomato with the treatment of Indole acetic acid (IAA).

### Impact of IAA on Morphological Characteristics of Tomato

The measured growth parameters of tomato (Table 5) show that the highest root length after one month of germination was recorded with 5mmol.L<sup>-1</sup> IAA treatment, followed by 10mmol.L<sup>-1</sup> compared to the control. The highest root fresh weight (2.59g) was recorded with 5mmol.L<sup>-1</sup> IAA treatment, followed by 10mmol.L<sup>-1</sup> treatment which was (2.22g) compared to the control (2.06g). The minimum root fresh weight was recorded with 20mmol.L<sup>-1</sup> IAA treatment. Additionally, the maximum root dry weight was recorded with 5mmol.L<sup>-1</sup>. The minimum root dry weight was recorded with 20mmol.L<sup>-1</sup> as shown in Table 5.

The application of IAA also significantly improved shoot length, after one month of germination, the highest





**Fig. 3:** Shows the different responses in the leaf area of (A) wheat and (B) tomato after 4, 6, and 8 weeks of treatment with different concentrations of Indole acetic acid (IAA).

shoot length (45.43cm) was recorded at 5mmol.L<sup>-1</sup> IAA treatment, followed by 10mmol.L<sup>-1</sup> IAA treatment which was 39.89cm compared to the control. The minimum shoot length was recorded with 1mmol.L<sup>-1</sup> IAA treatment. The highest shoot fresh weight was 9.01g which was recorded with 5mmol.L<sup>-1</sup> IAA treatment, followed by 10mmol.L<sup>-1</sup> which was 8.53g compared to the control 8.02gm. The maximum dry mass of the shoot was 2.42g recorded with 5mmol.L<sup>-1</sup> IAA treatment, followed by 10mmol.L<sup>-1</sup> which was 2.19g compared to the control 2.05g. The minimum dry mass of the shoot was recorded at 20mmol.L<sup>-1</sup> IAA treatment 1.77g.

Plant shoot height was examined during the growth period for two, three, four, and eight weeks to evaluate the effectiveness of the different concentrations of IAA, these results are presented in Table 6 and illustrated in Fig. 1.

The highest shoot length was recorded with 5mmol.L<sup>-1</sup> IAA treatment followed by 10mmol.L<sup>-1</sup> at all examination periods. The lowest shoot length was recorded with 1mmol.L<sup>-1</sup> IAA treatment at all examination periods.

The leaf area was also observed during the growth periods for four, six, and eight weeks and the results are presented in Table 6. And illustrated in Fig. 3. The highest leaf area was recorded with 5mmol.L<sup>-1</sup> treatment followed by 10mmol.L<sup>-1</sup> treatment compared with control.

Table 4 displays the impact of IAA on the chlorophyll levels of tomato plants. The outcomes demonstrate notable distinctions among the different treatments. The highest values for chlorophyll contents were recorded with 5mmol.L<sup>-1</sup> treatment followed by 10mmol.L<sup>-1</sup> treatment. Additionally, minimum chlorophyll contents' were obtained with 1mmol.L<sup>-1</sup> treatment, as compared with the control.

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 Table 3: Wheat leaf area monitoring a long 4, 6, and 8 weeks after IAA treatment

Experimental		IAA Treatments									
weeks	Control	0.1	1	2.5	5	10	20				
4	9.92±0.358ab	9.33±0.495ab	8.38±0.555ab	14.84±0.649a	12.92±0.128a	9.28±0.512ab	5.7±0.610c				
6	12.81±0.44ab	11.91±0.335ab	10.31±0.45c	17.72±0.477a	15.81±0.277a	12.85±0.162ab	9.11±0.753c				
8	14.48±1.118ab	14.93±0.405ab	12.5±0.639c	20.81±0.642a	18.15±0.455a	16.55±0.645a	12.58±0.652c				

The data are presented as mean $\pm$ SE from three independent biological replicates. Mean representative values with different letters are significantly different according to Tukey's multiple range test (P<0.05).

Table 4: Effect of different treatments of IAA c	on chlorophyll contents of wheat and tomato
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		Chlorophyll in Whea	nt		Chlorophyll in Tomato				
IAA Treatments	Chlorophyll a (mg/g)	Chlorophyll b (mg/g)	Total	Chlorophyll Chlorophyll a (mg/g)	Chlorophyll b (mg/g)	Total	Chlorophyll		
			(mg/g)			(mg/g)			
Control	0.21±0.02b	0.25±0.02b	0.46±0.01b	0.41±0.04ab	0.46± 0.03ab	0.87±0.03ab	)		
0.1	0.26±0.02a	0.30±0.02ab	0.56±0.01ab	o 0.35±0.03c	0.39±0.01c	0.74±0.04c			
1	0.28±0.03a	0.29±0.02ab	0.57±0.02ab	o 0.29±0.01c	0.32±0.02c	0.61±0.03c			
2.5	0.41±0.03a	0.49±0.03a	0.90±0.03a	0.45±0.02ab	0.57±0.03ab	1.02±0.06a			
5	0.32±0.03a	0.40±0.03a	0.72±0.02a	0.58±0.05a	0.64±0.07a	1.22± 0.05a			
10	0.25±0.02a	0.31± 0.02ab	0.56±0.01ab	o 0.53±0.01a	0.59±0.08a	1.12±0.05a			
20	0.15±0.02c	0.19±0.02c	0.34±0.02c	0.44±0.06ab	0.50±0.04ab	0.94±0.03ab	)		

The data are presented as mean $\pm$ SE from three independent biological replicates. Mean representative values with different letters are significantly different according to Tukey's multiple range test (P<0.05).

Table 5: Effect of different treatments of Indole acetic acid (IAA) on morphological attributes of tomato after one month of treatm
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IAA Treatments	Root length	Root fresh weight	Root dry weight	Shoot length	Shoot fresh weight	Shoot dry weight
Control	13.24±6.78ab	2.06± 0.22ab	0.30±0.06ab	33.43±1.32ab	8.02±0.28ab	2.05±0.19a
0.1	11.56±4.34b	1.99±0.17b	0.28±0.05ab	31.16±2.23b	7.83±0.22ab	1.91±0.07b
1	12.23±3.12b	1.82±0.28b	0.24±0.06b	29.53±3.93b	7.94±0.56ab	1.85±0.03b
2.5	15.33±5.84a	2.02±0.27ab	0.27±0.09b	37.26±3.44a	8.33±0.38ab	2.04±0.13a
5	17.3±2.95a	2.59± 0.22a	0.42±0.05a	45.43±2.23a	9.01±0.63a	2.42±0.33a
10	15.42±3.24a	2.22±0.37a	0.33±0.08ab	39.89±2.67a	8.53±0.44a	2.19±0.17a
20	10.34±5.08c	0.95±0.07c	0.19±0.09c	38.06±2.36a	7.27±0.22b	1.77±0.08c
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The data are presented as mean±SE from three independent biological replicates. Mean representative values with different letters are significantly different according to Tukey's multiple range test (P≤0.05).

Table 6: Plant height of Tomato monitoring for 2, 3, 4, and 8 weeks after IAA treatment

Experimental weeks	IAA Treatments									
	Control	0.1	1	2.5	5	10	20			
2	15.26±1.91ab	14.96±0.78c	14.66±1.38c	19.40±1.54a	24.16±0.93a	21.33±1.16a	20.6±0.64a			
3	20.25±1.4ab	22.43±2.05ab	20.19±2.9ab	25.30±3.06ab	31.63±1.06a	29.26±2.16a	28.1±1.02a			
4	33.43±1.32ab	31.16±2.23c	29.53±3.93c	37.26±3.44ab	45.43±2.23a	42.89±2.67a	40.06±2.36a			
8	66.24±6.78ab	59.56±4.34c	58.23±3.12c	75.33±5.84a	91.3±2.95a	81.32±3.24a	80.34±5.08a			

The data are presented as mean $\pm$ SE from three independent biological replicates. Mean representative values with different letters are significantly different according to Tukey's multiple range test (P $\leq$ 0.05).

**Table 7:** Antioxidant activities of Wheat (W) and Tomato (T) as Lipid Peroxidation Products (malondialdehyde, MDA), nitric oxide (NO), Glutathione (GSH), Glutathione peroxidase (GPx), and Glutathione-S-transferase (GST) Concentration (µmol/g. tissue) at Different Indole acetic acid (IAA) treatments

Lipid Peroxidation Product	Control	IAA-0.1	IAA-1	IAA-2.5	IAA-5	IAA-10	IAA-20		
MDA-W	17.37±0.41ab	18.07±0.38ab	19.73±0.25ab	30.7±0.51a	27.22±0.53a	20.03±1.26) a	23.87±1.36a		
MDA-T	8.57±0.5ab	10.8±0.72ab	16.7±0.36a	21.9±1.69a	77.9±2.1a	44.4±3.47a	35.87±0.76a		
NO-W	145±5ab	150.3±3.51ab	160±3.6ab	201.3±1.53a	311.7±7.64a	262.3±8.6a	228.7±3.21a		
NO-T	89.3±5.4ab	95.2±1.6ab	99.1±0.79ab	210±1.3a	177.6±2.5a	112.7±2.6a	153±2.7a		
GSH-W	2.21±5c	3.76±0.15ab	6.71±0.28ab	7.47±0.47a	14.22±0.63a	13.68±0.19a	9.12±0.75a		
GSH-T	14.22±0.63ab	18.68±0.82ab	57.39±3.05a	69.28±0.75a	122±4.76a	115.7±4.76a	91.88±3.46a		
GPx-W	13.3±3.6ab	17.5±0.86ab	28.9±2.8a	95.4±5.5a	84.2±5a	63.1±3.1 a	48.2±2.1a		
GPx-T	92.3±0.72ab	102.7±2.2ab	100.9±2.8ab	133.5±13.6a	193.4±5.9a	194.4±5.5a	164±4.1a		
GST-W	4.22±0.21ab	6.14±0.48ab	9.1±2ab	14.7±1.2a	12.56±0.68a	10.4±0.13a	11.1±0.42a		
GST-T	30.5±0.79ab	41±1.9a	46.2±2a	48.5±2.5a	64.9±3.2) a	56.6±0.68a	50.7±0.42a		

The data are presented as mean $\pm$ SE from three independent biological replicates. Mean representative values with different letters are significantly different in a row according to Tukey's multiple range test (P $\leq$ 0.05).

#### **Antioxidant Enzyme Activities Determination**

# Impact of IAA Treatments on Antioxidant Enzyme Activity

The results of the study on the effect of Indole-3-Acetic Acid (IAA) application on different antioxidant enzyme activities are presented in Table 7. The application of IAA has been found to promote antioxidant enzyme activities. Table 7 and Fig. 4 show that all plant groups exhibited a significant increase in malondialdehyde (MDA), nitric oxide (NO), glutathione (GSH), Glutathione Peroxidase (GPx), and glutathione -S-transferase (GST) activities in both wheat and tomato plants up to a certain concentration, after which there was a decrease in activity compared to the control group.

For wheat seeds, the ideal concentration for (MDA, GPx, and GST) activities was 2.5mmol.L<sup>-1</sup> followed by 5mmol.L<sup>-1</sup>. In the case of (NO and GSH), it was 5mmol.L<sup>-1</sup> treatment followed by 10mmol.L<sup>-1</sup>. For tomato seeds, the ideal concentration for the examined antioxidant enzyme activities was 5mmol.L<sup>-1</sup> treatment followed by 10mmol.L<sup>-1</sup>, except for NO, where the ideal concentration was 2.5mmol.L<sup>-1</sup> followed by 5mmol.L<sup>-1</sup>.



Fig. 4: Antioxidant activities of Wheat and Tomato as A- Lipid Peroxidation Products (malondialdehyde, MDA), B- Nitric oxide (NO), C- Glutathione (GSH), D- Glutathione peroxidase (GPx), and E- Glutathione-S-transferase (GST) Concentration at Different IAA treatments.

### DISCUSSION

The purpose of this study was to determine the potential impact of IAA on the growth of wheat and tomato plants. The application of various concentrations of IAA through seed priming significantly enhanced the growth of both wheat and tomato plants in comparison to the control group. The analysis revealed that IAA had a significant impact on the development of roots, shoots, and leaves of both wheat and tomato plants, including root and shoot length, root, and shoot fresh and dry weight, and leaf area (Table 1-5).

The study revealed that the most effective concentration of IAA for wheat plants was 2.5mmol.L<sup>-1</sup>, while for tomato plants, the ideal concentration was 5mmol.L<sup>-1</sup>, followed by 10mmol.L<sup>-1</sup>. It was observed that 2.5mmol.L<sup>-1</sup> treatment concentration enhanced all measured morphological attributes such as root length, root fresh and dry weight, shoot length and shoot fresh and dry weight in the wheat plant (Table 1). Our results agrees with the findings of Al-haidary and AL-zubaidy (2019), who revealed that Indole-3-acetic acid (IAA) is a plant hormone that promotes wheat growth. They found that foliar application of IAA at different growth stages of wheat (Triticum aestivum L.) resulted in increased plant height, chlorophyll content, spike length, number of spikes per square meter, 1000-grain weight, grain yield, and biological yield. The study concluded that the best results were achieved with a 100-ppm concentration of IAA. Our study revealed that IAA seed priming of wheat increases wheat chlorophyll content (chlorophyll a and chlorophyll b) with a treatment concentration of 2.5mmol.L<sup>-1</sup>.

The highest root length was observed with a 2.5mmol.L-1 treatment, followed by a 5mmol.L-1 treatment. However, the 10 and 20mmol.L-1 treatments caused root dwarfism Table 1. These results support the findings of Kumar et al. (2017), who concluded that the role of IAA in plant physiology is important in stimulating root thickness, and root number, increasing the plant's nutrient and mineral uptake, and promoting plant growth (Kumar et al., 2017).

Our results disagree with the findings of Edelmann (2022), who indicated that the effect of IAA on root length is still being studied. He suggests that the classical theory for auxin-regulated root growth, which posits the inhibitory action of IAA on the elongation growth of root cells, may not be accurate (Edelmann, 2022).

There is a noticeable effect of IAA 5mmol.L<sup>-1</sup> treatments on the morphological and physiological attributes of tomato plants as leaf surface area, plant height, shoot dry and fresh weight, root length, root dry and fresh weight, Chlorophyll content followed by 10mmol.L<sup>-1</sup> treatments. These findings could be ascribed to IAA's function in promoting plant growth and development through its stimulation of various processes, such as cell division, tissue growth, phototropism, gravitropism, apical dominance, lateral root initiation, vascular tissue differentiation, embryogenesis, senescence, and ripening (Naeem et al., 2004). Additionally, it leads to increased cell elongation and the accumulation of building blocks, along with higher saccharide content (Mostafa & Alhamd, 2011).

Our findings align with the findings of Fu et al. (2015), who elucidated the significant role of IAA in regulating

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plant growth. For instance, it governs the development of vascular tissues, cell elongation, and apical dominance. Similarly, Yurekli et al. (2003) elucidated that IAA stimulates cell elongation by modifying conditions such as an increase in osmotic cell contents and enhanced water permeability into the cell (Yurekli et al., 2003).

Commercially, auxins are employed to enhance crop production and regulate various aspects of plant growth and development. While they facilitate rapid growth, such as in shoot tissues, young leaves, and developing seeds, they may not directly promote lateral root development.

IAA can either remain in its free state or form a conjugated complex with sugars or amino acids in developing leaves and cotyledons (Olatunji et al., 2017). It participates in the ripening of fruit, root growth, and cell elongation activities. It also promotes cell division. Furthermore, it is distributed throughout the plant to regulate several physiological processes and is synthesized in the apical meristem of the plant (Pustovoitova & Zholkevich, 1992; Donoso et al., 2017).

Our findings suggest that the application of IAA can enhance the antioxidant enzyme activities of wheat and tomato plants up to certain concentrations, after which there is a reduction in activity. The study provides insights into the optimal concentration of IAA application for promoting antioxidant enzyme activities in wheat and tomato plants. The increase in oxidants like MDA and NO concentration in tomato (Kamran et al., 2021) and wheat (Bashri & Prasad, 2016) tissues is determined by the dosedependent nature of IAA as in Table 7 and Fig. 4. Drought-induced oxidative stress is prevented in soybean plants by IAA, which controls NO levels and enhances heme oxygenase-1 production and activity (Lecube et al., 2014). According to Spaepen et al. (2007), there is evidence that IAA and NO can interact and affect each other's signaling pathways in plants (Spaepen et al., 2007). It was demonstrated that the procedure involves a NOmediated cGMP-dependent pathway (Pagnussat et al., 2003). Likewise, a study has shown that NO plays a critical role in signaling plant responses to biotic and abiotic stimuli (Siddigui et al., 2011). Furthermore, NO has been linked to the upregulation of heme oxygenase-1 in soybean plants exposed to UVB light (Pagnussat et al., 2002). Research has demonstrated that IAA can cause plant tissues to produce NO, and that NO can alter how IAA affects a plant's ability to grow and develop (Mora et al., 2014). Additionally, in response to shifting environmental conditions, they can cooperate to control nutrient intake and root development. Reactive oxygen species cause LPO, which damages and kills cells by rupturing their membranes. This implies that the effects of IAA on LPO can differ based on the circumstances and be dose-dependent Table 7 and Fig. 4.

ROS levels in plant cells are regulated by GSH and related enzymes, which may have an impact on IAA signaling pathways. IAA and plant GSH have a complicated and intertwined connection overall, with both molecules being crucial to plant growth, development, and stress responses (Raza et al., 2022). Antioxidant enzymes such as GPx help to prevent LPO in wheat and tomato plants. NO

is a signaling molecule found in plants, particularly tomatoes, that regulates a few physiological processes and stress responses. Together with IAA, it might influence the growth, development, and stress tolerance of plants. It regulates the development and growth of tomato and wheat plants. It can influence the expression of antioxidant enzymes and alter the plant's defense mechanisms, which in turn influences the plant's reaction to stress. According to reports, IAA can stimulate the development of antioxidant enzymes in response to oxidative stress, which helps shield plant cells from reactive oxygen speciesinduced damage. Furthermore, it has been demonstrated that IAA controls GSH levels, a crucial cofactor for GPx. IAA may indirectly affect GPx activity and plant cells' total antioxidant capacity by adjusting GSH levels (Bela et al., 2015; Yang et al., 2017). Utilizing GSH, enzyme GPx catalyzes the reduction of hydrogen peroxide and lipid hydroperoxides, protecting tomato and wheat plants from oxidative damage as investigated in Table 7 and Fig. 4.

The increase in GST enzyme activity in tomatoes and wheat helps in detoxification by combining GSH with toxic chemicals to make them more soluble in water and make removal easier. The main antioxidant defense systems in plants that combat oxidative stress are non-enzymatic ones like GSH and enzymatic ones like GST (Hasanuzzaman et al., 2017). The antioxidant defense system and ROS accumulation in plant cells should ideally maintain a steady-state equilibrium to maintain proper redox biology responses, which regulate various processes necessary for plant growth and development (Sharma et al., 2019; Zandi & Schnug, 2022). This equilibrium is upset by an abundance of ROS, such as LPO and NO, which causes cellular damage, programmed cell death, and an increase in ROS production (Tanwir et al., 2022; Faizan et al., 2023).

#### Conclusion

From the present experiment, it can be concluded that various levels of plant growth regulators as indole acetic acid (IAA) significantly affected the various growth stages of wheat and tomato. The application of IAA as a seed priming, concentration of 2.5mmol.L<sup>-1</sup> enhanced the morphological and physiological parameters of wheat, despite Tomato having different responses for IAA treatment where 5mmol.L<sup>-1</sup> treatment was the ideal concentration of IAA followed by 10mmol.L<sup>-1</sup> treatment. Our results suggest that the application of IAA can also enhance the antioxidant enzyme activities of wheat and tomato plants up to certain concentrations, after which there is a reduction in activity. Further, insight analysis will be helpful in determining the correct mode of action for indole acetic acid.

#### REFERENCES

Ahmed, S. R., Anwar, Z., Shahbaz, U., Skalicky, M., Ijaz, A., Tariq, M. S., Zulfiqar, U., Brestic, M., Alabdallah, N. M., & Alsubeie, M. S. (2023). Potential role of silicon in plants against biotic and abiotic stresses. *Silicon*, 15(7), 3283-3303.

- Al-haidary, H.K.M.A. & AL-zubaidy, S.A.A., 2019. Foliar application of IAA at different growth stages and their influenced on growth and productivity of bread Wheat (*Triticum aestivum* L.). *Journal of Physics: Conf. Series* 1294, 092029. https://doi.org/10.1088/1742-6596/1294/9/092029
- Ali, A., Zafar, M. M., Farooq, Z., Ahmed, S. R., Ijaz, A., Anwar, Z., Abbas, H., Tariq, M. S., Tariq, H., & Mustafa, M. (2023). Breakthrough in CRISPR/Cas system: Current and future directions and challenges. *Biotechnology Journal*, 18(8), 2200642.
- Ali, M., Shaukat, F., Khan, W., Syed, A., Maqsood, J., Kamal, H., Ercisli, S., Balijagic, J., Ullah, R., & Bari, A. (2023). Microsatellite-based diversity analysis and the development of core-set germplasm in Pakistani barley lines. *Cellular and Molecular Biology*, 69(10), 100-108.
- Anwar, Z., Ijaz, A., Ditta, A., Wang, B., Liu, F., Khan, S. M.-U.-D., Haidar, S., Hassan, H. M., & Khan, M. K. R. (2023).
  Genomic Dynamics and Functional Insights under Salt Stress in Gossypium hirsutum L. *Genes*, 14(5), 1103.
- Arnon, D.I., 1949. Copper enzymes in isolated chloroplasts polyphenol oxidase in Beta vulgaris. *Plant Physiol.*, 24: 1-15.
- Asahira, T. (1967). Studies on fruit development in tomato. I. Ovule development and content of diffusible auxin in synthetic auxin-and gibberellin-induced parthenocarpic tomato fruits in relation to their development. *Mem. Research Inst. Food Science, Kyoto University*, 28, 47-74.
- Banerjee, A., & Roychoudhury, A. (2019). Role of glutathione in plant abiotic stress tolerance. *Reactive* oxygen, nitrogen and sulfur species in plants: production, metabolism, signaling and defense mechanisms, 159-172.
- Bashri, G., & Prasad, S. M. (2016). Exogenous IAA differentially affects growth, oxidative stress and antioxidants system in Cd stressed Trigonella foenum-graecum L. seedlings: Toxicity alleviation by up-regulation of ascorbate-glutathione cycle. *Ecotoxicology and Environmental Safety, 132*, 329-338.
- Batlang, U. (2008). Benzyladenine plus gibberellins (GA4+7) increase fruit size and yield in greenhouse-grown hot pepper (Capsicum annuum L.).
- Bela, K., Horváth, E., Gallé, Á., Szabados, L., Tari, I., & Csiszár, J. (2015). Plant glutathione peroxidases: emerging role of the antioxidant enzymes in plant development and stress responses. *Journal of Plant Physiology*, 176, 192-201.
- Beutler, E., Duron, O., & Kelly, B. M. (1963). Improved method for determination of blood glutathione.
- Buege, J. A., & Aust, S. D. (1978). [30] Microsomal lipid peroxidation. In *Methods in enzymology* (Vol. 52, pp. 302-310). Elsevier.
- Celik, I., & Tuluce, Y. (2006). Effects of indoleacetic acid and kinetin on lipid peroxidation and antioxidant defense in various tissues of rats. *Pesticide Biochemistry and Physiology*, *84*(1), 49-54.
- Das, K., & Roychoudhury, A. (2014). Reactive oxygen species (ROS) and response of antioxidants as ROS-

scavengers during environmental stress in plants. *Frontiers in Environmental Science, 2,* 53.

- Donoso, R., Leiva-Novoa, P., Zúñiga, A., Timmermann, T., Recabarren-Gajardo, G., & González, B. (2017). Biochemical and genetic bases of indole-3-acetic acid (auxin phytohormone) degradation by the plantgrowth-promoting rhizobacterium Paraburkholderia phytofirmans PsJN. *Applied and Environmental Microbiology*, 83(1), e01991-01916.
- Edelmann, H. G. (2022). Plant root development: is the classical theory for auxin-regulated root growth false? *Protoplasma*, 259(3), 823-832.
- Faizan, M., Hayat, S., & Ahmed, S. M. (2023). Reactive Oxygen Species: Prospects in Plant Metabolism. Springer Nature.
- Fu, S. F., Wei, J. Y., Chen, H. W., Liu, Y. Y., Lu, H. Y., & Chou, J. Y. (2015). Indole-3-acetic acid: A widespread physiological code in interactions of fungi with other organisms. *Plant signaling & behavior*, *10*(8), e1048052.
- Guerreiro, A. C., Gago, C. M., Miguel, M. G., & Antunes, M. D. (2013). The effect of temperature and film covers on the storage ability of Arbutus unedo L. fresh fruit. *Scientia Horticulturae*, 159, 96-102.
- Habig, W., Pabst, M., & Jakoby, W. (1974). Biological assay kit measures total GST activity. *WJ Biology Chemistry*, *249*, 7130-7139.
- Hasanuzzaman, M., Nahar, K., Anee, T. I., & Fujita, M. (2017). Glutathione in plants: biosynthesis and physiological role in environmental stress tolerance. *Physiology and Molecular Biology of Plants, 23*, 249-268.
- Heuvelink, E., & Körner, O. (2001). Parthenocarpic fruit growth reduces yield fluctuation and blossom-end rot in sweet pepper. *Annals of Botany, 88*(1), 69-74.
- Hossain, A., Bhutia, K. L., Pramanick, B., Maitra, S., Ibrahimova, U., Kumari, V. V., Ahmad, Z., Uzair, M., & Aftab, T. (2022). Glutathione in Higher Plants: Biosynthesis and Physiological Mechanisms During Heat and Drought-Induced Oxidative Stress. In Antioxidant Defense in Plants: Molecular Basis of Regulation (pp. 181-214). Springer.
- Jozefczak, M., Remans, T., Vangronsveld, J., & Cuypers, A. (2012). Glutathione is a key player in metal-induced oxidative stress defenses. *International Journal of Molecular Sciences*, 13(3), 3145-3175.
- Kamran, M., Danish, M., Saleem, M. H., Malik, Z., Parveen, A., Abbasi, G. H., Jamil, M., Ali, S., Afzal, S., & Riaz, M. (2021). Application of abscisic acid and 6benzylaminopurine modulated morpho-physiological and antioxidative defense responses of tomato (Solanum lycopersicum L.) by minimizing cobalt uptake. *Chemosphere*, 263, 128169.
- Kumar, N. V., Rajam, K. S., & Rani, M. E. (2017). Plant growth promotion efficacy of indole acetic acid (IAA) produced by a mangrove associated fungi-Trichoderma viride VKF3. *International Journal of Current Microbiology and Applied Sciences*, 6(11), 2692-2701.

- Lecube, M. L., Noriega, G. O., Santa Cruz, D. M., Tomaro, M. L., Batlle, A., & Balestrasse, K. B. (2014). Indole acetic acid is responsible for protection against oxidative stress caused by drought in soybean plants: the role of heme oxygenase induction. *Redox Report*, 19(6), 242-250.
- Montgomery, H.A.C. & Dymock, J.F., 1962. The rapid determination of nitrate in fresh and saline waters. *Analyst*, 87, 374-378.
- Mora, V., Bacaicoa, E., Baigorri, R., Zamarreno, A. M., & García-Mina, J. M. (2014). NO and IAA key regulators in the shoot growth promoting action of humic acid in Cucumis sativus L. *Journal of Plant Growth Regulation*, *33*(2), 430-439.
- Mostafa, G. G., & Alhamd, M. (2011). Effect of gibberellic acid and indole 3-acetic acid on improving growth and accumulation of phytochemical composition in Balanites aegyptiaca plants.
- Muhammad, N., Hakim, U. M. Q., Quraishi, U. M., Chaudhary, H. J., & Munis, M. F. H. (2016). Indole-3acetic acid induces biochemical and physiological changes in wheat under drought stress conditions. *Philippes Agriculture Science*, *99*(1), 19-24.
- Naeem, M., Bhatti, I., Ahmad, R. H., & Ashraf, M. Y. (2004). Effect of some growth hormones (GA3, IAA and kinetin) on the morphology and early or delayed initiation of bud of lentil (Lens culinaris Medik). *Pakistan Journal Botony*, 36(4), 801-809.
- Nawaz, M. S., Sami, S. A., Bano, M., Khan, M. R. Q., Anwar, Z., Ijaz, A., & Ahmed, T. (2023). Impact of salt stress on cotton.
- Olatunji, D., Geelen, D., & Verstraeten, I. (2017). Control of endogenous auxin levels in plant root development. *International Journal of Molecular Sciences, 18*(12), 2587.
- Pagnussat, G. C., Lanteri, M. L., & Lamattina, L. (2003). Nitric oxide and cyclic GMP are messengers in the indole acetic acid-induced adventitious rooting process. *Plant Physiology*, 132(3), 1241-1248.
- Pagnussat, G. C., Simontacchi, M., Puntarulo, S., & Lamattina, L. (2002). Nitric oxide is required for root organogenesis. *Plant Physiology*, 129(3), 954-956.
- Paglia, D.E. & Valentine, W.N., 1967. Studies on the quantitative and qualitative characterization of erythrocyte glutathione peroxidase. *Transitional Research*, 70(1), 158-169.
- Pustovoitova, T., & Zholkevich, V. (1992). Basic trends in the investigation of drought effects on physiological processes in plants. *Fiziol Biokhim Kul't Rast*, 24, 14-27.
- Raza, A., Salehi, H., Rahman, M. A., Zahid, Z., Madadkar Haghjou, M., Najafi-Kakavand, S., Charagh, S., Osman, H. S., Albaqami, M., & Zhuang, Y. (2022). Plant hormones and neurotransmitter interactions mediate antioxidant defenses under induced oxidative stress in plants. *Frontiers in Plant Science*, 13, 961872.
- Rehman, I., Nazim, R., & Meraj, A. (2023). Regulation and improvement of carotenoid metabolism in tomato. *International Journal Agriculture Bioscience, 12*, 199-207.

- Saeed, M. Z., Hayat, H., Shafiq, F., & Tareen, W.-U.-H. (2023). Assessing the prospects and challenges of organic agriculture in the pothwar region of Punjab, Pakistan.
- Saha, P., Das, N., Deb, P., & Suresh, C. (2009). Effect of NAA and GA3 on yield and quality of tomato (Lycopersicon esculentum Mill.). *Environment and Ecology*, 27(3), 1048-1050.
- Serrani, J. C., Fos, M., Atarés, A., & García-Martínez, J. L. (2007). Effect of gibberellin and auxin on parthenocarpic fruit growth induction in the cv Micro-Tom of tomato. *Journal of Plant Growth Regulation*, 26, 211-221.
- Sharma, P., Jha, A. B., & Dubey, R. S. (2019). Oxidative stress and antioxidative defense system in plants growing under abiotic stresses. In *Handbook of Plant* and Crop Stress, Fourth Edition (pp. 93-136). CRC press.
- Siddiqui, M. H., Al-Whaibi, M. H., & Basalah, M. O. (2011). Role of nitric oxide in tolerance of plants to abiotic stress. *Protoplasma*, 248, 447-455.
- Singh, P., Jaiswal, S., Tripathi, D. K., & Singh, V. P. (2024). Nitric oxide acts upstream of indole-3-acetic acid in ameliorating arsenate stress in tomato seedlings. *Plant Physiology and Biochemistry*, 108461.
- Spaepen, S., Vanderleyden, J., & Remans, R. (2007). Indole-3-acetic acid in microbial and microorganism-plant signaling. *FEMS Microbiology Reviews*, *31*(4), 425-448.
- Tanwir, K., Javed, M. T., Shahid, M., Niazi, N. K., Khan, S. A., & Iqbal, N. (2022). Reactive Oxygen Species and Antioxidants Defence in Plants under Hostile Environment. In *Improvement of Plant Production in the Era of Climate Change* (pp. 153-180). CRC Press.
- Wang, H., Jones, B., Li, Z., Frasse, P., Delalande, C., Regad,
  F., Chaabouni, S., Latche, A., Pech, J.-C., & Bouzayen,
  M. (2005). The tomato Aux/IAA transcription factor
  IAA9 is involved in fruit development and leaf
  morphogenesis. *The Plant Cell*, 17(10), 2676-2692.
- Wang, X., Wang, G., Guo, T., Xing, Y., Mo, F., Wang, H., Fan, J., & Zhang, F. (2021). Effects of plastic mulch and nitrogen fertilizer on the soil microbial community, enzymatic activity and yield performance in a dryland maize cropping system. *European Journal of Soil Science*, 72(1), 400-412.
- Yang, J., Cao, W., & Rui, Y. (2017). Interactions between nanoparticles and plants: phytotoxicity and defense mechanisms. *Journal of Plant Interactions*, 12(1), 158-169.
- Yemelyanov, V. V., Lastochkin, V. V., Chirkova, T. V., Lindberg, S. M., & Shishova, M. F. (2020). Indoleacetic acid levels in wheat and rice seedlings under oxygen deficiency and subsequent reoxygenation. *Biomolecules*, 10(2), 276.
- Yurekli, F., Geckil, H., & Topcuoglu, F. (2003). The synthesis of indole-3-acetic acid by the industrially important white-rot fungus Lentinus sajor-caju under different culture conditions. *Mycological Research*, 107(3), 305-309.
- Zafar, M. M., Chattha, W. S., Khan, A. I., Zafar, S., Subhan, M., Saleem, H., Ali, A., Ijaz, A., Anwar, Z., & Qiao, F. (2023). Drought and heat stress on cotton genotypes

suggested agro-physiological and biochemical features for climate resilience. *Frontiers in Plant Science*, *14*, 1265700.

Zafar, M. M., Jia, X., Shakeel, A., Sarfraz, Z., Manan, A., Imran, A., Mo, H., Ali, A., Youlu, Y., & Razzaq, A. (2022). Unraveling heat tolerance in upland cotton (Gossypium hirsutum L.) using univariate and multivariate analysis. *Frontiers in Plant Science, 12*, 727835.

Zandi, P., & Schnug, E. (2022). Reactive oxygen species, antioxidant responses and implications from a microbial modulation perspective. *Biology*, 11(2), 155.