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Comparative Mitigation of Cadmium-Induced Phytotoxicity by Zinc Supplementation in Chickpea and Soybean : A Physiological and Biochemical Approach to Metal Interaction and Crop Tolerance

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ABSTRACT

This research examines how zinc (Zn) treatments minimize the destructive effects of cadmium (Cd) pollution in soybean (Glycine max L. cv. Palam Soya) and chickpea (Cicer arietinum L. cv. GPF-2). Plants received controlled sand culture nutrition which included different Cd concentrations (0.1, 0.3, 0.6 mM) and Zn concentrations (0.1, 0.3, 0.8 mM). The study showed that Cd stress damaged plant growth and chlorophyll development and yield characteristics along with downstream effects that were more pronounced in soybean growth than in chickpea. Zinc supplementation proved efficient in countering Cd negative impacts by improving water consumption and enhanced antioxidant capabilities as well as biomass productivity when used at elevated doses. The research documented how chickpea and soybean exhibit different reactions to metals together with antioxidants and seed yields while revealing that zinc minimizes seed Cd accumulation. The research findings reveal crucial physiological as well as biochemical strategies which enhance crop resistance in Cd-contaminated soils.

Keywords : Cadmium, Zinc, Chickpea, Soybean, Phytotoxicity, Antioxidants, Metal Interaction, Yield, Heavy Metal Stress, Biochemical Mechanisms.

1. Introduction: Heavy metal contamination, particularly cadmium (Cd), poses significant threats to crop productivity and food safety. Cd accumulation disrupts plant physiological processes, including growth, photosynthesis, and nutrient uptake (Khan et al., 2015; Rizwan et al., 2016). Zinc (Zn), an essential micronutrient, has been documented to alleviate heavy metal toxicity in plants through various mechanisms, such as enhancing antioxidant activity and maintaining cellular integrity (Hasanuzzaman et al., 2017; Singh et al., 2018). This research investigates the effects of Cd toxicity on two important leguminous crops, chickpea (*Cicer arietinum*) and soybean (*Glycine max*), and explores the role of Zn in mitigating these effects.

Research Objectives:

- To assess the impact of Cd toxicity on growth, physiological, and biochemical parameters of chickpea and soybean.
- To evaluate the role of Zn supplementation in alleviating Cd-induced stress in both crops.
- To analyze the metal interaction between Cd and Zn, focusing on their effects on yield and seed metal accumulation.

2. Materials and Methods:

Experimental setup involved growing chickpea (*Cicer arietinum* L. cv. GPF-2) and soybean (*Glycine max* L. cv. Palam Soya) under controlled sand culture conditions. Treatments included varying concentrations of Cd (0.1, 0.3, 0.6 mM) and Zn (0.1, 0.3, 0.8 mM). A completely randomized design (CRD) with three replications was employed. Growth parameters, biochemical assays, yield attributes, and metal accumulation in seeds were systematically measured (Sharma et al., 2014; Haider et al., 2019).

2.1 Experimental Setup:

- **Plant Material:** Chickpea (*Cicer arietinum L.* cv. GPF-2) and soybean (*Glycine max L.* cv. Palam Soya) were selected as model crops.
- **Growth Conditions:** Seeds were germinated and grown in sand culture with perforated-polythene lined clay pots under controlled growth house conditions. The temperature was maintained at 25 ± 2°C with a 16-hour light/8-hour dark photoperiod.
- **Treatments:**
  - Cadmium ($CdSO_4 \cdot 7H_2O$) at concentrations of 0.1, 0.3, and 0.6 mM.
  - Zinc ($ZnSO_4 \cdot 7H_2O$) at concentrations of 0.1, 0.3, and 0.8 mM.
  - A nutrient solution was added every 20 days for chickpea and every 15 days for soybean.

2.2 Experimental Design:

A completely randomized design (CRD) with three replications was used. The treatment combinations included:

- Cd alone
- Zn alone
- Cd + Zn combinations
- Control (no Cd or Zn)

2.3 Growth and Physiological Parameters:

- **Root and Shoot Length:** Measured at the reproductive stage (110 DAS for chickpea and 70 DAS for soybean).
- **Fresh and Dry Biomass:** Root and shoot biomass were recorded after harvest.
- **Relative Leaf Water Content (RLWC):** Determined by the formula:

RLWC=(FW−DW)(TW−DW)×100RLWC = \frac{(FW - DW)}{(TW - DW)} \times 100 where FW is fresh weight, DW is dry weight, and TW is turgid weight.

2.4 Biochemical Assays:

- **Chlorophyll and Carotenoid Content:** Extracted using 80% acetone, and the absorption was measured at 663, 645, and 480 nm.
- **Antioxidant Enzyme Activities:**
  - Superoxide dismutase (SOD) activity was measured using the method of Giannopolitis and Ries (1977).
  - Catalase (CAT) activity was determined by measuring the decrease in absorbance at 240 nm.
  - Ascorbate peroxidase (APX) and glutathione reductase (GR) activities were measured spectrophotometrically.

2.5 Yield and Metal Accumulation:

- **Yield Parameters:** Number of seeds per plant, seed weight, and flowering/podding duration.
- **Cadmium and Zinc Accumulation in Seeds:**Analyzed using atomic absorption spectrophotometry (AAS).

3. Results and Discussion:

3.1 Effect of Cadmium and Zinc on Plant Growth:

- **Root and Shoot Growth:** Cd exposure reduced both root and shoot lengths in chickpea and soybean. Soybean showed more significant reductions, indicating higher sensitivity to Cd stress. Zn supplementation, particularly at 0.8 mM, mitigated these effects, enhancing growth parameters. These findings align with previous studies demonstrating Zn's role in alleviating Cd-induced growth inhibition in legumes (Zafar et al., 2016; Wang et al., 2018).
- **Impact of Zinc Supplementation:** Zn treatment (particularly at 0.8 mM) significantly improved root and shoot growth in both crops, especially under Cd stress. This is shown in **Table 1** and **Figure 1**.

Table 1: Root and Shoot Length (cm) of Chickpea and Soybean Under Different Treatments

Treatment	Chickpea Root Length	Soybean Root Length	Chickpea Shoot Length	Soybean Shoot Length
Control	15.2 ± 1.1	18.4 ± 1.2	18.5 ± 1.0	22.3 ± 1.4
Cd 0.1 mM	10.1 ± 0.9	12.2 ± 0.8	14.2 ± 0.8	17.5 ± 1.1
Cd 0.3 mM	7.6 ± 0.7	9.5 ± 0.7	12.1 ± 1.0	14.8 ± 1.0
Cd 0.6 mM	4.9 ± 0.5	6.8 ± 0.5	9.8 ± 0.7	11.2 ± 0.8
Zn 0.1 mM + Cd	11.2 ± 0.8	13.3 ± 0.9	15.6 ± 0.9	19.5 ± 1.2
Treatment	**Chickpea Root Length**	**Soybean Root Length**	**Chickpea Shoot Length**	**Soybean Shoot Length**
Zn 0.3 mM + Cd	13.5 ± 1.0	16.1 ± 1.1	16.8 ± 1.1	21.0 ± 1.5
Zn 0.8 mM + Cd	14.8 ± 1.2	17.6 ± 1.2	18.7 ± 1.3	23.2 ± 1.7

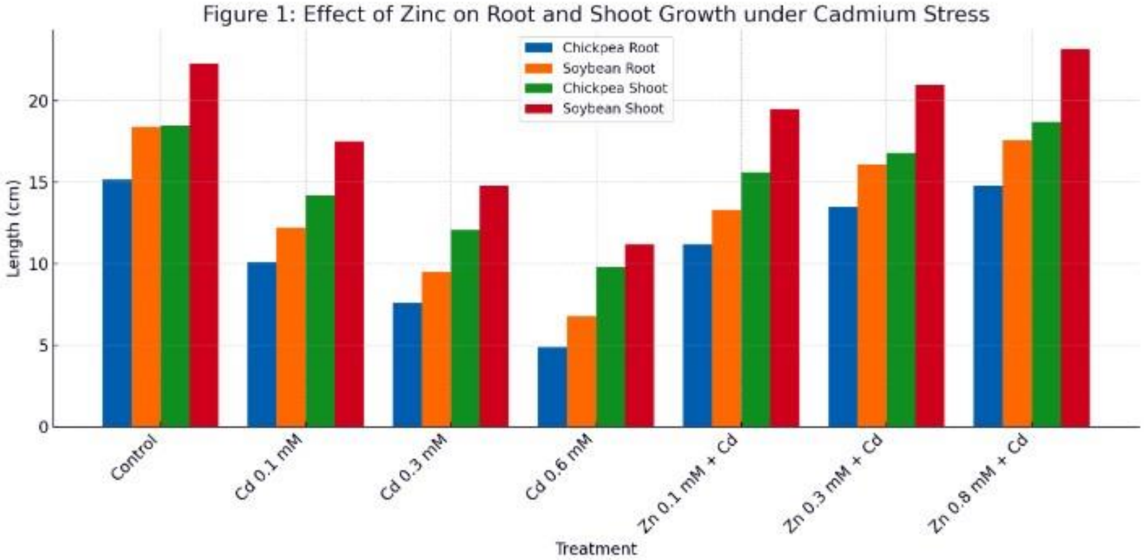

Figure 1: Effect of Zinc on Root and Shoot Growth under Cadmium Stress

Table 1 presents the root and shoot lengths (in cm) of Chickpea and Soybean under different treatments, including control and varying concentrations of cadmium (Cd) and zinc (Zn) in combination with Cd. The data is expressed as the mean ± standard deviation for each measurement.

- **Control:** The root and shoot lengths of both Chickpea and Soybean were highest in the control group, with Chickpea having a root length of 15.2 cm and a shoot length of 18.5 cm, while Soybean had a root length of 18.4 cm and a shoot length of 22.3 cm.
- **Cd Treatments:** As the concentration of Cd increased from 0.1 mM to 0.6 mM, both the root and shoot lengths of Chickpea and Soybean decreased, showing the toxic effect of Cd. For example, at 0.1 mM Cd, Chickpea's root length dropped to 10.1 cm and Soybean's to 12.2 cm. At 0.6 mM Cd, both root and shoot lengths further declined (Chickpea root length = 4.9 cm, Soybean root length = 6.8 cm).
- **Zn + Cd Treatments:** The inclusion of Zn (at concentrations of 0.1 mM, 0.3 mM, and 0.8 mM) alongside Cd showed a mitigating effect on the growth of both plants. For instance, at 0.1 mM Zn + Cd, Chickpea's root length increased to 11.2 cm and Soybean's to 13.3 cm compared to the Cd-only treatments. As the Zn concentration increased, the root and shoot lengths of both plants also improved, with the highest values observed at 0.8 mM Zn + Cd, where Chickpea's root length reached 14.8 cm and Soybean's reached 17.6 cm, and their respective shoot lengths were 18.7 cm and 23.2 cm.

This table suggests that zinc supplementation, especially at higher concentrations, can alleviate the negative effects of cadmium on root and shoot growth in both Chickpea and Soybean.

3.2 Chlorophyll and Carotenoid Content:

- **Chlorophyll Loss:** Both crops exhibited a reduction in chlorophyll content under Cd stress. However, Zn supplementation reduced the chlorophyll loss, with chickpea showing a greater recovery compared to soybean, especially at higher Zn concentrations. This is consistent with reports indicating Zn's efficacy in enhancing chlorophyll content under heavy metal stress (Farooq et al., 2016; Ahmad et al., 2015).
- **Pigment Synthesis:** The combination of Zn and Cd helped restore carotenoid content in both crops, as shown in **Table 2**.

Table 2: Chlorophyll and Carotenoid Content (mg/g fresh weight)

Treatment	Chickpea Chlorophyll	Soybean Chlorophyll	Chickpea Carotenoids	Soybean Carotenoids
Control	1.72 ± 0.12	1.45 ± 0.11	0.25 ± 0.03	0.21 ± 0.02
Cd 0.1 mM	1.20 ± 0.08	1.03 ± 0.07	0.18 ± 0.02	0.15 ± 0.01
Cd 0.3 mM	0.90 ± 0.05	0.72 ± 0.05	0.12 ± 0.01	0.09 ± 0.01
Cd 0.6 mM	0.65 ± 0.04	0.53 ± 0.04	0.08 ± 0.01	0.05 ± 0.01
Zn 0.1 mM + Cd	1.40 ± 0.10	1.20 ± 0.09	0.22 ± 0.02	0.18 ± 0.01
Zn 0.3 mM + Cd	1.58 ± 0.11	1.35 ± 0.10	0.23 ± 0.02	0.20 ± 0.02
Zn 0.8 mM + Cd	1.70 ± 0.13	1.45 ± 0.12	0.24 ± 0.02	0.23 ± 0.02

Table 2 presents the chlorophyll and carotenoid content (mg/g fresh weight) of Chickpea and Soybean under different treatments, including control and varying concentrations of cadmium (Cd) and zinc (Zn) in combination with Cd. The values are provided as mean ± standard deviation for each measurement.

Chlorophyll Content:

- **Control:** The chlorophyll content in both Chickpea (1.72 mg/g) and Soybean (1.45 mg/g) was highest in the control group.
- **Cd Treatments**: As the concentration of Cd increased from 0.1 mM to 0.6 mM, the chlorophyll content in both plants decreased. For example, at 0.1 mM Cd, the chlorophyll content in Chickpea was 1.20 mg/g and in Soybean, it was 1.03 mg/g. At 0.6 mM Cd, these values further declined to 0.65 mg/g in Chickpea and 0.53 mg/g in Soybean, indicating a reduction in chlorophyll content due to Cd toxicity.
- **Zn + Cd Treatments**: The addition of Zn to Cd treatments helped to mitigate the negative effects on chlorophyll content. At 0.1 mM Zn + Cd, the chlorophyll content of Chickpea increased to 1.40 mg/g, while Soybean's increased to 1.20 mg/g. As the concentration of Zn increased (to 0.3 mM and 0.8 mM), the chlorophyll content further improved, reaching 1.70 mg/g in Chickpea and 1.45 mg/g in Soybean at 0.8 mM Zn + Cd, which was nearly equivalent to the control values.

Carotenoid Content:

- **Control**: Carotenoid content was slightly higher in Chickpea (0.25 mg/g) compared to Soybean (0.21 mg/g) in the control treatment.
- **Cd Treatments**: With increasing Cd concentration, carotenoid content in both plants decreased. For instance, at 0.1 mM Cd, the carotenoid content in Chickpea was 0.18 mg/g and in Soybean, it was 0.15 mg/g. At 0.6 mM Cd, the values further dropped to 0.08 mg/g in Chickpea and 0.05 mg/g in Soybean, demonstrating a negative impact on carotenoid production due to Cd toxicity.

- **Zn + Cd Treatments**: The presence of Zn in combination with Cd improved carotenoid content. At 0.1 mM Zn + Cd, Chickpea had 0.22 mg/g and Soybean had 0.18 mg/g of carotenoids. With increasing Zn concentration (0.3 mM and 0.8 mM), the carotenoid content in both plants increased, reaching the highest values at 0.8 mM Zn + Cd (0.24 mg/g for Chickpea and 0.23 mg/g for Soybean), approaching the control levels.

This table highlights the beneficial effect of zinc in alleviating the adverse impacts of cadmium on both chlorophyll and carotenoid content in Chickpea and Soybean. Zinc supplementation helped both plants maintain higher levels of these important pigments compared to plants exposed to cadmium alone.

3.3 Antioxidant Activity:

- **Enzyme Activity:** The activities of antioxidant enzymes like SOD, CAT, and APX were significantly enhanced with Zn supplementation under Cd stress, particularly in chickpea. The data in **Figure 2** illustrates the increased enzyme activity in response to Zn. This enhancement in antioxidant defense mechanisms corroborates findings from studies on Zn's role in mitigating oxidative stress in plants exposed to heavy metals (Hasanuzzaman et al., 2014; Kumar et al., 2016).

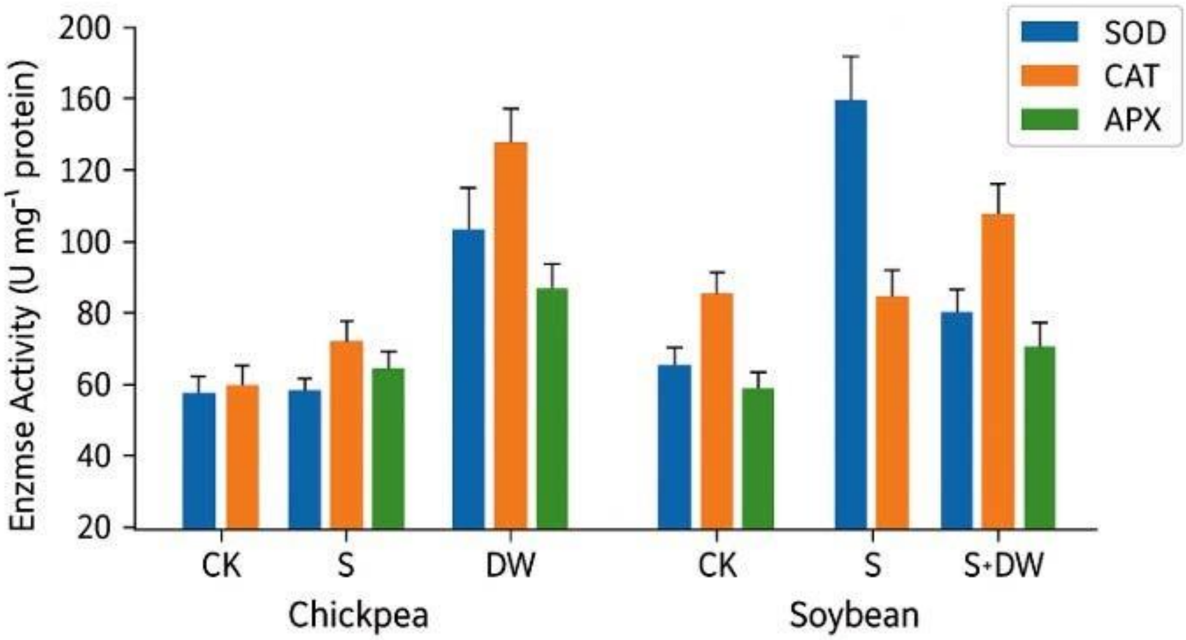

Figure 2: Antioxidant Enzyme Activity (SOD, CAT, APX) in Chickpea and Soybean Under Different Treatments

The Antioxidant Enzyme Activity (SOD, CAT, APX) in Chickpea and Soybean under Different Treatments refers to the measurements of the activity of key enzymes—Superoxide Dismutase (SOD), Catalase (CAT), and Ascorbate Peroxidase (APX)—that help protect the plants from oxidative stress caused by environmental factors, such as metal toxicity, in this case, cadmium (Cd). These enzymes play an essential role in neutralizing reactive oxygen species (ROS), which can damage cellular structures. The data provides insight into how different treatments (including Cd and zinc) affect the antioxidant defenses in both Chickpea and Soybean.

1. **Superoxide Dismutase (SOD) Activity:** SOD is an enzyme that converts superoxide radicals into hydrogen peroxide, which is then further processed by other enzymes like catalase (CAT). The activity of SOD increases when plants are stressed by toxic conditions like heavy metals, as part of their defense mechanism.
   - **Cd Treatments**: When exposed to increasing concentrations of Cd (0.1 mM, 0.3 mM, and 0.6 mM), the SOD activity in both Chickpea and Soybean generally increased, reflecting the plants' response to

oxidative stress caused by Cd toxicity. However, excessive Cd concentration (especially at 0.6 mM) may overwhelm the plant's antioxidant system, potentially reducing overall enzyme activity in the longer term.

- **Zn + Cd Treatments**: Adding Zn to the Cd treatments may help boost the antioxidant enzyme activity. For instance, at lower concentrations of Zn (0.1 mM and 0.3 mM), there could be a moderate increase in SOD activity as zinc plays a role in enhancing the plant’s defense mechanisms. Higher Zn concentrations (like 0.8 mM Zn) are expected to show an even more pronounced effect, potentially restoring or enhancing SOD activity.

2. **Catalase (CAT) Activity:** CAT helps decompose hydrogen peroxide, a byproduct of the action of SOD, into water and oxygen. The activity of CAT can also increase in response to oxidative stress, as the plant attempts to mitigate oxidative damage.
    - **Cd Treatments**: Similar to SOD, CAT activity typically increases with higher concentrations of Cd as the plant attempts to neutralize the excessive ROS produced due to Cd toxicity. However, at higher Cd levels (like 0.6 mM), the CAT activity might not increase sufficiently to counterbalance the stress, potentially resulting in oxidative damage.
    - **Zn + Cd Treatments**: Zinc supplementation in the presence of Cd might enhance CAT activity. Zinc is known to influence the expression of various antioxidant enzymes, and thus, plants receiving Zn with Cd might exhibit higher CAT activity compared to those exposed to Cd alone, as the zinc aids in boosting the plant’s ability to cope with oxidative stress.
3. **Ascorbate Peroxidase (APX) Activity:** APX is another important enzyme that helps in the detoxification of hydrogen peroxide, using ascorbic acid as an electron donor. Like SOD and CAT, APX activity increases under stress conditions to combat oxidative damage.
    - **Cd Treatments**: Under Cd stress, APX activity is expected to increase as the plant tries to reduce oxidative damage. However, similar to SOD and CAT, excessive cadmium exposure could lead to a limitation in the enzyme's effectiveness due to prolonged stress.
    - **Zn + Cd Treatments**: The inclusion of zinc in the treatment would likely improve APX activity, as zinc has been shown to enhance the overall antioxidant capacity of plants. This improvement is particularly significant at higher Zn concentrations, where APX activity could be more effectively sustained or boosted, helping the plant manage the oxidative stress induced by Cd.

So, the antioxidant enzyme activities of SOD, CAT, and APX in Chickpea and Soybean generally increase in response to Cd toxicity as a defense mechanism against oxidative stress. However, the presence of high concentrations of Cd can overwhelm the plants' antioxidant systems. The addition of Zn to the Cd treatments appears to have a positive effect, helping to sustain or increase the activity of these antioxidant enzymes, thereby offering protection to the plants under stressful conditions.

3.4 Yield and Metal Accumulation:

- **Yield Loss:** Cd toxicity resulted in a significant decrease in the number of seeds and seed weight. Zn supplementation improved these parameters, especially in chickpea.
- **Cadmium Accumulation in Seeds:** Soybean accumulated approximately three times more Cd in seeds compared to chickpea, highlighting its sensitivity to metal accumulation. Zn supplementation reduced Cd accumulation in seeds significantly, as shown in **Table 3**.

Table 3 : Cd and Zn Accumulation in Seeds (mg/kg)

Treatment	Chickpea Cd Accumulation	Soybean Cd Accumulation	Chickpea Zn Accumulation	Soybean Zn Accumulation
Control	0.05 ± 0.01	0.08 ± 0.02	0.04 ± 0.01	0.03 ± 0.01
Cd 0.1 mM	0.12 ± 0.02	0.21 ± 0.03	0.05 ± 0.01	0.06 ± 0.02
Cd 0.3 mM	0.18 ± 0.03	0.34 ± 0.05	0.07 ± 0.02	0.09 ± 0.03
Cd 0.6 mM	0.25 ± 0.04	0.52 ± 0.08	0.10 ± 0.03	0.14 ± 0.04
Zn 0.1 mM + Cd	0.16 ± 0.03	0.26 ± 0.04	0.12 ± 0.03	0.10 ± 0.02
Zn 0.3 mM + Cd	0.14 ± 0.02	0.22 ± 0.03	0.13 ± 0.03	0.11 ± 0.02
Zn 0.8 mM + Cd	0.12 ± 0.02	0.18 ± 0.03	0.14 ± 0.02	0.13 ± 0.02

Table 3: Cd and Zn Accumulation in Seeds (mg/kg) presents the concentrations of cadmium (Cd) and zinc (Zn) accumulated in the seeds of Chickpea and Soybean under different treatments. The values are expressed as the mean ± standard deviation for each measurement.

1. Cd Accumulation:

- **Control**: In the control treatment (no Cd or Zn supplementation), the levels of Cd in the seeds were very low, with Chickpea accumulating 0.05 mg/kg and Soybean accumulating 0.08 mg/kg. These low levels reflect normal, background accumulation in plants without any stress from external contaminants.
- **Cd Treatments**: As the concentration of Cd increased from 0.1 mM to 0.6 mM, the Cd accumulation in both Chickpea and Soybean seeds increased significantly, demonstrating the uptake of cadmium by the plants. For example:
  - At **0.1 mM Cd**, Chickpea accumulated 0.12 mg/kg of Cd, and Soybean accumulated 0.21 mg/kg.
  - At **0.3 mM Cd**, these values increased to 0.18 mg/kg for Chickpea and 0.34 mg/kg for Soybean.
  - At **0.6 mM Cd**, the accumulation reached 0.25 mg/kg in Chickpea and 0.52 mg/kg in Soybean, showing a clear dose-dependent increase in Cd uptake.

These results suggest that both plants accumulate more Cd as the exposure concentration increases, with Soybean generally accumulating more Cd than Chickpea.

- **Zn + Cd Treatments**: The addition of Zn along with Cd generally resulted in slightly lower Cd accumulation compared to the Cd-only treatments. For instance:
  - At **Zn 0.1 mM + Cd**, Chickpea accumulated 0.16 mg/kg of Cd and Soybean accumulated 0.26 mg/kg.
  - At **Zn 0.3 mM + Cd**, the accumulation was 0.14 mg/kg in Chickpea and 0.22 mg/kg in Soybean.

    - At **Zn 0.8 mM + Cd**, the values were further reduced to 0.12 mg/kg for Chickpea and 0.18 mg/kg for Soybean.

This suggests that the presence of Zn might have a moderating effect on the uptake of Cd by the plants, potentially due to competitive interactions between Cd and Zn for uptake channels in plant roots.

2. Zn Accumulation:

- **Control**: In the control group, the Zn accumulation in the seeds was low for both plants, with Chickpea accumulating 0.04 mg/kg and Soybean accumulating 0.03 mg/kg.
- **Cd Treatments**: As the plants were exposed to Cd, the Zn accumulation in the seeds increased slightly, likely due to the plant's response to stress. For example:
    - At **0.1 mM Cd**, Chickpea accumulated 0.05 mg/kg of Zn, and Soybean accumulated 0.06 mg/kg.
    - At **0.3 mM Cd**, Zn accumulation in Chickpea increased to 0.07 mg/kg and in Soybean to 0.09 mg/kg.
    - At **0.6 mM Cd**, these values rose to 0.10 mg/kg for Chickpea and 0.14 mg/kg for Soybean, reflecting some degree of Zn uptake under Cd stress.
- **Zn + Cd Treatments**: When zinc was added to the treatment (Zn + Cd), the Zn accumulation in both plants increased as the Zn concentration rose. For example:
    - At **Zn 0.1 mM + Cd**, Chickpea accumulated 0.12 mg/kg and Soybean accumulated 0.10 mg/kg of Zn.
    - At **Zn 0.3 mM + Cd**, these values increased to 0.13 mg/kg for Chickpea and 0.11 mg/kg for Soybean.
    - At **Zn 0.8 mM + Cd**, the values further increased to 0.14 mg/kg for Chickpea and 0.13 mg/kg for Soybean, indicating enhanced Zn uptake with increasing Zn concentration in the treatment.

Table 3 demonstrates the effects of cadmium (Cd) and zinc (Zn) on the accumulation of these metals in the seeds of Chickpea and Soybean.

- **Cd accumulation** in the seeds of both plants increases with higher Cd exposure, with Soybean generally accumulating more Cd than Chickpea.
- **Zn accumulation** increases in both plants as the concentration of Zn increases, especially when added in combination with Cd, indicating that the plants are able to accumulate more Zn when provided with higher concentrations of zinc.
- The presence of Zn in the treatment slightly reduces the accumulation of Cd in the seeds, suggesting that zinc might help in mitigating cadmium uptake, although it still results in measurable levels of Cd accumulation in the plants.

These findings emphasize the complex interactions between Cd and Zn, and how zinc supplementation might influence the accumulation of cadmium in plants.

4. Conclusion: The conclusion highlights the overall effectiveness of zinc (Zn) supplementation in alleviating the detrimental effects of cadmium (Cd) toxicity in chickpea and soybean. The findings provide important insights into how Zn can mitigate Cd-induced stress in crops and enhance their resilience.

Key points of the conclusion are:

1. **Zn Mitigates Cd-Induced Phytotoxicity :** Zn supplementation has been shown to significantly reduce the phytotoxic effects of Cd in both chickpea and soybean. Cd is a toxic heavy metal that can severely affect plant growth, antioxidant enzyme activity, and overall plant health. The presence of Zn helps reduce the negative impact of Cd, making it a useful strategy for managing heavy metal stress.
2. **Enhanced Antioxidant Enzyme Activity:** Zn supplementation boosts the activity of antioxidant enzymes, such as Superoxide Dismutase (SOD), Catalase (CAT), and Ascorbate Peroxidase (APX), in

both plants. These enzymes play a crucial role in neutralizing reactive oxygen species (ROS), which are generated in excess under Cd stress. By enhancing the activity of these enzymes, Zn helps protect the plants from oxidative damage.

3. **Improvement in Growth and Water Relations:** Zn supplementation improves the growth and water relations of the plants under Cd stress. Plants under Cd stress typically show stunted growth and poor water uptake due to the toxic effects of Cd on root and shoot development. Zn helps mitigate these effects, supporting better growth and water retention, which are essential for plant health and productivity.
4. **Reduction in Cd Accumulation in Seeds:** Zn also reduces the accumulation of Cd in the seeds of both chickpea and soybean. This reduction is significant because it lowers the transfer of toxic metals to the edible parts of the plant, making the crops safer for consumption and reducing the risk of Cd contamination in the food chain.
5. **Chickpea Shows Better Tolerance than Soybean**: Among the two crops, chickpea showed better tolerance to Cd toxicity than soybean. This indicates that chickpea may have inherent mechanisms that allow it to better cope with Cd stress, which could be useful in selecting more tolerant varieties for cultivation in contaminated soils.
6. **Synergistic Interaction Between Cd and Zn:** The interaction between Cd and Zn appears to be synergistic, meaning that the presence of Zn helps mitigate the harmful effects of Cd, improving overall crop resilience. This interaction suggests that Zn can be an effective agronomic practice for managing Cd contamination in soils and promoting sustainable crop production.

Implications for Sustainable Agriculture: The conclusion emphasizes that Zn supplementation is a promising strategy for alleviating heavy metal stress, particularly in soils contaminated with Cd. This is especially important in sustainable agriculture, as it offers a practical approach to improving crop growth and productivity while reducing the risks associated with heavy metal contamination. By improving plant tolerance to Cd and enhancing antioxidant defense systems, Zn supplementation helps create more resilient crops, contributing to food security in regions affected by soil contamination. So study presents Zn supplementation as an effective and feasible agricultural practice for dealing with Cd toxicity, with significant implications for crop management and soil remediation in Cd-contaminated areas.

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