

# Investigating the Impact of Acid Precipitation Adaptation on Plant Species Across pH Gradients

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## Abstract

This study investigates the dose-response relationship between acid precipitation and malondialdehyde (MDA) accumulation in plants, utilizing sophisticated curve-fitting or linear-fitting techniques to pinpoint toxicity thresholds arising from simulated acid rain (SAR) stress. Four distinct types of dose-response relationship patterns emerged: promotion, non-affection, low promotion-high suppression, and full suppression. The research meticulously examined the dose-response relationship of the inhibition rate of MDA content in plant leaves after 50 days of exposure to SAR across 18 plant species, with pH levels of 5.6 (control), 4.0, 3.0, and 2.0. By applying precise dose-response relationship fitting, the EC<sub>10</sub> value—reflecting the SAR pH that elicits a 10% increase in MDA levels—was calculated, unveiling critical toxicity thresholds. The results revealed striking variations in species-specific MDA responses, providing vital insights into the ecological impact of acid rain and establishing key toxicity benchmarks for future studies.

**Keywords:** Acid rain, Dose-response relationship, Malondialdehyde, Plant species

## Highlights

- Toxic effects on different plants were observed.
- MDA accumulation in plant leaves was used to assess stress from SAR.
- The dose-response relationship and EC<sub>10</sub> are jointly used to determine toxicity thresholds.
- The toxic thresholds for SAR on 18 plant species have been determined.



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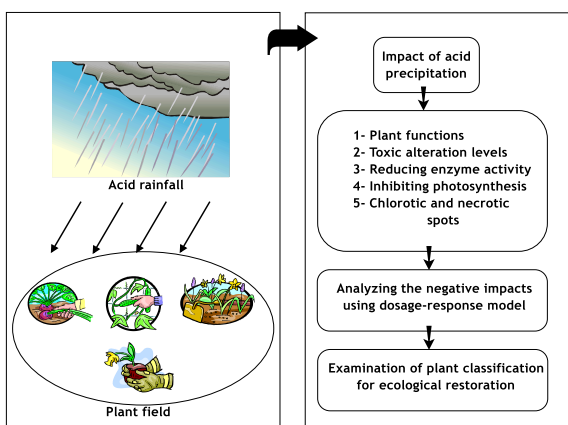
growing concerns about the detrimental environmental effects of this phenomenon. It is essential to recognize that plant responses to sustained changes in acidity are ongoing processes. Estimating toxicity threshold values based on predetermined pH levels may introduce systematic errors due to the design of experimental gradients, which can compromise the accuracy of these estimations. In this sense, this study makes the following contributions to the current literature:

1. The inhibitory rate of MDA concerning SAR is assessed across 18 plant species, through adosage-response relationship.
2. Plant species are classified based on their sensitivity to acid precipitation, providing a foundation for the selection of appropriate species for ecological restoration in the studied area.

**2. Materials and methods**

*2.1. Experimental design and establishment of dose-response relationship*

This study assesses the effects of acid precipitation on plants by investigating 18 plant species in the Chengdu Plain, China. The evaluation specifically involved 2-year-old potted trees, each measuring 25 cm in height and 23 cm in diameter. Four pH levels were established for the investigation: pH 5.6 (benchmark), pH 4.0, pH 3.0, and pH 2.0. Each level is tested with four replicates, comprising four trees per species. Also, to prevent cross-exposure during acid precipitation, the trees are cultivated in separate, isolated enclosures. Additionally, to ensure data accuracy, the pH of the simulated acid rain solution is measured before each application (Pandey *et al.* 2009). If discrepancies arise between the intended and measured pH values, a new solution is prepared accordingly (Figure 2).



**Figure 2.** Conceptual framework.

Beyond that, to analyze the impact of acid precipitation, an agricultural hand knapsack sprayer is implemented to ensure that droplets are formed on the leaf surfaces. Accordingly, spraying was performed once every 10 days, with a total of five applications administered over a 50-day period of acid precipitation stress.

The MDA content was determined using the thiobarbituric acid (TBA) method (Zhang Zhiliang *et al.* 2009) and

analyzed with a UV-Vis spectrophotometer (Model: TU-1810, Purkinje General Instrument Co., China).

*2.2. Fitting of dose-response relationships and identification of threshold values*

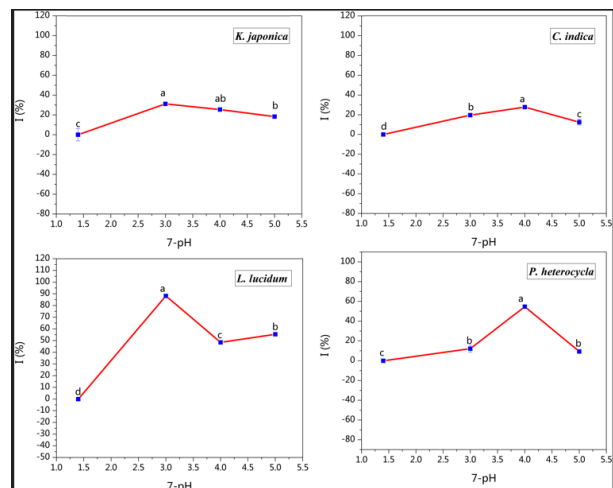
The inhibition rate of MDA is calculated using the method provided by Sun *et al.* (Sun *et al.* 2010). The dose-response relationship picture is plotted with '7 - pH value' on the x-axis and the inhibition rate on the y-axis. Also, a linear fit is conducted using two acid precipitation treatment points with inhibition rates near -10% to identify the EC<sub>10</sub> value.

$$\lambda = z.(7 - PH) + u \tag{1}$$

Where, λ is the inhibition rate of MDA, and z and u are coefficients.

*2.3. Data Processing and Analysis*

Data calculations were performed using Excel 2024. Analysis of variance (ANOVA) was conducted using DPS 7.05, a data processing system designed for statistical analysis and experimental design. The least significant difference (LSD) method was applied for multiple comparisons to determine whether the differences between group means were statistically significant. Dose-response relationship fitting was carried out using Origin 2023.



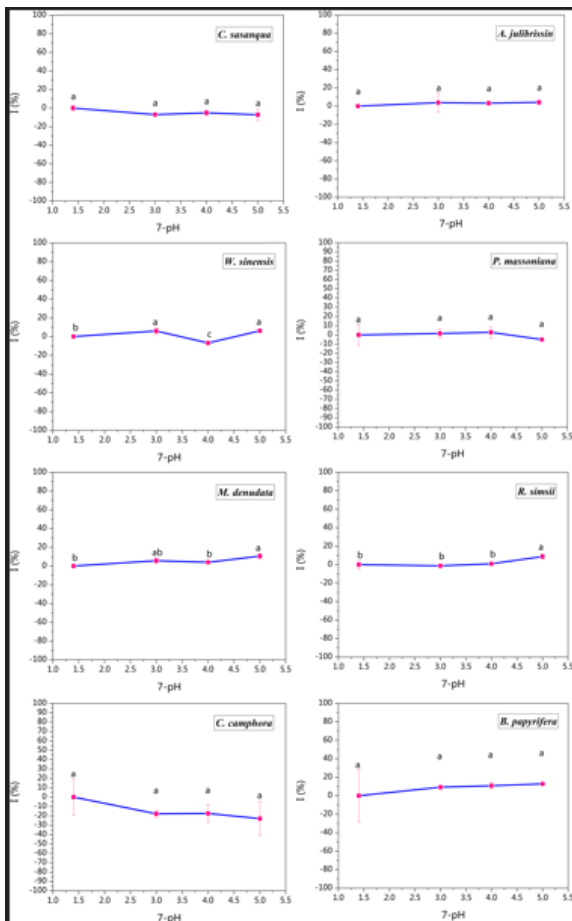
**Figure 3.** Dosage-response relationship showing promotion of SAR on MDA.

**3. Results and Discussion**

*3.1. Evaluation of the dose-response relationship of SAR on MDA in plants*

MDA is a key product of membrane lipid peroxidation, and its accumulation can worsen membrane damage. Consequently, MDA content is frequently utilized as an indicator in studies of plant aging physiology and resistance physiology. It serves to assess the extent of membrane lipid peroxidation and indirectly gauge the level of damage to the membrane system and the plant's stress resistance. After 50 days of SAR stress, the effects on MDA levels in 18 plant species were exhibited as varying patterns, which could be categorized into four types: promotion, non-affectation, low promotion-high suppression, and suppression.

In promotional type, the exposure to SAR resulted in a reduction of MDA by over 10% in 4 plant species—*K. japonica*, *C. indica*, *L. lucidum*, and *P. heterocycla*—compared to the control, with statistically significant differences (as shown in **Figure 3**). Based on the results, the aforementioned plants demonstrate a degree of stress resistance and can actively cope with adverse conditions under the SAR tests ( $\text{pH} > 2.0$ ). They have elevated the activity of antioxidant enzymes or synthesized more non-enzymatic antioxidants to enhance membrane system stability and mitigate the adverse effects of membrane lipid peroxidation on plants, leading to a decrease in MDA content in leaves.



**Figure 4.** Dosage-response relationship showing non-affected SAR on MDA.

**Table 1.**  $EC_{10}$  of SAR on MDA of 18 Types of Plants.

Plants Name	$EC_{10}$ pH level	PlantsName	$EC_{10}$ pH level
<i>K. japonica</i>	<2.0	<i>R. simsii</i>	<2.0
<i>C. indica</i>	<2.0	<i>C. camphora</i>	<2.0
<i>L. lucidum</i>	<2.0	<i>B. papyrifera</i>	<2.0
<i>P. heterocycla</i>	<2.0	<i>P. granatum</i>	2.3
<i>C. sasanqua</i>	<2.0	<i>M. basjoo</i>	3.4
<i>A. julibrissin</i>	<2.0	<i>P. fortuneana</i>	3.4
<i>W. sinensis</i>	<2.0	<i>H. nepalensis</i>	4.3
<i>P. massoniana</i>	<2.0	<i>B. spectabilis</i>	4.7
<i>M. denudata</i>	<2.0	<i>G. biloba</i>	5.4

In the unaffected category, the MDA content of 8 plant species—*C. sasanqua*, *A. julibrissin*, *W. sinensis*, *P. massoniana*, *M. denudata*, *R. simsii*, *C. camphora*, and *B. papyrifera*—under SAR conditions showed no significant variation compared to the control (**Figure 4**).

These results indicate that, within the SAR pH levels used in this study ( $\text{pH} \geq 2.0$ ), SAR does not significantly affect the MDA content in the leaves of these species. Alternatively, plants may actively activate protective mechanisms and promptly eliminate adverse effects.

In the low promotion-high suppression type, SAR at  $\text{pH} \geq 3.0$  significantly reduced the content of MDA in leaves compared to the control, as shown in the inhibition rate (Fig. 5). Conversely, SAR at  $\text{pH} < 3.0$  resulted in an increase in MDA content in the plants compared to the control, causing the inhibition rate to shift from positive to negative. These findings indicate that SAR with lower acidity enhances the self-regulation ability of plants, resulting in a significant reduction in MDA levels in the tested plants. On the other hand, SAR with higher acidity exacerbates lipid peroxidation and elevates MDA content in plant cell membranes.

### 3.2. Evaluation of the toxic threshold of SAR on MDA content in plants

This study employed a pH value of SAR that induces a 10% increase in MDA content relative to the control ( $EC_{10}$ ) as the toxicity threshold.  $EC_{10}$  values were established based on the dose-response relationships associated with SAR stress (**Table 1**). For the 12 plant species categorized as exhibiting promotion or non-affected responses, which did not exhibit suppression effects within the study's pH range, the  $EC_{10}$  was set to  $\text{pH} < 2.0$ . For plants in the low promotion-high suppression category—such as *P. granatum*—and those in the suppression category—such as *M. basjoo*, *H. nepalensis*, *P. fortuneana*, *B. spectabilis*, and *G. biloba*— $EC_{10}$  values were calculated using the methods and formula outlined in this study.

This study proposed the toxicity threshold of plants to SAR stress by measuring the content of MDA in plants and employing dose-response relationship fitting analysis. This approach provides a novel method for evaluating plant tolerance to acid rain.

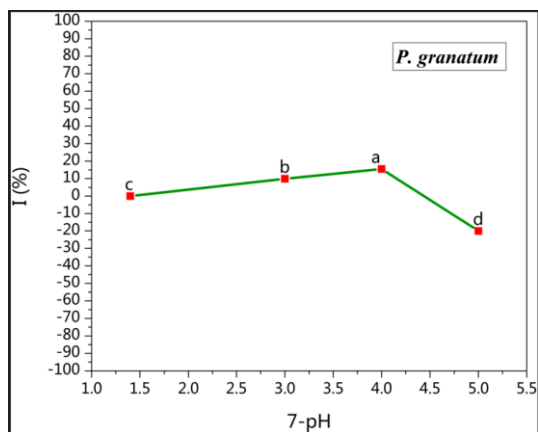


Figure 5. Dosage–response relationship showing low promotion–high suppression of SAR on MDA.

The significant correlation between MDA content and acid rain resistance provides a basis for further investigation into plant response mechanisms. However, as a single indicator, MDA does not fully reflect the plant's tolerance to acid rain, as the plant's ability to resist acid rain is influenced by multiple factors.

In general, the analysis results for *C. sasanqua*, *C. camphora*, and *B. papyrifera* were consistent among the seven overlapping plant species when compared to the net photosynthetic rate. Additionally, the results for *K. japonica* and *C. indica* were consistent among the twelve overlapping plant species when compared to total chlorophyll content.

In summary, the observed dose-response relationships were generally in line with those reported in this study, further confirming that SAR significantly affects total MDA content in plants.

The present study not only aligns with but also extends previous research on plant responses to acid rain. For instance, the strong tolerance of *K. japonica* and *C. indica* corroborates the dose-response patterns in chlorophyll content reported by Gou *et al.* (2021). Conversely, the marked sensitivity of *G. biloba* and *H. nepalensis*, indicated by their high EC<sub>10</sub> values, is consistent with previous observations of visible leaf damage under acidic conditions (Silva *et al.*, 2005). Furthermore, the variability in MDA response types among species underscores the importance of a multi-indicator approach for a comprehensive assessment of acid rain tolerance, as has been emphasized in previous research (Gou *et al.* 2025).

Building upon this rationale for a multi-faceted assessment, given that different indicators have varied responses to acid rain stress, future research needs to combine a comprehensive analysis using multiple indicators to provide a more accurate theoretical basis for predicting plant toxicity thresholds under acid rain stress.

4. Conclusion

This study robustly assessed the effects of acid precipitation on different plant species across a range of pH levels. Key insights derived from this way include: 1) MDA content in plant leaves serves as an effective indicator for assessing the dose-response relationship

between SAR and plants; 2) SAR causes both increases and decreases in MDA content in plant leaves, indicating that plants adaptive response mechanisms to the effects of SAR.; 3) among the 18 plant species exposed to SAR, the toxicity thresholds (EC<sub>10</sub>) for *K. japonica*, *C. indica*, *L. lucidum*, *P. heterocycla*, *C. sasanqua*, *A. julibrissin*, *W. sinensis*, *P. massoniana*, *M. denudata*, *R. simsii*, *C. camphora*, and *B. papyrifera* were determined to be pH<2.0. These species are identified as tolerant to acid rain and are therefore recommended for use in ecological restoration or greening projects in acid rain-affected regions of southwestern China.

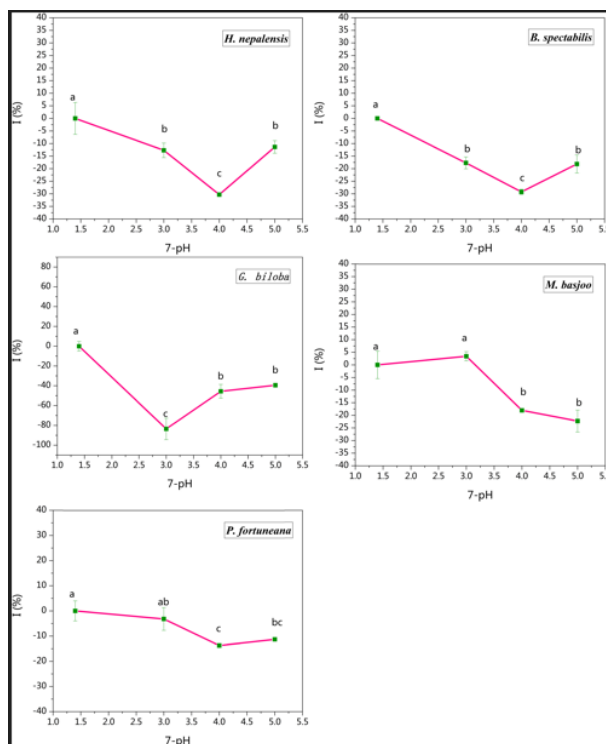


Figure 6. Dosage–response relationship showing suppression of SAR on MDA.

Data availability statement

All relevant data are included in the paper or its Supplementary Information.

Conflict of interest

The authors declare there is no conflict.

References

Ahirwal, J., Maiti, S. K., & Singh, A. K. (2016). Ecological restoration of coal mine-degraded lands in dry tropical climate: what has been done and what needs to be done? *Environmental quality management*, 26(1), 25-36. <https://doi.org/10.1002/tqem.21481>

Ahmad, G., Khan, A. A., & Mohamed, H. I. (2021). Changes in Growth, Yield, Photosynthetic Pigments, Biochemical Substances, Oxidative Damage, and Antioxidant Activities Induced by Treatment with Different pH of Artificial acid rain in Pumpkin (*Cucurbita Moschata*). *Gesunde Pflanzen*, 73(4), 623-637. <https://doi.org/10.1007/s10343-021-00583-1>

Debnath, B., & Ahammed, G. J. (2020). Effect of acid rain on plant growth and development: physiological and molecular interventions. *Contaminants in Agriculture: Sources, Impacts*

- and Management, 103-114. [https://doi.org/10.1007/978-3-030-41552-5\\_5](https://doi.org/10.1007/978-3-030-41552-5_5)
- Du, E., Clark, C. M., & de Vries, W. (2024). Forest remediation options in the face of excess nitrogen deposition. In *Atmospheric Nitrogen Deposition to Global Forests* (pp. 263-271). Academic Press. <https://doi.org/10.1016/B978-0-323-91140-5.00004-X>
- Gou, S. Z., Chen, Y. W., Xia, Z. D., et al. (2021). Dosage-response relationship on total chlorophyll content in response to simulated acid rain in 26 plant species. *Southwest China Journal of Agricultural Sciences*, 34(6). [in Chinese]
- Gou, S. Z., Hu, W. L., Ran, Y. P., et al. (2025). Multi-indicator comprehensive analysis of toxicity threshold of acid rain on *Nerium indicum* Mill based on dose-response relationships. *Southwest China Journal of Agricultural Sciences*, 38(4). [in Chinese]
- Lamers, L. P., Vile, M. A., Grootjans, A. P., Acreman, M. C., van Diggelen, R., Evans, M. G & Smolders, A. J. (2015). Ecological restoration of rich fens in Europe and North America: from trial and error to an evidence-based approach. *Biological Reviews*, 90(1), 182-203. <https://doi.org/10.1111/brv.12102>
- Li, Y. C., Zhang, M., Shu, M., Ho, S. S. H., Liu, Z. F., Wang, X. X., & Zhao, X. Q. (2016). Chemical characteristics of rainwater in Sichuan basin, a case study of Ya'an. *Environmental Science and Pollution Research*, 23, 13088-13099. <https://doi.org/10.1007/s11356-016-6363-4>
- Liu, O. Y., & Russo, A. (2021). Assessing the contribution of urban green spaces in green infrastructure strategy planning for urban ecosystem conditions and services. *Sustainable Cities and Society*, 68, 102772. <https://doi.org/10.1016/j.scs.2021.102772>
- McGivney, E., Gustafsson, J. P., Belyazid, S., Zetterberg, T., & Löfgren, S. (2019). Assessing the impact of acid rain and forest harvest intensity with the HD-MINTEQ model—soil chemistry of three Swedish conifer sites from 1880 to 2080. *Soil*, 5(1), 63-77. <https://doi.org/10.5194/soil-5-63-2019>
- Odiyi, B. O., & Eniola, A. O. (2015). The Effect of simulated acid rain on plant growth component of Cowpea (*Vigna unguiculata*) L. Walps. *Jordan Journal of Biological Sciences*, 8(1), 51-54. DOI: 10.12816/0004132
- Pandey, S. N., & Sinha, B. K. (2009). *Plant Physiology*. New Delhi: Vikas Publishing House.
- Prakash, J., Agrawal, S. B., & Agrawal, M. (2023). Global trends of acidity in rainfall and its impact on plants and soil. *Journal of Soil Science and Plant Nutrition*, 23(1), 398-419. <https://doi.org/10.1007/s42729-022-01051-z>
- Qin, G., & Huang, M. (2001). A study on rain acidification processes in ten cities of China. *Water, Air, and Soil Pollution*, 130(1-4), 163-174. <https://doi.org/10.1023/A:1012267922923>
- Ren, R. E. (1997). On acid rain in China: past, present and its future. *Journal of Beijing University of Technology*, 23(3), 128-132. [in Chinese]
- Sani, S., Sulaiman, M., Shuaibu, A. M., Kura, A. U., & Rabi, S. (2024). Impact of Climate Change on Environmental Chemistry: A Review. *Current Research in Interdisciplinary Studies*, 3(3), 28-49. DOI : 10.58614/cris332
- Selvaraj K, Selvanarayanan R, Venkatesan S K G, et al. Future-proof coffee plant disease detection based on counterfactual recommendation with a hybrid vision transformer and convolutional neural network model[J]. *Agrociencia*, 2025: 1-24.
- Selvanarayanan R, Rajendran S, Algburi S, et al. Empowering coffee farming using counterfactual recommendation based RNN driven IoT integrated soil quality command system[J]. *Scientific Reports*, 2024, 14(1): 6269.
- Silva, L. D., Azevedo, A. A., Silva, E. D., & Oliva, M. A. (2005). Effects of simulated acid rain on the growth of five Brazilian tree species and anatomy of the most sensitive species (*Joannesia princeps*). *Australian Journal of Botany*, 53(8), 789-796. DOI: 10.1071/BT04096
- Sun, B. Y., Kan, S. H., Zhang, Y. Z., Deng, S. H., Wu, J., Yuan, H. & Li, Y. W. (2010). Certain antioxidant enzymes and lipid peroxidation of radish (*Raphanus sativus* L.) as early warning biomarkers of soil copper exposure. *Journal of Hazardous Materials*, 183(1-3), 833-838. <https://doi.org/10.1016/j.jhazmat.2010.07.102>
- Thomas, G., Sheridan, C., & Holm, P. E. (2022). A critical review of phytoremediation for acid mine drainage-impacted environments. *Science of the Total Environment*, 811, 152230. <https://doi.org/10.1016/j.scitotenv.2021.152230>
- Tong Z, Ding Y, Ma S, et al. How to mitigate climate change? Dynamic linkages between clean energy and systemically important banks[J]. *Global NEST Journal*, 2025.
- Wang Z, Wang F, Ma S. Research on the Coupled and Coordinated Relationship Between Ecological Environment and Economic Development in China and its Evolution in Time and Space[J]. *Polish Journal of Environmental Studies*, 2025, 34(3).
- Xuan, C., Xiaoran, S., Zhaoji, S., Jiaen, Z., Zhong, Q., Huimin, X., & Hui, W. (2021). Analysis of the spatio-temporal changes in acid rain and their causes in China (1998-2018). *Journal of Resources and Ecology*, 12(5), 593-599.
- Zhang X, Li D, Yan H, et al. Does Air pollution affect the green innovation of industrial enterprises? Insights from Urban Sewage Control Policies in China[J]. *Global NEST Journal*, 2025.
- Zhang, Z. L., Qu, W. J., & Li, X. F. (2009). *Plant Physiology Experiment Guide* (4th ed.). Beijing: Higher Education Press. [in Chinese]