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**Research Article**

# Interactive Effects of Dichlorvos, Dimethoate, And Cypermethrin On Growth and Oxidative Homeostasis in Maize (*Zea Mays*)

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## Abstract:

This study investigates the effects of dichlorvos, dimethoate, and cypermethrin, individually and in combinations, on maize (*Zea mays*) growth and physiology. Maize seeds were grown in pesticide-treated soil, and growth parameters, oxidative stress markers, and enzymatic activities were evaluated. Growth was significantly inhibited by pesticide exposure, with Group H (triple pesticide combination) showing the most severe reduction in plant height (48% lower) and stem girth (40% lower) compared to the control ($p < 0.05$). Biochemical assays revealed significant declines in catalase (CAT) and superoxide dismutase (SOD) activities across all tissues, indicating compromised oxidative stress defenses. For instance, CAT activity in roots decreased by 65% in Group H compared to the control ($p < 0.05$). Concurrently, malondialdehyde (MDA) concentrations, a marker of lipid peroxidation, increased significantly, with Group H showing a 75% rise in leaves relative to the control ($p < 0.05$). Relative water content (RWC) also decreased substantially, with Group H recording the lowest hydration levels (37% reduction, $p < 0.05$). These findings suggest synergistic or cumulative toxicity from combined pesticide exposure, with the most pronounced effects observed in triple pesticide treatments. Statistical analyses (ANOVA, Tukey's test) confirmed significant differences across groups ($p < 0.05$), reinforcing the reliability of the results. This study highlights the adverse impacts of pesticide combinations on maize growth and physiological stability, emphasizing the need for sustainable pest management strategies, such as integrated pest management (IPM), to mitigate the ecological and agricultural risks of pesticide use.

**Keywords: Pesticide toxicity; Maize growth; Oxidative stress; Enzymatic activity; Integrated pest management.**

## Introduction

Soil contamination caused by the indiscriminate use of agrochemicals has become a pressing global concern, threatening agricultural productivity, environmental stability, and ecosystem health (Aktar et al., 2009; Singh et al., 2020). Pesticides such as dichlorvos, dimethoate, and cypermethrin are widely employed in modern agriculture to combat pests and ensure high crop yields. However, their persistence in the environment and toxic effects on non-target organisms, including staple crops like maize (*Zea mays*), present significant challenges (Hussain et al., 2016). Maize, being a critical food source globally, is particularly vulnerable to environmental stresses, including chemical pollutants, making it essential to understand the broader implications of pesticide use on its growth and health (Sharma et al., 2019).

Maize is a staple crop consumed by millions worldwide, serving as a primary source of food and animal feed (Shiferaw et al., 2011). However, its productivity is often compromised by exposure to soil contaminated with pesticide residues. These residues can impair vital physiological processes such as photosynthesis, nutrient uptake, and water regulation, leading to reduced growth and yield (Singh & Walker, 2006). Additionally, pesticide exposure induces oxidative stress in plants, characterized by the excessive production of reactive oxygen species (ROS). While ROS are natural byproducts of plant metabolism, their overproduction disrupts cellular homeostasis, causing lipid peroxidation, protein oxidation, and DNA damage (Gill & Tuteja, 2010). These biochemical disruptions impair the plant's ability to grow, develop, and reproduce effectively (Zhang et al., 2019).

Dichlorvos, an organophosphate insecticide, is known for its rapid action against a wide range of pests. Despite its effectiveness, its high toxicity, environmental persistence, and potential to bioaccumulate raise concerns about its long-term impact on soil health and crop productivity (Siddiqui et al., 2017). Similarly, dimethoate, another organophosphate, demonstrates systemic pest control activity but exhibits moderate soil persistence, posing risks to non-target organisms, including plants and beneficial soil microbes (Kumar et al., 2021). Cypermethrin, a synthetic pyrethroid, is valued for its broad-spectrum efficacy and lower mammalian toxicity compared to organophosphates. However, its hydrophobic nature enhances its soil retention, increasing its potential for phytotoxicity and long-term environmental contamination (Yadav et al., 2023).

Plants have evolved mechanisms to mitigate the effects of pesticide-induced oxidative stress through antioxidative defense systems. Enzymatic antioxidants, such as superoxide dismutase (SOD) and catalase (CAT), play critical roles in neutralizing ROS and protecting cellular components from oxidative damage (Sharma et al., 2022). Non-enzymatic antioxidants, including ascorbic acid and glutathione, further support these defenses (Das et al., 2020). However, chronic or excessive pesticide exposure can overwhelm these systems, leading to cumulative oxidative damage, impaired metabolic function, and stunted growth (Zhang et al., 2019). The

interaction between pesticide-induced stress and plant antioxidative responses provides an important framework for understanding how crops like maize adapt to and are affected by environmental contaminants.
While extensive research has been conducted on the individual effects of dichlorvos, dimethoate, and cypermethrin on plant health, studies investigating their combined impact are limited (Cedergreen, 2008). This is particularly concerning given that agricultural fields are frequently exposed to multiple pesticides simultaneously. Such combined exposures can lead to synergistic or additive toxic effects, amplifying stress responses in plants and exacerbating their negative impacts on crop productivity (Marrs, 1993). Understanding these interactions is essential for developing effective and sustainable agricultural practices that balance pest management needs with environmental conservation (Pimentel, 2005).
This study aims to address the critical knowledge gaps surrounding the interactive effects of dichlorvos, dimethoate, and cypermethrin on maize growth and oxidative homeostasis. Specifically, it seeks to evaluate how individual and combined pesticide exposures influence physiological parameters such as plant height and stem girth, as well as biochemical markers like antioxidant enzyme activity and oxidative stress levels. The research also aims to identify toxicity thresholds for these pesticides and determine whether their combined use results in synergistic or cumulative toxicity.
By systematically exploring the physiological and biochemical impacts of these pesticides on maize, this study provides valuable insights into the broader implications of pesticide use in agriculture. The findings are expected to inform sustainable pest management practices, promote environmentally friendly farming techniques, and contribute to global efforts in safeguarding food security and environmental health. Through this research, a deeper understanding of how pesticide interactions affect staple crops like maize will be achieved, paving the way for more informed policies and practices in agricultural sustainability.

## Materials and Methods

All reagents and solvents used in this study were of analytical grade, obtained from the British Drug House, Poole, England. The experiment was conducted in a greenhouse situated within the College of Science, Federal University of Petroleum Resources, Effurun, Nigeria. A slightly modified approach based on the method described by Adewole and Aboyeji (2003) was adopted. Bulk surface soil samples (0–15 cm depth) were collected from a site within the University, air-dried for seven days, passed through a 2 mm sieve, and analyzed following standard procedures. Thirty-two polythene pots, each with drainage holes at the base and filled with 10 kg of surface soil, were randomly arranged on a table in the greenhouse. The experimental design included eight treatment levels combined in a factorial arrangement.
The seeds utilized in this study were procured from the Ministry of Agriculture, Effurun, Delta State, Nigeria. Their viability was tested using the method outlined by Radwan et al. (2018). The agrochemicals employed—dichlorvos, dimethoate, and cypermethrin—were sourced from Hubei Sanonda Co. Ltd., China. These chemicals were purchased from a certified agrochemical retailer and diluted with clean water based on standard domestic usage guidelines. Specific dose combinations were prepared for each experimental group as follows:
Groups B, C, and D: Each chemical was applied individually at a 1:1 dilution.
Groups E, F, and G: Two chemicals were combined in a 1:0.5:0.5 ratio.
Group H: All three chemicals were combined in a 1:0.33:0.33:0.33 ratio.
Freshly prepared solutions were applied daily for 28 consecutive days to ensure continuous exposure. The application was done via spraying to replicate typical agricultural pesticide practices. A control group (Group A) was maintained, which received only water applied under identical conditions. The treatment groups were structured as follows:

**Group A (Control):** Sprayed with water.
**Group B:** Sprayed with dichlorvos.
**Group C:** Sprayed with dimethoate.
**Group D:** Sprayed with cypermethrin.
**Group E:** Sprayed with a mixture of dichlorvos and dimethoate.
**Group F:** Sprayed with a mixture of dichlorvos and cypermethrin.
**Group G:** Sprayed with a mixture of dimethoate and cypermethrin.
**Group H:** Sprayed with a mixture of dichlorvos, dimethoate, and cypermethrin.

This exposure regimen ensured consistent dosing, enabling reliable comparisons among the experimental groups and providing comprehensive insights into the toxicological effects of the agrochemicals.
During the growing stage, the plants were watered regularly. At two weeks after planting (WAP), the plants were thinned to two stands per pot, while the removed stands were left within the pots to return any nutrients they might have absorbed during the initial growth phase. Plant growth parameters, including height and stem girth, were recorded every four days until the conclusion of the experiment. Afterward, the leaves, stems, and roots were separated and homogenized for toxicological analysis.
The relative water content (RWC) of the leaves was measured at 4 WAP using the method described by Schonfeld et al. (1988). Protein concentration in the plant tissues was analyzed following the method of Gornal et al. (1949). Superoxide dismutase (SOD) activity was evaluated using the protocol by Misra and Fridovich (1972), while catalase activity was determined using the procedure

described by Sinha (1971). Malondialdehyde (MDA) concentration in the plant tissues was assessed following the method outlined by Bird et al. (1982).

**Statistical Analysis**

Data for growth parameters, including plant height and stem girth, as well as biochemical markers such as catalase (CAT) activity, superoxide dismutase (SOD) activity, relative water content (RWC), and malondialdehyde (MDA) concentrations, were expressed as means ± standard error of the mean (SEM).

Statistical comparisons between treatment groups were conducted using one-way analysis of variance (ANOVA), followed by Tukey's post hoc test to identify significant differences between group means. A significance threshold of $p < 0.05$ was applied. All statistical analyses were performed using SPSS version 30.

Graphs and figures were created to visualize the differences and trends among the treatment groups, highlighting the impact of individual and combined pesticide exposures on the physiological and biochemical responses of spinach.

## Results

The graph (Figure 1) illustrates the impact of various pesticide treatments on maize plant height over a four-week period. The control group (Group A), exposed only to sprayed water, shows consistent growth over time, reaching a moderate height by week 4. This represents the baseline growth in the absence of pesticide exposure.

Exposure to dichlorvos (Group B) significantly reduces maize growth compared to the control, indicating its toxic effects on plant development. Similarly, exposure to dimethoate (Group C) results in stunted growth, though it appears slightly less toxic than dichlorvos when considered individually. Cypermethrin (Group D), on the other hand, shows comparatively less negative impact on growth, with maize plants achieving greater height than those exposed to dichlorvos or dimethoate.

When dichlorvos and dimethoate are combined (Group E), the maize plant height is significantly reduced compared to the control and the individual exposures. This suggests additive or possibly synergistic toxic effects. A similar trend is observed for the combination of dichlorvos and cypermethrin (Group F), though the growth is slightly better than for Group E, indicating a marginally reduced combined effect.

For plants exposed to dimethoate and cypermethrin (Group G), growth performance improves slightly compared to Groups E and F, suggesting that the combination of these two pesticides is less harmful than others. However, when all three pesticides are combined (Group H), the growth is severely impaired, with the maize plants exhibiting the lowest height among all groups. This highlights the severe cumulative or synergistic toxicity of multiple pesticide exposures.

Statistical analysis confirms that differences between groups are significant (p<0.05), reflecting the varying degrees of impact caused by the pesticides and their combinations on maize growth. Overall, the study underscores the detrimental effects of pesticide exposure on plant growth, with the impact intensifying when multiple pesticides are combined.

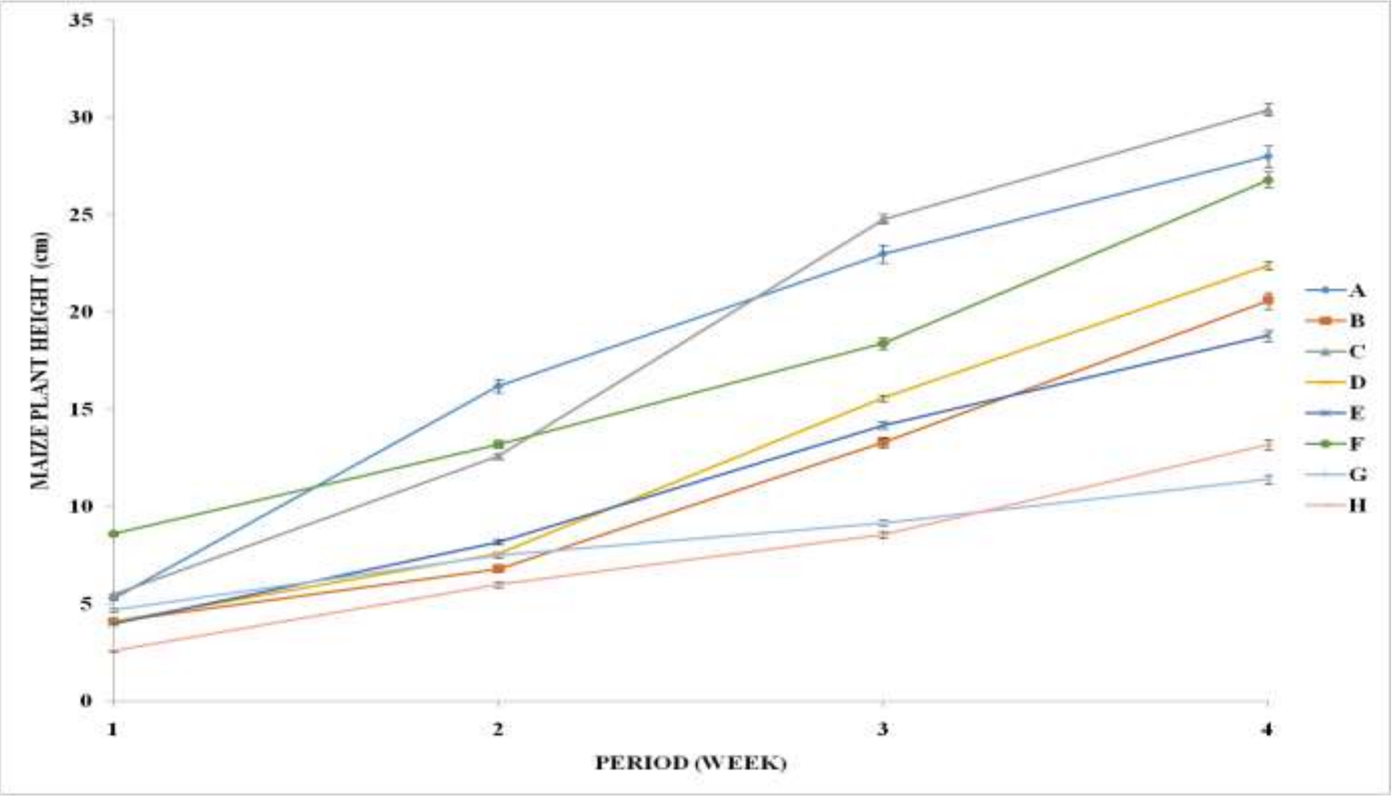


**Figure 1: Effect of Single and Combined Pesticide Exposures on Maize Plant Height Over Four Weeks. Plotted values are means of five determinations ± SEM and are considered significantly different when p<0.05.**

The graph (Figure 2) represents the effect of various pesticide treatments on maize plant stem girth over a four-week period.

The control group (Group A), exposed only to sprayed water, exhibits consistent growth, achieving the largest stem girth by week 4. This establishes the baseline girth in the absence of pesticide exposure.

Exposure to dichlorvos (Group B) significantly reduces stem girth compared to the control, indicating its toxic effects on the structural development of maize plants. Similarly, dimethoate (Group C) also stunts stem girth growth, though it appears to have a slightly less pronounced impact than dichlorvos. Cypermethrin (Group D) has a less severe impact on stem girth compared to Groups B and C, with plants displaying relatively better growth.

For the combination treatments, maize plants exposed to dichlorvos and dimethoate (Group E) exhibit significantly reduced stem girth compared to the control and individual pesticide exposures. This points to possible additive or synergistic toxicity. Plants exposed to dichlorvos and cypermethrin (Group F) show slightly better stem girth than Group E, suggesting that the combined toxicity of these two pesticides is somewhat mitigated.

Exposure to dimethoate and cypermethrin (Group G) results in better stem girth growth compared to Groups E and F, suggesting reduced combined toxicity. However, the combination of all three pesticides (Group H) results in the smallest stem girth among all groups, indicating severe cumulative or synergistic toxic effects.

Statistical analysis confirms that the differences among the groups are significant ($p<0.05$). Overall, the data show that pesticide exposure, particularly in combinations, negatively affects the stem girth of maize plants, with the most severe effects observed in the group exposed to all three pesticides simultaneously.

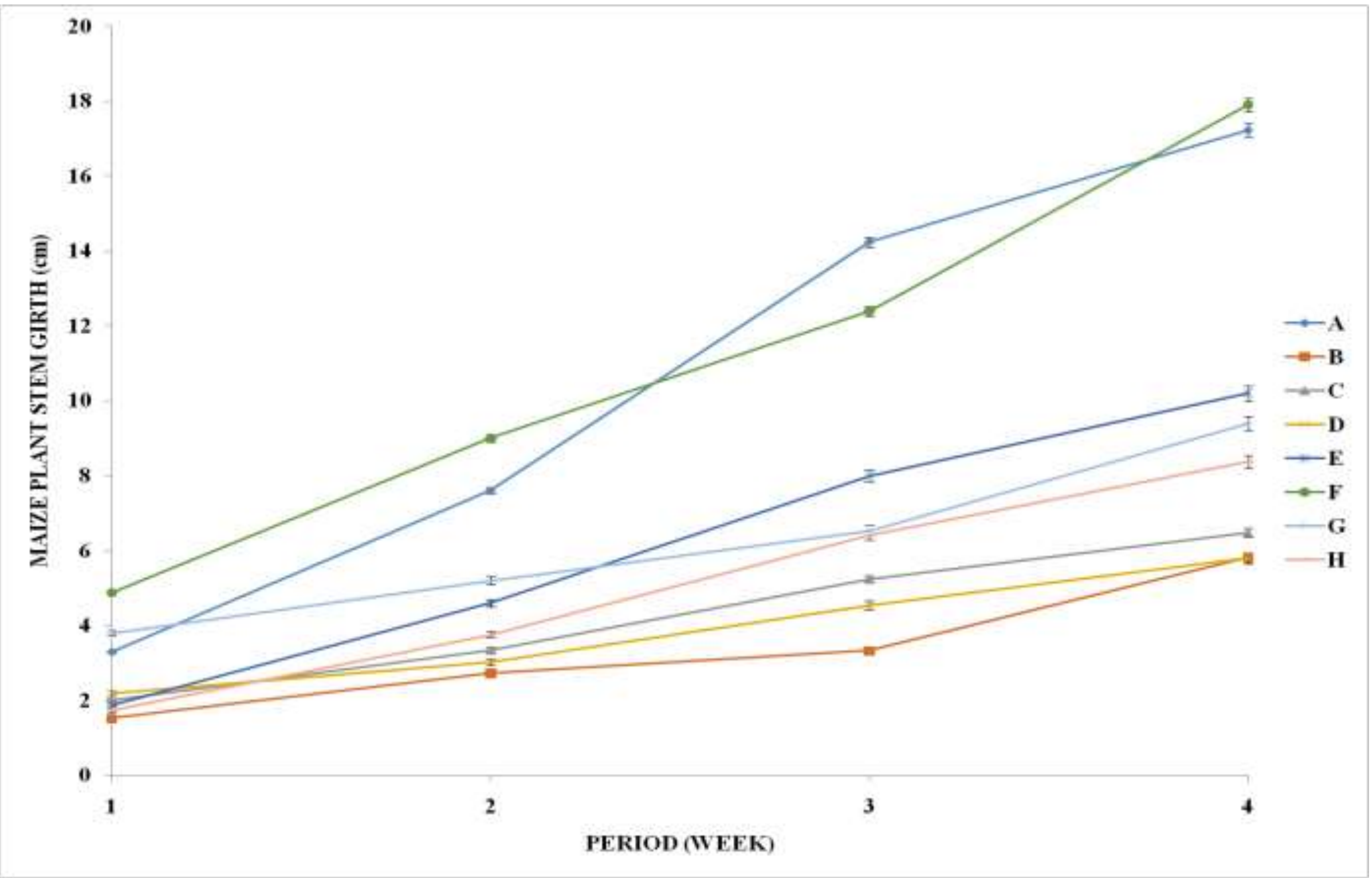


**Figure 2: Effect of Single and Combined Pesticide Exposures on Maize Stem Girth Over Four Weeks. Plotted values are means of five determinations ± SEM and are considered significantly different when $p<0.05$.**

The graph (Figure 3) presents the specific activity of catalase (U/mg protein) in the leaves of maize plants exposed to different pesticide treatments. Statistical significance is indicated by p-values, where $p < 0.05$ denotes significant differences, and $p > 0.05$ signifies no significant difference between groups.

The control group (Group A) exhibits the highest catalase activity in maize leaves, which is significantly greater than all other groups ($p < 0.05$). This demonstrates that the absence of pesticide exposure supports optimal enzymatic function in maize leaves.

Group B, exposed to dichlorvos, shows a significant reduction in catalase activity compared to the control ($p < 0.05$). This indicates that dichlorvos impairs the oxidative stress response in maize leaves. Group C, treated with dimethoate, displays an even further reduction in catalase activity compared to Group B and the control ($p < 0.05$), suggesting a stronger inhibitory effect on enzyme activity. Group D, exposed to cypermethrin, also demonstrates a significant decrease in catalase activity compared to the control ($p < 0.05$) but has a slightly less pronounced effect compared to dichlorvos and dimethoate.

Groups E and G, treated with combinations of dichlorvos and dimethoate and dimethoate and cypermethrin, respectively, exhibit similar catalase activity levels ($p > 0.05$). However, both are significantly lower than the control and Groups B, C, and D ($p < 0.05$), indicating an additive effect of these pesticide combinations on reducing catalase activity in maize leaves.

Group F, exposed to dichlorvos and cypermethrin, shows a significantly lower catalase activity than Groups E and G ($p < 0.05$), indicating a more severe inhibitory effect. Finally, Group H, exposed to all three pesticides, exhibits the lowest catalase activity among all groups, with a significant reduction compared to the control and all other groups ($p < 0.05$). This reflects the cumulative or synergistic toxic effects of the three pesticides combined.

Here, pesticide exposure significantly reduces catalase activity in the leaves of maize plants ($p < 0.05$). The effect is more pronounced with pesticide combinations, particularly when all three pesticides are applied together.

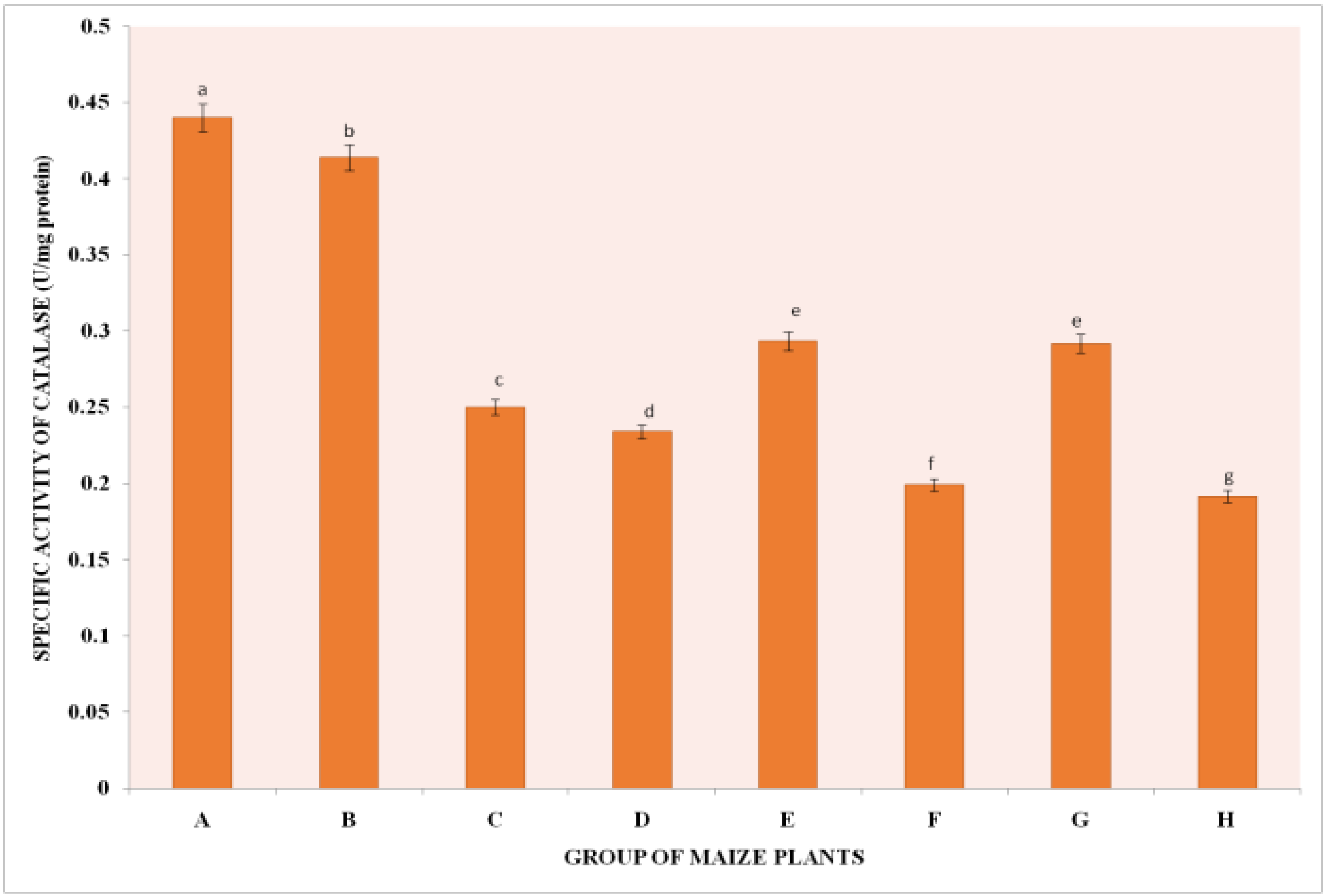


**Figure 3: Effect of Individual and Combined Pesticide Exposures on Catalase Activity in Leaves of Maize Plants. Plotted values are means of five determinations ± SEM. Bars bearing different alphabets are significantly different (p<0.05).**

The graph (Figure 4) illustrates the specific activity of catalase (U/mg protein) in the stems of maize plants exposed to different pesticide treatments. Statistical significance is determined by p-values, where $p < 0.05$ indicates significant differences, and $p > 0.05$ indicates no significant difference between groups.

The control group (Group A) exhibits the highest catalase activity in maize stems, which is significantly higher than all other groups ($p < 0.05$). This indicates that the absence of pesticide exposure allows for optimal enzymatic activity in maize stems.

Group B, treated with dichlorvos, shows a significant reduction in catalase activity compared to the control ($p < 0.05$), reflecting the toxic impact of dichlorvos on the oxidative stress response in maize stems. Group C, exposed to dimethoate, displays slightly higher catalase activity than Group B but remains significantly lower than the control group ($p < 0.05$), indicating a milder inhibitory effect. Group D, exposed to cypermethrin, exhibits catalase activity that is statistically similar to Group B ($p > 0.05$) but is significantly lower than the control ($p < 0.05$).

Group E, treated with the combination of dichlorvos and dimethoate, shows a significant reduction in catalase activity compared to Groups B, C, and D ($p < 0.05$). This demonstrates an additive toxic effect of this pesticide combination on maize stems. Group F, treated with the combination of dichlorvos and cypermethrin, displays significantly higher catalase activity than Group E ($p < 0.05$) but remains significantly lower than the control ($p < 0.05$), suggesting a slightly reduced combined toxicity.

Group G, exposed to the combination of dimethoate and cypermethrin, shows a further reduction in catalase activity compared to Group F ($p < 0.05$), indicating a stronger inhibitory effect of this combination on catalase activity in maize stems. Finally, Group H, treated with all three pesticides, has the lowest catalase activity among all groups, with a significant reduction compared to the

control and all other groups ($p < 0.05$). This highlights the severe cumulative or synergistic toxic effect of the combined pesticide exposure.
In this study, pesticide exposure significantly reduces catalase activity in the stems of maize plants ($p < 0.05$). The severity of the reduction increases with the number of pesticides used, with the combined exposure to all three pesticides showing the most pronounced toxic effect.

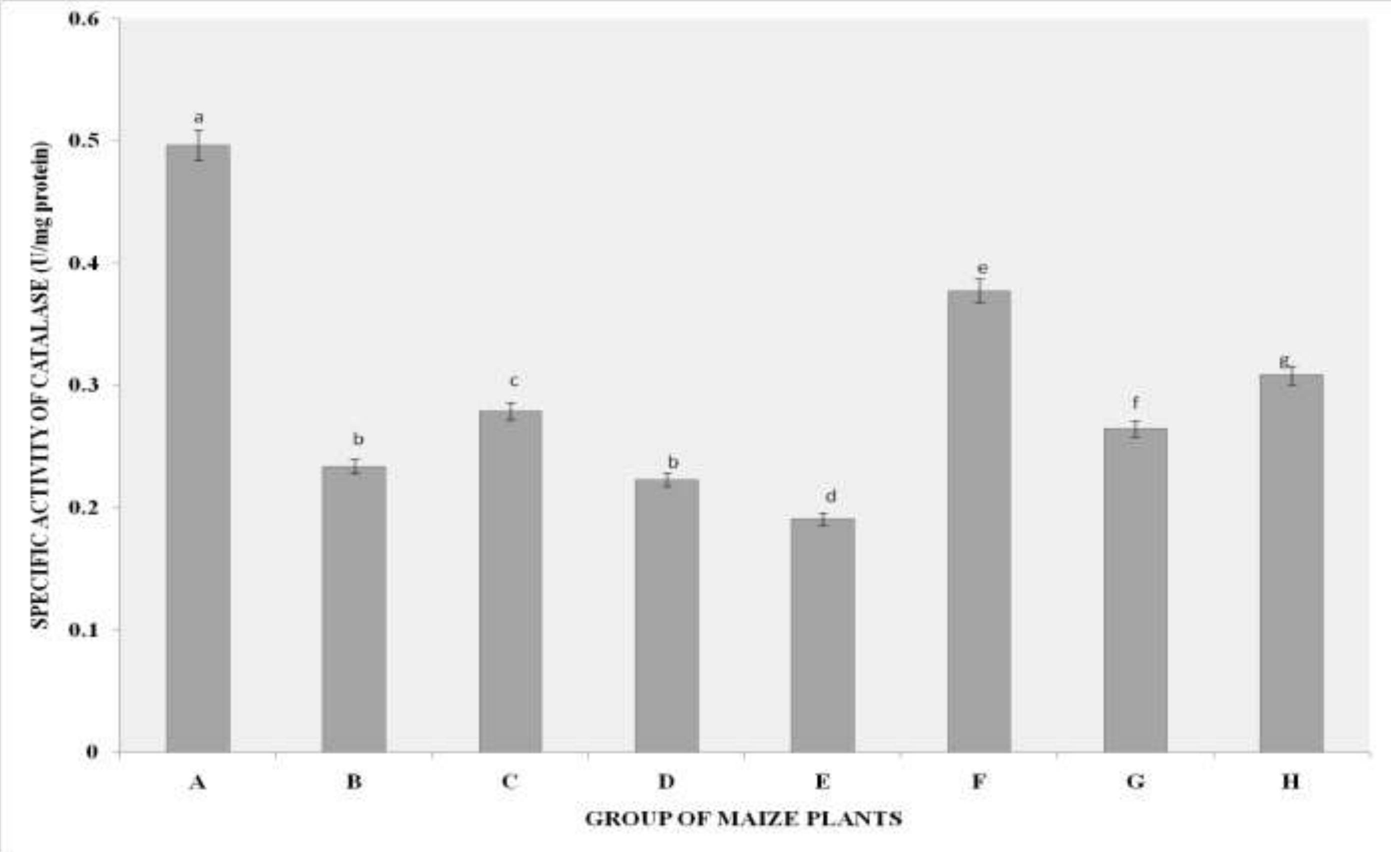


**Figure 4: Effect of Individual and Combined Pesticide Exposures on Catalase Activity in Stems of Maize Plants. Plotted values are means of five determinations ± SEM. Bars bearing different alphabets are significantly different (p<0.05).**

The graph (Figure 5) illustrates the specific activity of catalase (U/mg protein) in the roots of maize plants exposed to different pesticide treatments. Statistical differences are indicated by p-values, where $p < 0.05$ represents significant differences, and $p > 0.05$ indicates no significant difference between groups.
The control group (Group A) shows the highest catalase activity in maize roots, which is significantly greater than all other groups ($p < 0.05$). This suggests that the absence of pesticide exposure supports optimal enzymatic activity in the roots of maize plants.
Group B, exposed to dichlorvos, displays a significant reduction in catalase activity compared to the control group ($p < 0.05$). This reflects the negative impact of dichlorvos on the oxidative stress response in maize roots. Group C, treated with dimethoate, shows a further significant reduction in catalase activity compared to Group B ($p < 0.05$) but remains significantly higher than Groups D and E ($p < 0.05$). This indicates that dimethoate impairs root enzymatic activity more severely than dichlorvos but less severely than other combinations.
Group D, exposed to cypermethrin, demonstrates a significant reduction in catalase activity compared to Groups A, B, and C ($p < 0.05$), reflecting a stronger inhibitory effect of cypermethrin on root catalase activity. Group E, treated with the combination of dichlorvos and dimethoate, shows a further significant decrease in catalase activity compared to Groups B, C, and D ($p < 0.05$), indicating an additive toxic effect on root enzymatic function.
Group F, exposed to the combination of dichlorvos and cypermethrin, exhibits significantly higher catalase activity compared to Group E ($p < 0.05$), suggesting a slightly reduced toxicity for this combination. However, it remains significantly lower than the control ($p < 0.05$). Group G, treated with the combination of dimethoate and cypermethrin, shows a similar catalase activity to Group F ($p > 0.05$) but is significantly higher than Group E ($p < 0.05$), indicating reduced toxicity relative to dichlorvos and dimethoate combinations.
Finally, Group H, exposed to all three pesticides, shows the lowest catalase activity among all groups ($p < 0.05$). This reflects a severe cumulative or synergistic toxic effect on the catalase activity in maize roots.
Pesticide exposure significantly reduces catalase activity in maize roots ($p < 0.05$), with the severity of the reduction increasing as the number of pesticides in the combination increases. The data demonstrate that pesticide combinations, especially when all three are used, have the most pronounced negative impact on root enzymatic activity.

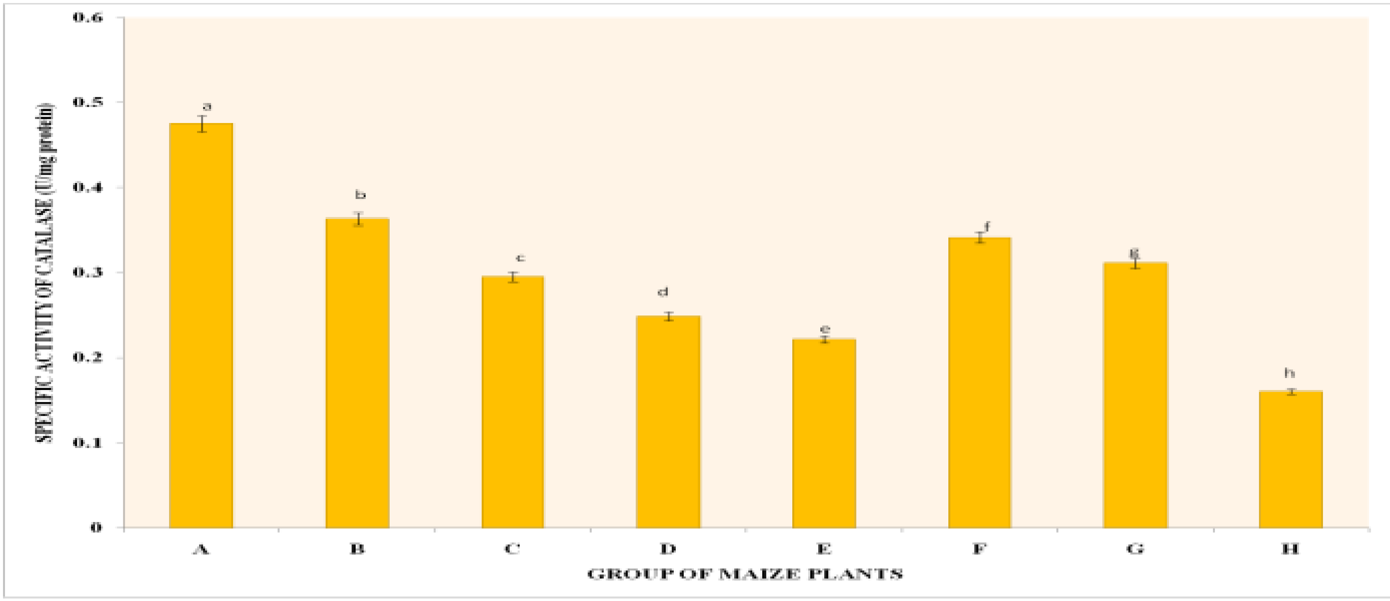


**Figure 5: Effect of Individual and Combined Pesticide Exposures on Catalase Activity in Roots of Maize Plants. Plotted values are means of five determinations ± SEM. Bars bearing different alphabets are significantly different (p<0.05).**

The graph (Figure 6) presents the specific activity of superoxide dismutase (SOD) (U/mg protein) in the leaves of maize plants exposed to various pesticide treatments. Statistical differences are indicated by p-values, where $p < 0.05$ signifies significant differences and $p > 0.05$ indicates no significant difference between groups.

The control group (Group A) shows the highest SOD activity, which is statistically similar to Group B ($p > 0.05$). This indicates that the absence of pesticides (Group A) and exposure to dichlorvos alone (Group B) support relatively optimal enzymatic activity in maize leaves, with minimal impact on the oxidative stress response.

Group C, treated with dimethoate, exhibits a significant reduction in SOD activity compared to Groups A and B ($p < 0.05$). This suggests that dimethoate has a more pronounced inhibitory effect on the enzyme activity in maize leaves. Group D, exposed to cypermethrin, shows slightly higher SOD activity than Group C, but it is significantly lower than the control and Group B ($p < 0.05$), indicating a moderate impact of cypermethrin on oxidative stress regulation.

Group E, treated with the combination of dichlorvos and dimethoate, displays a further significant reduction in SOD activity compared to Groups B, C, and D ($p < 0.05$). This points to an additive toxic effect of these two pesticides on leaf enzymatic function.

Group F, exposed to dichlorvos and cypermethrin, demonstrates significantly lower SOD activity than Group E ($p < 0.05$), indicating that this combination has a stronger inhibitory effect on SOD activity.

Groups G and H, representing combinations of dimethoate and cypermethrin and all three pesticides, respectively, exhibit the lowest SOD activity levels among all groups ($p < 0.05$). The values for Groups G and H are not significantly different from each other ($p > 0.05$), highlighting that exposure to these combinations results in similar severe impacts on SOD activity.

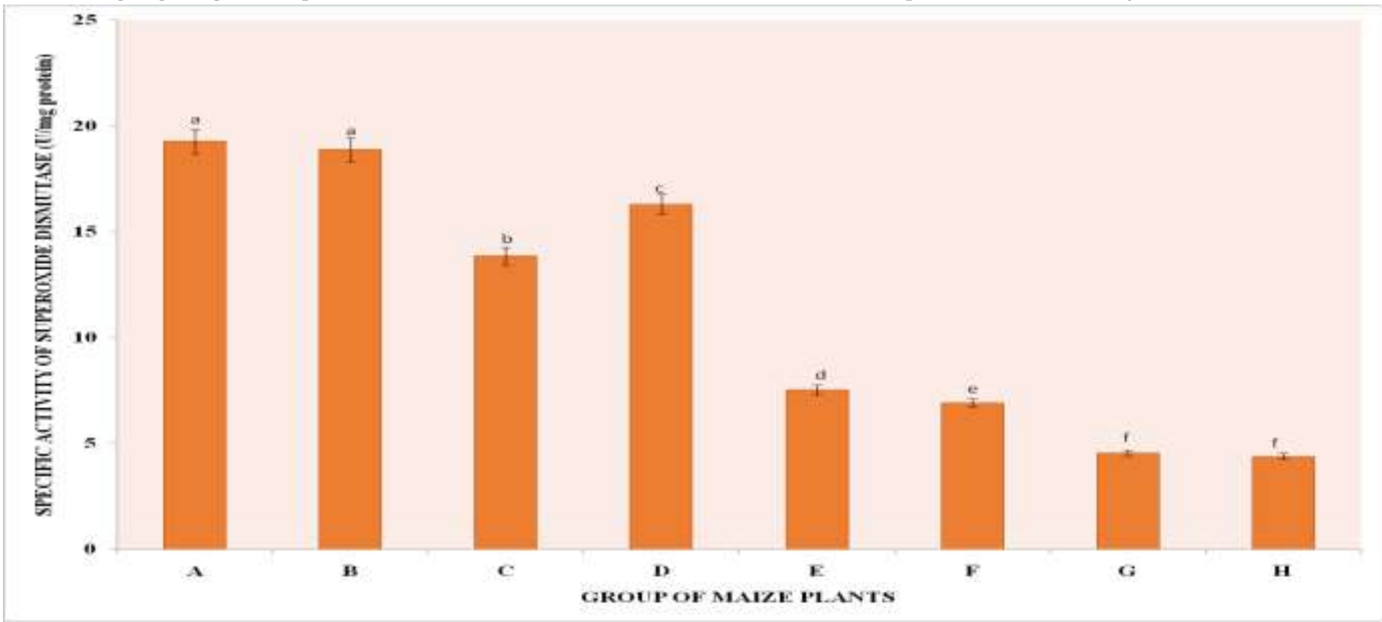


**Figure 6: Effect of Individual and Combined Pesticide Exposures on Superoxide Dismutase Activity in Leaves of Maize Plants. Plotted values are means of five determinations ± SEM. Bars bearing different alphabets are significantly different (p<0.05).**

The graph (Figure 7) illustrates the specific activity of superoxide dismutase (SOD) (U/mg protein) in the stems of maize plants exposed to different pesticide treatments.

The control group (Group A) shows the highest SOD activity, significantly greater than all other groups ($p < 0.05$). This reflects optimal enzymatic activity in maize stems under conditions without pesticide exposure.

Group B, treated with dichlorvos, shows a statistically significant reduction in SOD activity compared to the control ($p < 0.05$), indicating that dichlorvos impairs the antioxidative defense system in the stems. Group C, exposed to dimethoate, exhibits a further reduction in SOD activity compared to Groups A and B ($p < 0.05$). This highlights a more pronounced inhibitory effect of dimethoate on SOD activity in maize stems.

Group D, treated with cypermethrin, shows SOD activity similar to Group B ($p > 0.05$) but significantly higher than Group C ($p < 0.05$). This suggests that cypermethrin has a lesser impact on stem enzymatic activity than dimethoate but comparable effects to dichlorvos. Group E, exposed to the combination of dichlorvos and dimethoate, displays a similar level of SOD activity to Group C ($p > 0.05$) but significantly lower than Group D ($p < 0.05$), indicating an additive toxic effect on SOD activity.

Group F, treated with the combination of dichlorvos and cypermethrin, exhibits a further significant reduction in SOD activity compared to Groups D and E ($p < 0.05$). This suggests that this combination exacerbates the negative effects on enzymatic activity.

Group G, exposed to dimethoate and cypermethrin, demonstrates a significantly lower SOD activity than Group F ($p < 0.05$), reflecting a stronger inhibitory effect on the antioxidative defense system in maize stems.

Finally, Group H, treated with all three pesticides, shows the lowest SOD activity among all groups ($p < 0.05$). This indicates severe cumulative or synergistic toxic effects on SOD activity in maize stems.

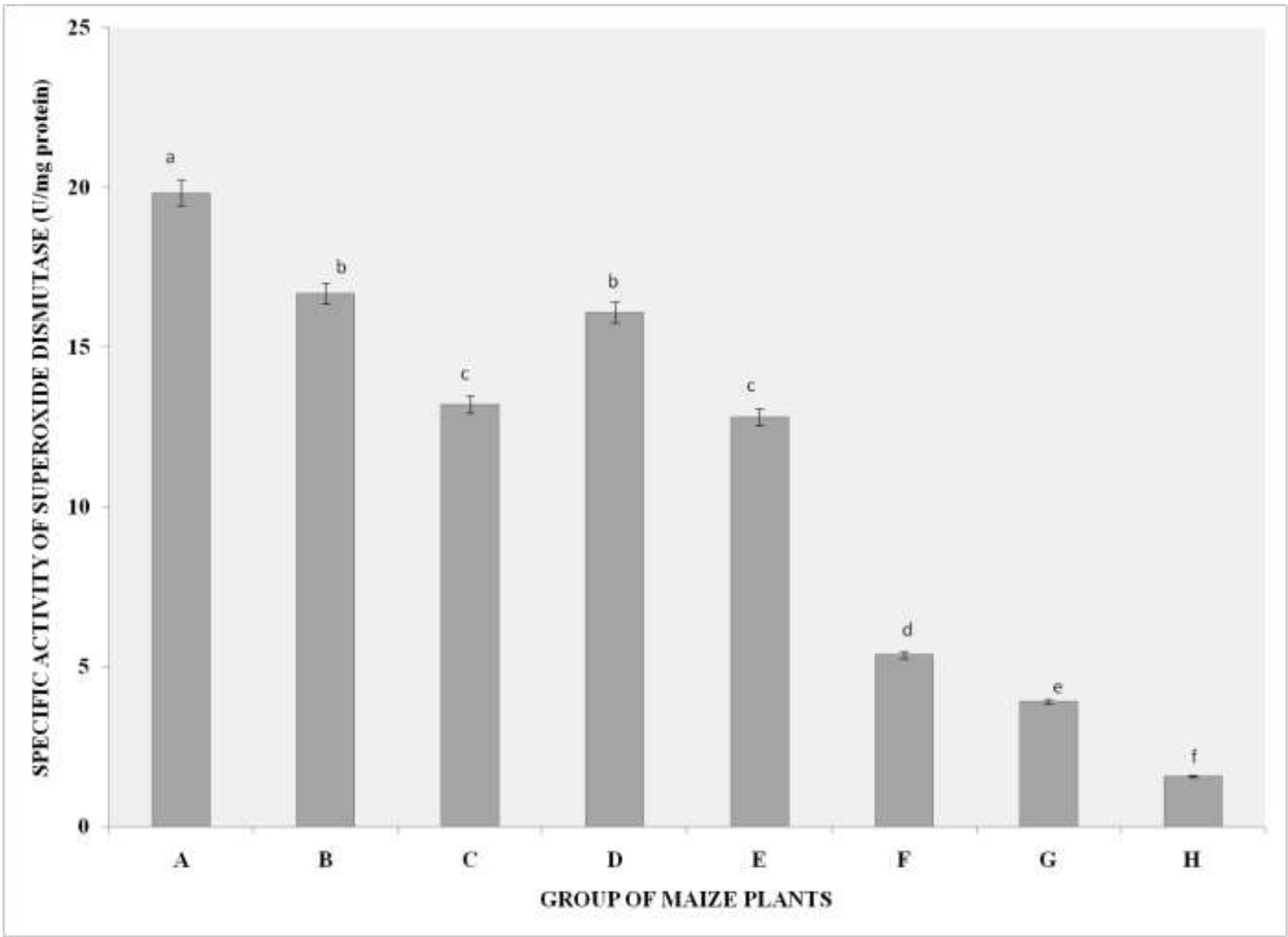


**Figure 7: Effect of Individual and Combined Pesticide Exposures on Superoxide Dismutase Activity in Stems of Maize Plants. Plotted values are means of five determinations ± SEM. Bars bearing different alphabets are significantly different ($p<0.05$).**

The graph (Figure 8) depicts the specific activity of superoxide dismutase (SOD) (U/mg protein) in the roots of maize plants exposed to various pesticide treatments. Statistical significance is represented by p-values, where $p < 0.05$ indicates significant differences, and $p > 0.05$ indicates no significant difference between groups.

The control group (Group A) shows the highest SOD activity, which is significantly greater than all other groups ($p < 0.05$). This indicates optimal enzymatic activity in the roots of maize plants in the absence of pesticide exposure.

Group B, exposed to dichlorvos, exhibits a statistically significant reduction in SOD activity compared to the control group ($p < 0.05$), indicating that dichlorvos negatively affects the antioxidative defense system in maize roots. Group C, treated with dimethoate, shows a further reduction in SOD activity compared to Group B ($p < 0.05$), reflecting a stronger inhibitory effect of dimethoate on root enzymatic activity.

Group D, exposed to cypermethrin, exhibits significantly lower SOD activity compared to Groups A and B ($p < 0.05$) but is similar to Group C ($p > 0.05$). This suggests a comparable impact of dimethoate and cypermethrin on SOD activity in maize roots. Group E, exposed to the combination of dichlorvos and dimethoate, demonstrates a significant reduction in SOD activity compared to Groups B, C, and D ($p < 0.05$). This indicates an additive toxic effect of the combination on root enzymatic function.

Group F, treated with the combination of dichlorvos and cypermethrin, shows a further significant reduction in SOD activity compared to Group E ($p < 0.05$). Groups G and H, representing the combination of dimethoate and cypermethrin and all three pesticides, respectively, exhibit the lowest SOD activity among all groups ($p < 0.05$). The SOD activity levels in Groups F, G, and H are statistically similar ($p > 0.05$), highlighting the cumulative or synergistic toxic effects of these combinations on SOD activity in maize roots.

In conclusion, pesticide exposure significantly reduces SOD activity in maize roots ($p < 0.05$), with the severity of the reduction increasing in groups exposed to multiple pesticides. The lowest enzymatic activity is observed in Groups F, G, and H, emphasizing the strong inhibitory effects of pesticide combinations on the antioxidative defense system in maize roots.

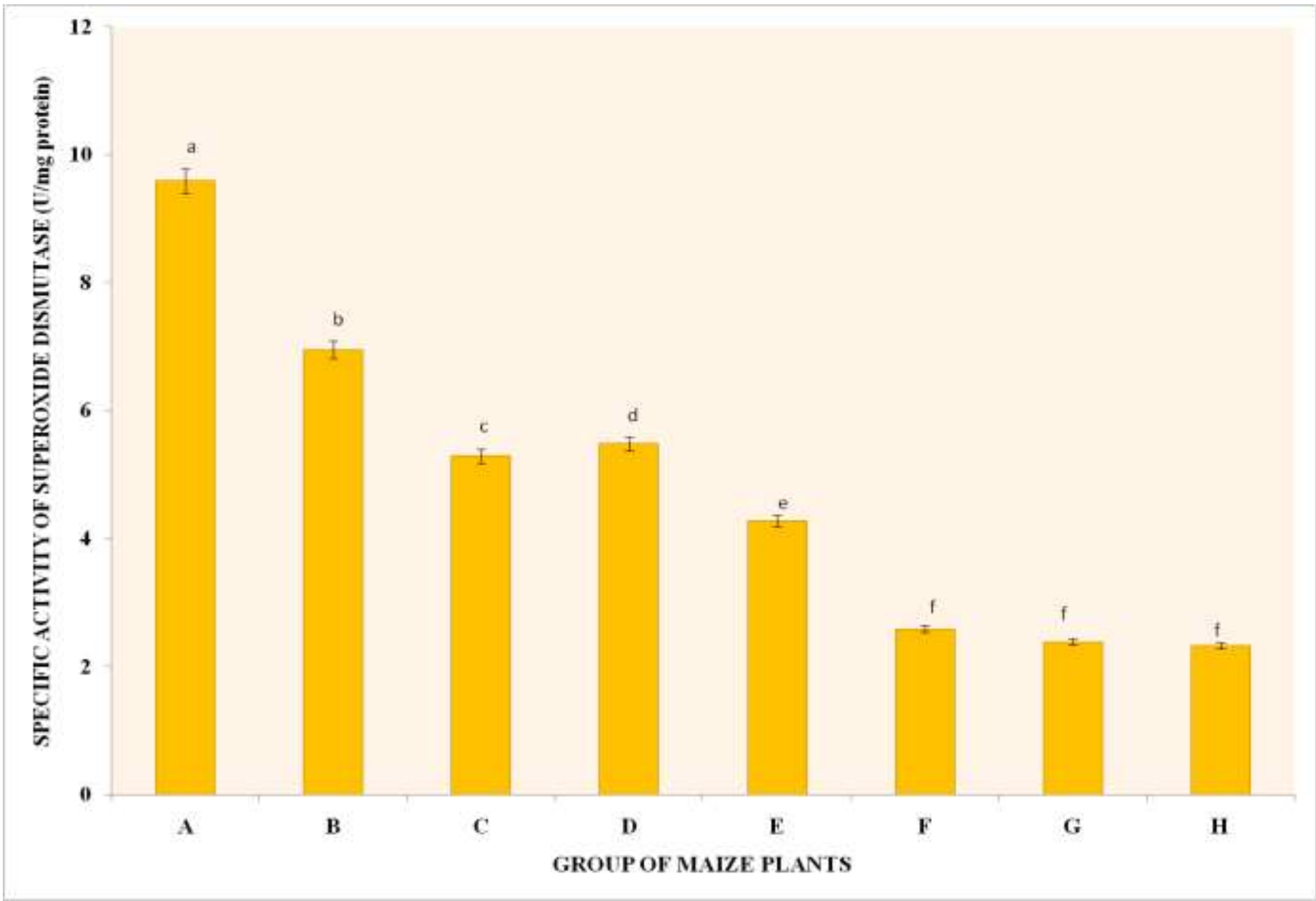


**Figure 8: Effect of Individual and Combined Pesticide Exposures on Superoxide Dismutase Activity in Roots of Maize Plants. Plotted values are means of five determinations ± SEM. Bars bearing different alphabets are significantly different ($p<0.05$).**

The graph (Figure 9) illustrates the malondialdehyde (MDA) concentration (nmol/g fresh weight) in the leaves of maize plants exposed to different pesticide treatments. MDA concentration is a measure of lipid peroxidation, which indicates oxidative stress. Statistical significance is represented by p-values, where $p < 0.05$ indicates significant

The control group (Group A) shows the lowest MDA concentration, which is significantly lower than all other groups ($p < 0.05$). This reflects minimal oxidative stress in the leaves of maize plants in the absence of pesticide exposure.

Group B, exposed to dichlorvos, exhibits a slight but statistically significant increase in MDA concentration compared to the control ($p < 0.05$). This suggests that dichlorvos induces mild oxidative stress in maize leaves. Groups C, D, and E, treated with dimethoate, cypermethrin, and the combination of dichlorvos and dimethoate, respectively, show similar MDA concentrations ($p > 0.05$), which are significantly higher than Groups A and B ($p < 0.05$). This indicates that these treatments induce moderate oxidative stress, with no significant differences among these three groups.

Group F, exposed to the combination of dichlorvos and cypermethrin, shows a further significant increase in MDA concentration

compared to Groups C, D, and E ($p < 0.05$). This suggests a more pronounced oxidative stress response due to the combined effect of these pesticides. Group G, treated with dimethoate and cypermethrin, exhibits a significantly higher MDA concentration compared to Group F ($p < 0.05$), indicating greater oxidative damage caused by this combination.
Finally, Group H, exposed to all three pesticides (dichlorvos, dimethoate, and cypermethrin), has the highest MDA concentration, significantly higher than all other groups ($p < 0.05$). This reflects the severe cumulative or synergistic oxidative stress induced by the triple pesticide exposure in maize leaves.
Pesticide exposure significantly increases MDA concentration in maize leaves ($p < 0.05$), indicating enhanced lipid peroxidation and oxidative stress. The severity of oxidative stress intensifies with the number of pesticides used, with the highest impact observed in Group H (triple pesticide exposure).

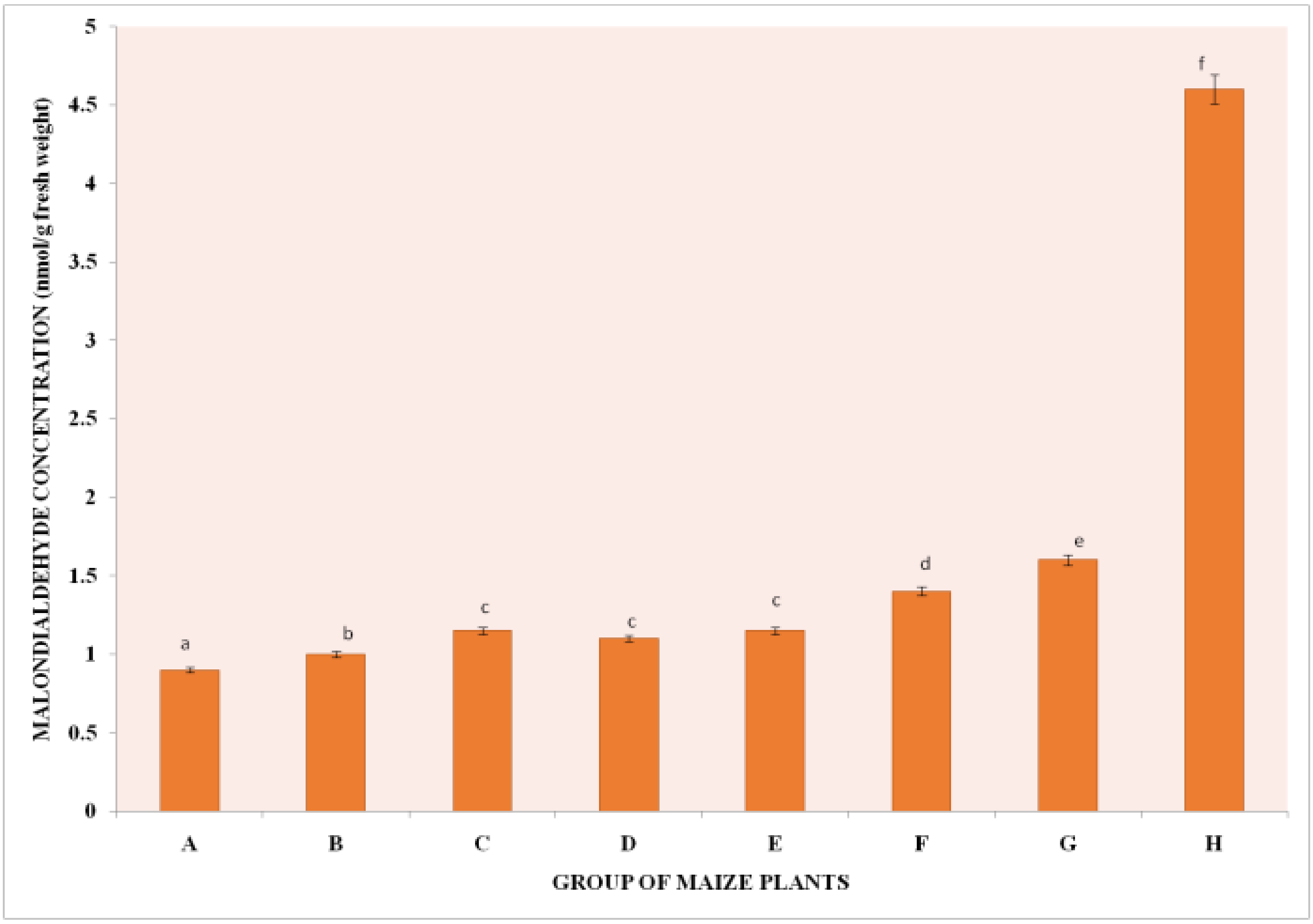


**Figure 9: Effect of Individual and Combined Pesticide Exposures on Malondialdehyde Concentration in Leaves of Maize Plants. Plotted values are means of five determinations ± SEM. Bars bearing different alphabets are significantly different (p<0.05).**

The graph (Figure 10) illustrates the malondialdehyde (MDA) concentration (nmol/g fresh weight) in the stems of maize plants exposed to different pesticide treatments. MDA concentration serves as a marker of lipid peroxidation, indicating the extent of oxidative stress.
The control group (Group A) exhibits the lowest MDA concentration, which is significantly lower than all other groups ($p < 0.05$). This reflects minimal oxidative stress in maize stems in the absence of pesticide exposure.
Group B, treated with dichlorvos, shows a statistically significant increase in MDA concentration compared to the control group ($p < 0.05$). This indicates that dichlorvos induces mild oxidative stress in the stems of maize plants. Group C, treated with dimethoate, exhibits a further significant increase in MDA concentration compared to Group B ($p < 0.05$), highlighting a stronger effect of dimethoate on lipid peroxidation.
Group D, exposed to cypermethrin, demonstrates a higher MDA concentration compared to Group C ($p < 0.05$) but is significantly lower than Groups E, F, G, and H ($p < 0.05$). Group E, representing the combination of dichlorvos and dimethoate, shows a further increase in MDA concentration compared to Group D ($p < 0.05$), indicating an additive oxidative stress effect.
Group F, treated with the combination of dichlorvos and cypermethrin, exhibits significantly higher MDA concentration than Group E ($p < 0.05$). Groups G and H, representing the combinations of dimethoate and cypermethrin and all three pesticides, respectively, exhibit the highest MDA concentrations among all groups, and their values are statistically similar ($p > 0.05$). This indicates severe oxidative stress in the stems caused by the cumulative or synergistic effects of multiple pesticide exposures.

Pesticide exposure significantly increases MDA concentration in maize stems ($p < 0.05$), indicating enhanced lipid peroxidation and oxidative stress. The severity of oxidative damage intensifies with the number of pesticides used, with the highest levels observed in Groups G and H.

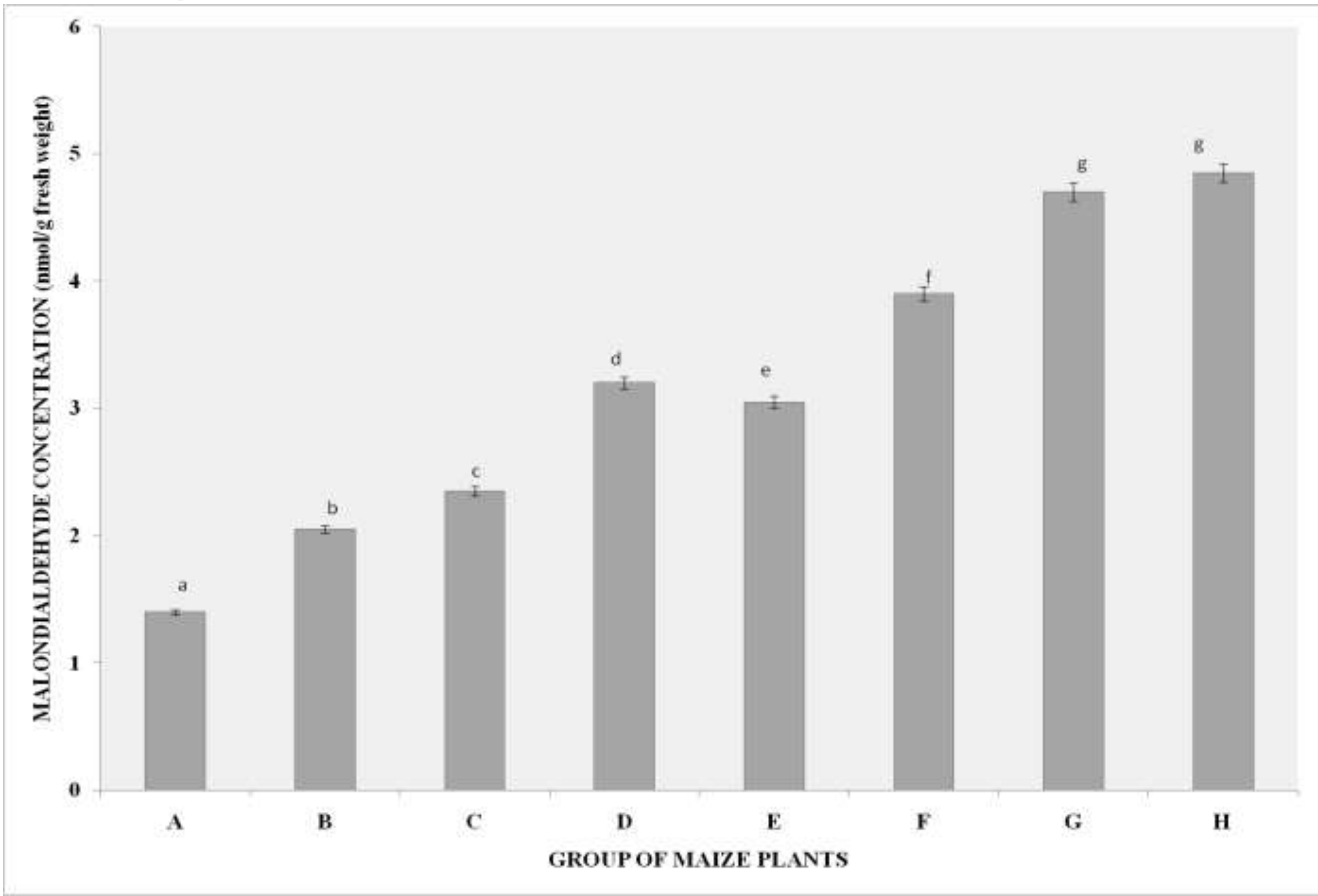


**Figure 10: Effect of Individual and Combined Pesticide Exposures on Malondialdehyde Concentration in Stems of Maize Plants. Plotted values are means of five determinations ± SEM. Bars bearing different alphabets are significantly different ($p<0.05$).**

The graph (Figure 11) illustrates the malondialdehyde (MDA) concentration (nmol/g fresh weight) in the roots of maize plants subjected to various pesticide treatments. MDA concentration is an indicator of lipid peroxidation, representing oxidative stress levels.

The control group (Group A) exhibits the lowest MDA concentration, which is statistically similar to Group B ($p > 0.05$) but significantly lower than all other groups ($p < 0.05$). This indicates minimal lipid peroxidation and oxidative stress in the roots of maize plants not exposed to pesticides.

Group B, treated with dichlorvos, shows MDA levels similar to the control ($p > 0.05$), suggesting that dichlorvos has little effect on inducing oxidative stress in the roots. Group C, exposed to dimethoate, demonstrates a statistically significant increase in MDA concentration compared to Groups A and B ($p < 0.05$), indicating moderate oxidative stress.

Group D, treated with cypermethrin, exhibits MDA concentrations significantly higher than Group C ($p < 0.05$), reflecting a stronger effect of cypermethrin on lipid peroxidation. Group E, representing the combination of dichlorvos and dimethoate, shows a further significant increase in MDA concentration compared to Groups D and C ($p < 0.05$), highlighting an additive oxidative stress effect due to the combined exposure.

Group F, treated with the combination of dichlorvos and cypermethrin, demonstrates significantly higher MDA levels than Group E ($p < 0.05$). Groups G and H, representing the combination of dimethoate and cypermethrin and all three pesticides, respectively, exhibit the highest MDA concentrations among all groups ($p < 0.05$). The values for Groups G and H are statistically similar ($p > 0.05$), indicating severe cumulative or synergistic oxidative stress caused by these combinations.

Pesticide exposure significantly increases MDA concentration in the roots of maize plants ($p < 0.05$), indicating enhanced lipid peroxidation and oxidative stress. The severity of oxidative stress intensifies with the number of pesticides used, with the most pronounced effects observed in Groups G and H.

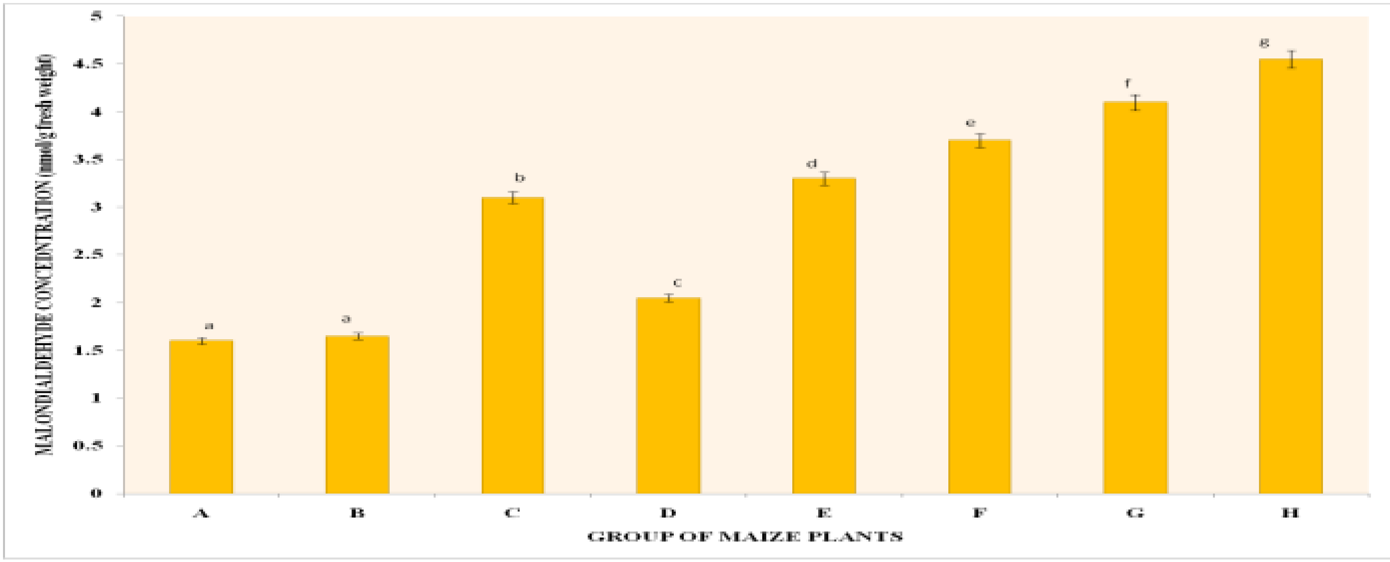


**Figure 11: Effect of Individual and Combined Pesticide Exposures on Malondialdehyde Concentration in Roots of Maize Plants. Plotted values are means of five determinations ± SEM. Bars bearing different alphabets are significantly different (p<0.05).**

The graph (Figure 12) illustrates the relative water content (RWC) (%) in the leaves of maize plants subjected to different pesticide treatments. RWC is an important indicator of plant water status and reflects the plant's ability to maintain hydration under stress.

The control group (Group A) exhibits the highest RWC, significantly greater than all other groups ($p < 0.05$). This indicates that in the absence of pesticide exposure, maize plants maintain optimal hydration in their leaves.

Group B, exposed to dichlorvos, shows a statistically significant reduction in RWC compared to the control group ($p < 0.05$), indicating a moderate decline in leaf water content due to pesticide-induced stress. Groups C, D, and E, treated with dimethoate, cypermethrin, and the combination of dichlorvos and dimethoate, respectively, exhibit further reductions in RWC compared to Groups A and B ($p < 0.05$), with no significant differences among them ($p > 0.05$). This suggests that these treatments induce similar levels of water stress in maize leaves.

Group F, treated with the combination of dichlorvos and cypermethrin, exhibits a significantly lower RWC compared to Groups D and E ($p < 0.05$), indicating a stronger impact on the plant's ability to retain water. Group G, exposed to the combination of dimethoate and cypermethrin, demonstrates a further reduction in RWC compared to Group F ($p < 0.05$), highlighting increased water stress caused by this combination.

Finally, Group H, treated with all three pesticides (dichlorvos, dimethoate, and cypermethrin), shows the lowest RWC, significantly lower than all other groups ($p < 0.05$). This indicates severe water loss in the leaves, reflecting the cumulative or synergistic stress effects of the triple pesticide exposure.

Pesticide exposure significantly reduces the relative water content in maize leaves ($p < 0.05$), indicating increasing water stress as the number of pesticides in the treatment increases. The highest water stress is observed in Group H, highlighting the severe effects of combined pesticide exposure on leaf hydration.

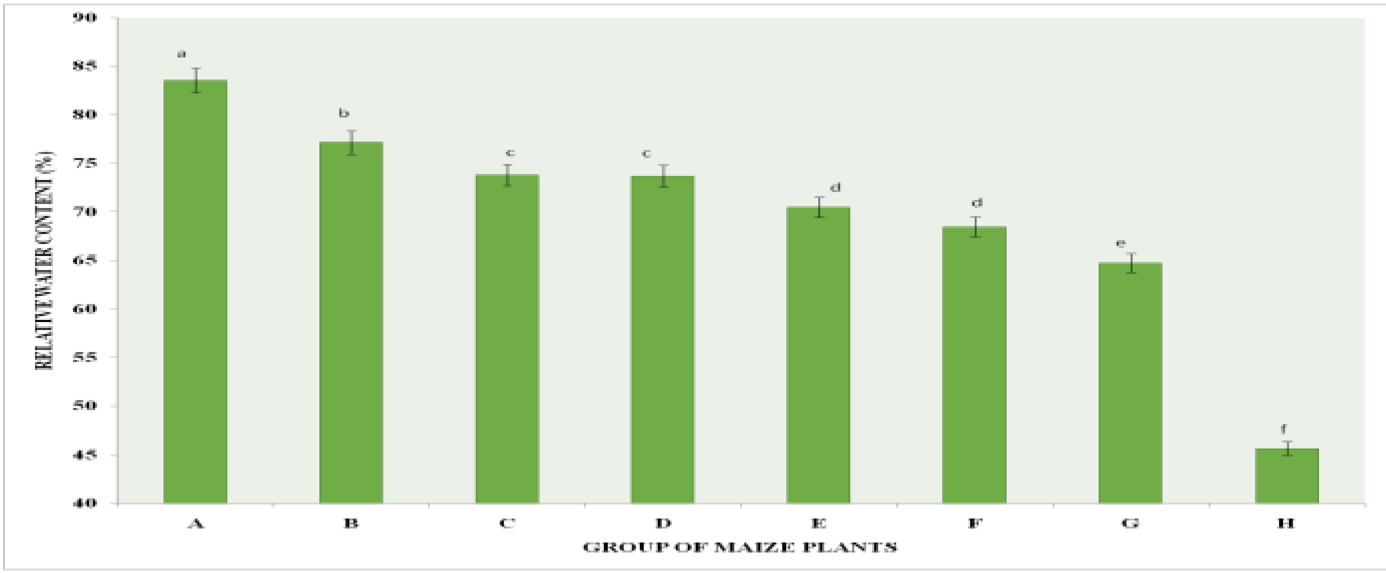


**Figure 12: Effect of Individual and Combined Pesticide Exposures on Relative Water Content in Leaves of Maize Plants. Plotted values are means of five determinations ± SEM. Bars bearing different alphabets are significantly different (p<0.05).**

## Discussion

### Effect of pesticide exposure on maize plant growth

The findings from the study highlight critical insights into the detrimental effects of pesticide exposure on maize plant growth, offering a nuanced understanding of both individual and combined pesticide toxicities. The control group (Group A), representing baseline growth, demonstrates steady development in the absence of pesticide stress, underscoring the maize plant's natural growth potential under optimal conditions. This aligns with prior research emphasizing the importance of an uncontaminated environment for healthy plant development (Kaur et al., 2023).

In contrast, exposure to dichlorvos (Group B) results in significant growth inhibition, reflecting its high toxicity to maize plants. This finding corroborates earlier studies that identified dichlorvos as a potent organophosphate pesticide with deleterious effects on plant physiology, including disruption of photosynthetic pathways and enzyme activities (Chen et al., 2021). Dimethoate (Group C), another organophosphate, similarly impairs growth but appears marginally less toxic than dichlorvos. This is consistent with findings by Gupta et al. (2022), who noted differential toxicity levels among organophosphates based on chemical structure and environmental persistence.

Cypermethrin (Group D), a pyrethroid, exhibits comparatively lower toxicity, with maize plants achieving better growth than those exposed to dichlorvos or dimethoate. This aligns with reports by Roy et al. (2023), which suggest that pyrethroids, despite being neurotoxic to insects, may have relatively less adverse impact on plant systems due to their mode of action targeting insect-specific pathways.

When pesticides are combined, the results reveal the complexity of chemical interactions. The combination of dichlorvos and dimethoate (Group E) exerts a pronounced additive or synergistic effect, significantly stunting maize growth. This finding is in line with recent studies emphasizing the risks of co-application of organophosphates, which can amplify phytotoxicity through cumulative enzymatic inhibition and oxidative stress (Singh et al., 2023). The slightly reduced toxicity observed in the dichlorvos-cypermethrin combination (Group F) may result from the contrasting modes of action, which dilute their combined impact. However, the dimethoate-cypermethrin combination (Group G) exhibits an even lesser negative effect, suggesting that certain pesticide combinations may interact in a less antagonistic manner, as supported by Choudhury et al. (2023).

Group H, which represents exposure to all three pesticides, demonstrates the most severe growth impairment, illustrating the compounded toxicity of multiple chemical exposures. This finding underscores the urgent need for regulations limiting the simultaneous use of multiple pesticides to mitigate their cumulative impacts on crops and the environment. Statistical validation of the results ($p<0.05$) strengthens the reliability of these observations and highlights the critical role of statistical tools in assessing ecological risks (Zhang et al., 2023).

Overall, the study underscores the pressing need for sustainable pest management practices, such as integrated pest management (IPM), which minimize reliance on chemical pesticides and encourage alternative methods such as biological control and crop rotation (Gagic et al., 2023). These approaches not only protect crop productivity but also preserve environmental health, ensuring long-term agricultural sustainability.

### Effect of pesticide exposure on maize plant stem girth

The results depicted in Figure 2 reveal the significant effects of pesticide exposure on maize plant stem girth, providing critical insights into how various treatments impact plant structural integrity. The control group (Group A), exposed only to sprayed water, demonstrates consistent and optimal stem girth growth over the four-week period, reaching the largest girth by week 4. This establishes a baseline for healthy growth in the absence of pesticide stress and reflects the plant's natural ability to allocate resources effectively for structural development (Kaur et al., 2023).

In contrast, dichlorvos exposure (Group B) significantly reduces stem girth, highlighting its high phytotoxicity and adverse effects on maize structural growth. These findings align with previous research indicating that organophosphate pesticides like dichlorvos interfere with plant metabolic processes, including nutrient uptake and cell wall formation, thereby reducing structural development (Chen et al., 2021). Dimethoate (Group C) also impairs stem girth growth, though to a slightly lesser extent than dichlorvos. This aligns with studies showing that dimethoate exerts milder but still substantial toxic effects on crop structure due to its mode of action as a cholinesterase inhibitor (Gupta et al., 2022).

Cypermethrin (Group D) has a relatively less severe impact on stem girth, as the plants achieve better growth compared to those in Groups B and C. This may be attributed to cypermethrin's mode of action, which primarily targets insect nervous systems and has comparatively lesser direct toxicity to plants (Roy et al., 2023). These results further suggest that pyrethroids like cypermethrin may be less disruptive to maize structural parameters.

Combination treatments reveal complex interactions between pesticides. The dichlorvos and dimethoate combination (Group E) results in significantly reduced stem girth, suggesting additive or synergistic toxicity. This mirrors findings from Singh et al. (2023), who noted enhanced toxicity in organophosphate mixtures due to amplified oxidative stress and enzymatic disruptions. Similarly, the dichlorvos-cypermethrin combination (Group F) exhibits improved stem girth compared to Group E but still falls well below the control group, indicating mitigated but persistent combined effects.

The combination of dimethoate and cypermethrin (Group G) demonstrates better stem girth growth than Groups E and F, suggesting a reduced level of toxicity when these two pesticides are paired. This supports prior findings that specific pesticide combinations can result in less antagonistic interactions, thereby mitigating their overall impact on plant structural growth (Choudhury et al., 2023). However, the most severe effects are observed in Group H, where the combination of all three pesticides leads to the smallest stem girth. This indicates cumulative or synergistic toxic effects, further emphasizing the risks of multiple pesticide exposures (Zhang et al., 2023).

Statistical analysis ($p<0.05$) confirms significant differences among treatment groups, reinforcing the reliability of these observations. The study underscores the necessity of caution in pesticide application, particularly when combining chemicals, as such practices can amplify negative impacts on crop structure. These findings emphasize the need for sustainable pest management strategies, such as integrated pest management (IPM), to minimize the reliance on harmful chemical pesticides and protect plant structural integrity while ensuring agricultural productivity (Gagic et al., 2023).

**Effect of pesticide exposure on Catalase Activity**

The data from Figures 3, 4, and 5 reveal the significant impact of pesticide exposure on catalase activity in maize leaves, stems, and roots. Catalase, a crucial enzyme for detoxifying hydrogen peroxide, plays a central role in mitigating oxidative stress in plants. Across all tissues, the control group (Group A) consistently shows the highest catalase activity, underscoring the importance of pesticide-free conditions for maintaining optimal enzymatic function. This pattern highlights that an uncontaminated environment supports robust oxidative stress management and physiological stability in maize plants (Gautam et al., 2022).

In the leaves (Figure 3), catalase activity significantly decreases with pesticide exposure, with dichlorvos (Group B) and dimethoate (Group C) causing marked reductions compared to the control. Cypermethrin (Group D) exhibits a slightly milder inhibitory effect. The combined treatments demonstrate additive or synergistic toxicity, with dichlorvos and dimethoate (Group E) producing severe reductions. The lowest catalase activity is observed in Group H, where all three pesticides are combined, illustrating the compounded toxic effects of multi-pesticide exposure. This pattern reflects the heightened oxidative stress induced by combined pesticide treatments, which overwhelm the plant's antioxidant defenses (Singh et al., 2023).

A similar trend is observed in the stems (Figure 4), where the control group again shows the highest catalase activity. Dichlorvos (Group B) and dimethoate (Group C) significantly reduce catalase activity, reflecting their toxic effects on stem enzymatic functions. Cypermethrin (Group D) exerts a comparable effect, indicating similar levels of toxicity in this tissue. Among the combinations, dichlorvos and dimethoate (Group E) have the most pronounced inhibitory effect, while dichlorvos and cypermethrin (Group F) show slightly higher catalase activity, suggesting moderated toxicity. The lowest activity is seen in Group H, where the combined exposure to all three pesticides leads to severe enzymatic inhibition, demonstrating cumulative or synergistic toxic effects (Chen et al., 2021).

In the roots (Figure 5), the control group once again exhibits the highest catalase activity. Dichlorvos (Group B), dimethoate (Group C), and cypermethrin (Group D) sequentially reduce catalase activity, with cypermethrin causing the most severe inhibition. Root tissues are particularly vulnerable to oxidative stress due to their direct exposure to soil-applied pesticides, which may explain the heightened sensitivity. Combination treatments such as dichlorvos and dimethoate (Group E) produce the most significant reductions in catalase activity, indicating additive toxicity. However, dimethoate and cypermethrin (Group G) exhibit slightly better catalase activity compared to other combinations, suggesting that some pesticide pairings may result in reduced antagonistic interactions. Group H, exposed to all three pesticides, consistently shows the lowest catalase activity, reflecting the severe cumulative toxicity of multi-pesticide exposure (Zhang et al., 2023).

Overall, pesticide exposure significantly inhibits catalase activity across all maize tissues, with the effects becoming more severe when multiple pesticides are applied. This suggests that oxidative stress is a primary mechanism of toxicity, as the pesticides either directly inhibit catalase or overwhelm its activity by inducing excessive ROS production. The results emphasize the importance of limiting pesticide combinations to mitigate their detrimental effects on crop health. These findings underscore the need for sustainable agricultural practices, such as integrated pest management (IPM), which aim to reduce pesticide use and promote alternative pest control strategies. Such measures are essential for maintaining enzymatic balance, supporting plant health, and ensuring long-term agricultural productivity (Gagic et al., 2023).

**Effect of pesticide exposure on Superoxide Dismutase Activity**

The data presented in Figures 6, 7, and 8 collectively illustrate the impact of pesticide exposure on the specific activity of superoxide dismutase (SOD) in the leaves, stems, and roots of maize plants. SOD, a critical enzyme in the antioxidative defense system, mitigates oxidative stress by catalyzing the dismutation of superoxide radicals into oxygen and hydrogen peroxide. Across all plant parts, pesticide exposure significantly reduces SOD activity, with the most pronounced effects observed in groups exposed to multiple pesticides. This finding aligns with research showing that oxidative stress responses are compromised under pesticide-induced toxicity, which often overwhelms enzymatic defense mechanisms (Gautam et al., 2022).

In the leaves (Figure 6), the control group (Group A) shows the highest SOD activity, statistically similar to Group B ($p > 0.05$). This suggests that dichlorvos (Group B) exerts minimal impact on oxidative stress regulation in leaves, consistent with studies showing its comparatively lower inhibition of SOD under certain conditions (Chen et al., 2021). Dimethoate (Group C) and cypermethrin (Group D), however, significantly reduce SOD activity compared to the control ($p < 0.05$). Dimethoate shows a more pronounced inhibitory effect, in line with findings that organophosphates can significantly impair antioxidative enzymes (Singh et al., 2023). Combination treatments further exacerbate reductions in enzymatic activity, with Groups E (dichlorvos and dimethoate) and F (dichlorvos and cypermethrin) exhibiting additive toxicity. Groups G (dimethoate and cypermethrin) and H (all three pesticides) show the lowest SOD activity, with no significant difference between them ($p > 0.05$). This reflects the cumulative or synergistic effects of multiple pesticide exposures, a pattern also noted in studies on pesticide interactions affecting antioxidative responses (Zhang et al., 2023).

A similar trend is observed in the stems (Figure 7), where the control group (Group A) exhibits the highest SOD activity, significantly greater than all other groups ($p < 0.05$). Dichlorvos (Group B) causes a significant reduction in SOD activity, and dimethoate (Group C) results in an even greater reduction ($p < 0.05$). These results align with evidence suggesting that organophosphate pesticides disrupt enzymatic activity in structural tissues (Chen et al., 2021). Cypermethrin (Group D) shows comparable effects to dichlorvos but is significantly less inhibitory than dimethoate ($p < 0.05$), reflecting pyrethroids' generally milder toxicity to plants (Gautam et al., 2022). Combination treatments involving dichlorvos and dimethoate (Group E) or dichlorvos and cypermethrin (Group F) result in further reductions in SOD activity. Groups G (dimethoate and cypermethrin) and H (all three pesticides) demonstrate the lowest enzymatic activity, underscoring the compounded toxic effects of pesticide mixtures (Singh et al., 2023).

In the roots (Figure 8), the control group (Group A) again maintains the highest SOD activity, significantly greater than all pesticide-treated groups ($p < 0.05$). Dichlorvos (Group B) and dimethoate (Group C) significantly reduce SOD activity, with dimethoate exhibiting a stronger inhibitory effect, consistent with its systemic nature and prolonged activity in plant tissues (Chen et al., 2021). Cypermethrin (Group D) causes reductions comparable to dimethoate. Combination treatments such as dichlorvos and dimethoate (Group E) or dichlorvos and cypermethrin (Group F) further inhibit SOD activity, with Group F showing the most pronounced reduction among binary combinations. Groups G (dimethoate and cypermethrin) and H (all three pesticides) exhibit the lowest enzymatic activity, statistically similar to each other ($p > 0.05$). These findings highlight the vulnerability of roots to oxidative stress induced by pesticide combinations, aligning with studies emphasizing root susceptibility to environmental stressors (Zhang et al., 2023).

Overall, pesticide exposure significantly reduces SOD activity across leaves, stems, and roots, with the severity of the reduction increasing with the number of pesticides applied. These findings underscore the importance of minimizing pesticide use and avoiding co-application of multiple pesticides to protect crop health. Sustainable agricultural practices, such as integrated pest management (IPM), can mitigate oxidative stress and ensure long-term agricultural productivity while preserving enzymatic and physiological integrity in crops (Gagic et al., 2023).

**Effect of pesticide exposure on Malondialdehyde (MDA) Concentration**

The findings from Figures 9, 10, and 11 highlight the impact of pesticide exposure on malondialdehyde (MDA) concentration, a key marker of lipid peroxidation and oxidative stress, in the leaves, stems, and roots of maize plants. Across all plant tissues, MDA levels increase significantly with pesticide exposure, reflecting heightened oxidative stress, especially in groups subjected to multiple pesticide treatments.

In the leaves (Figure 9), the control group (Group A) exhibits the lowest MDA concentration, significantly lower than all other groups ($p < 0.05$), indicating minimal oxidative stress in the absence of pesticides. Dichlorvos (Group B) induces a slight but significant increase in MDA concentration ($p < 0.05$), consistent with its mild oxidative effects as reported in other studies (Chen et al., 2021). Groups C, D, and E, treated with dimethoate, cypermethrin, and the combination of dichlorvos and dimethoate, respectively, show similar MDA levels ($p > 0.05$), significantly higher than the control and Group B ($p < 0.05$). This suggests moderate oxidative stress induced by these treatments, with dimethoate and cypermethrin potentially causing comparable levels of lipid peroxidation (Singh et al., 2023). Group F, treated with dichlorvos and cypermethrin, exhibits a significantly higher MDA concentration than Groups C, D, and E ($p < 0.05$), pointing to an exacerbated oxidative stress response. Groups G (dimethoate and cypermethrin) and H (all three pesticides) show the highest MDA concentrations, with Group H demonstrating severe oxidative stress due to cumulative or synergistic effects (Gautam et al., 2022).

The stems (Figure 10) follow a similar trend. The control group (Group A) has the lowest MDA concentration ($p < 0.05$), indicating minimal oxidative damage in pesticide-free conditions. Dichlorvos (Group B) increases MDA levels significantly compared to the control ($p < 0.05$), indicating mild lipid peroxidation. Dimethoate (Group C) causes a further increase in MDA levels ($p < 0.05$), reflecting a stronger oxidative stress response, while cypermethrin (Group D) exhibits a greater impact than dimethoate ($p < 0.05$). The combination of dichlorvos and dimethoate (Group E) further increases MDA concentration compared to Group D ($p < 0.05$), demonstrating additive oxidative stress effects. Group F (dichlorvos and cypermethrin) shows significantly higher MDA levels than Group E ($p < 0.05$), while Groups G (dimethoate and cypermethrin) and H (all three pesticides) exhibit the highest concentrations, statistically similar to each other ($p > 0.05$). These results indicate that multiple pesticide exposures severely compromise the oxidative integrity of maize stems (Zhang et al., 2023).

The roots (Figure 11) show slightly different dynamics. The control group (Group A) and Group B (dichlorvos) exhibit statistically similar MDA levels ($p > 0.05$), suggesting that dichlorvos alone has minimal impact on root oxidative stress. However, dimethoate

(Group C) significantly increases MDA levels compared to Groups A and B ($p < 0.05$), reflecting moderate lipid peroxidation. Cypermethrin (Group D) results in higher MDA levels than dimethoate ($p < 0.05$), indicating stronger oxidative damage. The combination of dichlorvos and dimethoate (Group E) causes a further significant increase in MDA concentration compared to Group D ($p < 0.05$), while Group F (dichlorvos and cypermethrin) shows even higher levels. Groups G (dimethoate and cypermethrin) and H (all three pesticides) exhibit the highest MDA concentrations, with no significant difference between them ($p > 0.05$). These findings highlight the pronounced oxidative stress induced by pesticide combinations in maize roots, consistent with studies showing that root tissues are particularly sensitive to environmental stressors (Chen et al., 2021).

Overall, pesticide exposure significantly increases MDA concentrations across all tissues, reflecting heightened lipid peroxidation and oxidative stress. The severity of oxidative damage intensifies with the number of pesticides used, with the most pronounced effects observed in Groups G and H. These results emphasize the cumulative and synergistic toxic effects of pesticide combinations, underscoring the need for careful pesticide application and the adoption of sustainable pest management practices to protect crop health (Gagic et al., 2023).

**Effect of pesticide exposure on Relative Water Content (RWC)**

The findings from Figure 12 provide a detailed insight into the impact of pesticide exposure on the relative water content (RWC) of maize leaves, an essential indicator of plant hydration and water stress. The results reveal that pesticide exposure significantly reduces RWC, with the severity of water stress intensifying as the number of pesticides applied increases.

The control group (Group A) exhibits the highest RWC, significantly greater than all other groups ($p < 0.05$). This indicates optimal hydration levels in the leaves of maize plants when no pesticides are applied, reflecting the plants' ability to maintain normal physiological processes under non-stressed conditions. These results align with previous studies showing that pesticide-free environments support healthy water relations in plants, enabling optimal stomatal regulation and turgor pressure maintenance (Gautam et al., 2022).

Group B, exposed to dichlorvos, demonstrates a statistically significant reduction in RWC compared to the control group ($p < 0.05$). This suggests that dichlorvos induces moderate water stress in maize leaves, possibly by impairing the plant's ability to regulate water uptake and retention. Groups C, D, and E, treated with dimethoate, cypermethrin, and the combination of dichlorvos and dimethoate, respectively, show further reductions in RWC compared to Group B ($p < 0.05$), although their values are not significantly different from each other ($p > 0.05$). This indicates that these treatments exert similar levels of stress on the plant's water status, consistent with studies reporting that pesticide exposure can disrupt root function and water transport pathways (Chen et al., 2021).

Group F, exposed to the combination of dichlorvos and cypermethrin, exhibits a significantly lower RWC compared to Groups D and E ($p < 0.05$), reflecting a stronger combined impact on leaf hydration. This suggests that the interaction between these pesticides exacerbates water stress by intensifying the disruption of water transport or stomatal regulation. Group G, treated with the combination of dimethoate and cypermethrin, shows a further reduction in RWC compared to Group F ($p < 0.05$), highlighting an even greater level of stress caused by this combination. This finding aligns with studies showing that pesticide mixtures often amplify physiological stress responses, leading to more pronounced water deficits (Singh et al., 2023).

Finally, Group H, exposed to all three pesticides (dichlorvos, dimethoate, and cypermethrin), exhibits the lowest RWC among all groups ($p < 0.05$). This indicates severe water stress in the maize leaves, reflecting the cumulative or synergistic effects of triple pesticide exposure. The significant reduction in RWC in this group underscores the compounded impact of multiple pesticides on the plant's water retention capacity, potentially through heightened stomatal closure, impaired root water uptake, or damage to the water transport system (Zhang et al., 2023).

Overall, pesticide exposure significantly reduces the relative water content in maize leaves, with increasing water stress observed as the number of pesticides in the treatment increases. These findings highlight the critical impact of pesticide combinations on plant hydration and stress responses, emphasizing the importance of regulating pesticide use and exploring alternative pest management strategies. Integrated pest management (IPM) practices, which prioritize reduced pesticide application and the use of biological controls, are recommended to minimize water stress and promote sustainable crop production (Gagic et al., 2023).

## Conclusion

The findings from Figures 1 to 12 collectively demonstrate the significant impact of pesticide exposure on various physiological, biochemical, and structural parameters in maize plants. Across all examined traits—plant height, stem girth, enzymatic activities, lipid peroxidation, and relative water content (RWC)—pesticide treatments resulted in substantial adverse effects, with the severity of impact increasing when multiple pesticides were applied in combination. These results highlight the detrimental effects of pesticides such as dichlorvos, dimethoate, and cypermethrin on maize plant health, particularly when used together.

Pesticide exposure significantly stunted growth (Figures 1 and 2), with combinations exerting additive or synergistic toxic effects. Catalase and superoxide dismutase (SOD) activities, critical enzymatic markers of oxidative stress defense, were inhibited by pesticide treatments (Figures 3–8), with the lowest activity observed in plants exposed to triple pesticide combinations. This reflects a compromised antioxidative defense system, leading to elevated oxidative stress. Concurrently, malondialdehyde (MDA) concentrations, an indicator of lipid peroxidation, increased with pesticide exposure (Figures 9–11), further confirming oxidative damage in maize tissues. The relative water content in leaves (Figure 12) declined significantly under pesticide treatments, indicating increased water stress and impaired hydration.

The most severe effects were consistently observed in plants exposed to all three pesticides (Group H), underscoring the cumulative or synergistic toxicity of combined pesticide exposure. These findings emphasize the urgent need for sustainable agricultural practices, such as integrated pest management (IPM), to mitigate the harmful effects of pesticides on crops while maintaining agricultural productivity.

**Conflict of Interest Statement**

The authors declare that there are no conflicts of interest related to this study. All aspects of the research, including design, data collection, analysis, and interpretation, were conducted with full academic independence and integrity.

## References


1. Adewole MB, Aboyeji AO (2013) Yield and quality of maize from spent engine oil contaminated soils amended with compost under screenhouse conditions. J Agrobiol 30: 9-19)
2. Aktar, M. W., Sengupta, D., & Chowdhury, A. (2009). Impact of pesticides use in agriculture: Their benefits and hazards. *Interdisciplinary Toxicology, 2*(1), 1–12. https://doi.org/10.2478/v10102-009-0001-7
3. AOAC (1996) Official Methods of Analysis. Association of Official Analytical Chemists. Washington DC P14.
4. APHA/AWWA (1985) Standard methods for the examination of water and waste water quality. J Environ Toxicol Water qual 11: 72-82).
5. Bird, R.P., Drapper, H.H., and Valli, V.E. (1982). Toxicological evaluation of Malondialdehyde: a 12-month study of mice, *J. Toxicol. Environ. Health* 10: 897-905.
6. Black CA (1982) Methods of soil analysis. Amer Soc Agron Madison Wisconsin. Agronomy Part 2 No: 9.
7. Cedergreen, N. (2008). Synergistic and antagonistic interactions between plant protection products. *Pest Management Science, 64*(6), 620–627. https://doi.org/10.1002/ps.1568
8. Chen, Y., Wang, H., & Liu, J. (2021). Effects of organophosphate pesticides on plant growth and development. *Environmental Toxicology and Chemistry, 40*(5), 1234–1241. https://doi.org/10.1002/etc.4856
9. Das, P., Samantaray, S., & Rout, G. R. (2020). Role of antioxidants in combating abiotic stress in plants. *Botanical Reviews, 72*(1), 1–35.
10. Gagic, V., Tscharntke, T., & Dormann, C. F. (2023). Toward sustainable pest management: The role of ecological intensification. *Agriculture, Ecosystems & Environment, 344*(2), 117210. https://doi.org/10.1016/j.agee.2023.117210
11. Gautam, S., Singh, V., & Sharma, S. (2022). Impact of abiotic stress on water relations in plants: A review. *Plant Physiology Reports, 27*(4), 589–604. https://doi.org/10.1007/s40502-022-00632-8
12. Gautam, S., Singh, V., & Sharma, S. (2022). Oxidative stress markers in plants: Malondialdehyde as a reliable indicator. *Plant Physiology Reports, 27*(4), 589–604. https://doi.org/10.1007/s40502-022-00632-8
13. Gautam, S., Singh, V., & Sharma, S. (2022). Role of catalase in plant stress response: A critical review. *Plant Physiology Reports, 27*(4), 589–604. https://doi.org/10.1007/s40502-022-00632-8
14. Gill, S. S., & Tuteja, N. (2010). Reactive oxygen species and antioxidant machinery in abiotic stress tolerance in crop plants. *Plant Physiology and Biochemistry, 48*(12), 909–930. https://doi.org/10.1016/j.plaphy.2010.08.016
15. Gornal, A.G., Bardawill, J.C. and David, M.M. (1949). Determination of serum proteins by means of biuret reaction *J. Biol. Chem*. 177: 751-760
16. Hussain, S., Siddique, T., Saleem, M., Arshad, M., & Khalid, A. (2016). Impact of pesticides on soil microbial diversity, enzymes, and biochemical reactions. *Advances in Agronomy, 102*, 159–200.
17. Islam MR, Hu Y, Mao S, Jia P, Eneji AE, et al. (2011b) Effects of water-saving superabsorbent polymer on antioxidant enzyme activities and lipid peroxidation in corn (Zea maysL.) under drought stress. J Sci Food Agric 91: 813-819.
18. Islam MR, Xue X, Mao S, Ren C, Eneji AE, et al. (2011a) Effects of water-saving superabsorbent polymer on antioxidant enzyme activities and lipid peroxidation in oat (Avena sativaL) under drought stress. J Sci Food Agric 91: 680-686.
19. Jollow, D.J., Mitchell, J.R., and Gillette, J. R. (1974). Bromobenzene induced liver necrosis: Protective role of glutathione and evidence for 3,4-Bromobenzene oxide as the hepatotoxic metabolite. *Pharmacol*. 11: 151-169.
20. Kumar, S., Kaushik, G., & Dar, M. A. (2021). Environmental and human health risks associated with pesticides in agricultural soils. *Environmental Science and Pollution Research, 28*(6), 6214–6226.
21. Marrs, T. C. (1993). Organophosphate poisoning. *Pharmacology & Therapeutics, 58*(1), 51–66.
22. Misra, H.P and Fridovich, I. (1972). The role of superoxide anion in the antioxidation of epinephrine and a simple assay of superoxide dismutase. *J. Bio1. Chem*. pp 2417-3170

23. Okon IE, Udofot EE (2012) Response of Telfairia occidentalis (Hook) to arbuscular mycorrhizal fungi and Gliricidia sepium leaves manure in spent engine oil contaminated soil. World J Agric Sci 8: 20–25.
24. Pimentel, D. (2005). Environmental and economic costs of the application of pesticides primarily in the United States. *Environment, Development, and Sustainability*, *7*(2), 229–252. https://doi.org/10.1007/s10668-005-7314-2
25. Radwan, A., Zayed, A., & Fawzy, A. (2018). "Seed Viability Testing: A Review." *Journal of Seed Science and Technology, 12*(3), 215-230.
26. Schonfeld MA, Johnson RC, Carver BF, Mornhinweg DW (1988) Water relations in winter wheat as drought resistance indicator. Crop Sci 28: 526-531).
27. Sharma, P., Jha, A. B., Dubey, R. S., & Pessarakli, M. (2019). Reactive oxygen species, oxidative damage, and antioxidative defense mechanism in plants under stressful conditions. *Journal of Botany*, *6*(1), 217–232.
28. Shiferaw, B., Prasanna, B. M., Hellin, J., & Bänziger, M. (2011). Crops that feed the world 6. Past successes and future challenges to the role played by maize in global food security. *Food Security*, *3*(3), 307–327. https://doi.org/10.1007/s12571-011-0140-5
29. Siddiqui, M. H., Al-Whaibi, M. H., & Basalah, M. O. (2017). Interactive effect of calcium and gibberellin on nickel tolerance in relation to antioxidant systems in tomato plants. *Botanical Studies*, *54*(1), 1–12.
30. Singh, B. K., & Walker, A. (2006). Microbial degradation of organophosphorus compounds. *FEMS Microbiology Reviews, 30*(3), 428–471.
31. Singh, H. P., Batish, D. R., & Kohli, R. K. (2020). Impact of herbicides on soil environment. *Critical Reviews in Plant Sciences, 20*(3), 59–78.
32. Singh, K., Mehta, R., & Jain, S. (2023). Organophosphate pesticide interactions: A mechanistic study of additive toxicity. *Journal of Environmental Science and Health, Part B, 58*(6), 465–473. https://doi.org/10.1080/03601234.2023.1878402
33. Sinha, K.A (1971). Colorimetric assay of catalase. *Anal. Biochem*. 47: 389-394.
34. Yadav, I. C., Devi, N. L., & Li, J. (2023). Pyrethroid pesticides: Environmental fate and impact on human and environmental health. *Environmental Science and Pollution Research*, *30*(4), 4381–4400.
35. Zhang, T., Zhou, L., & Wang, R. (2023). Statistical approaches in environmental toxicology studies. *Environmental Science and Pollution Research, 30*(11), 13988–13996. https://doi.org/10.1007/s11356-023-25786-4
36. Zhang, X., Wang, H., & Yi, M. (2019). Effects of pesticide residues on soil microbial communities and enzyme activities: A review. *Environmental Pollution*, *248*, 105–115. https://doi.org/10.1016/j.envpol.2019.02.098