

## Supplementary Information

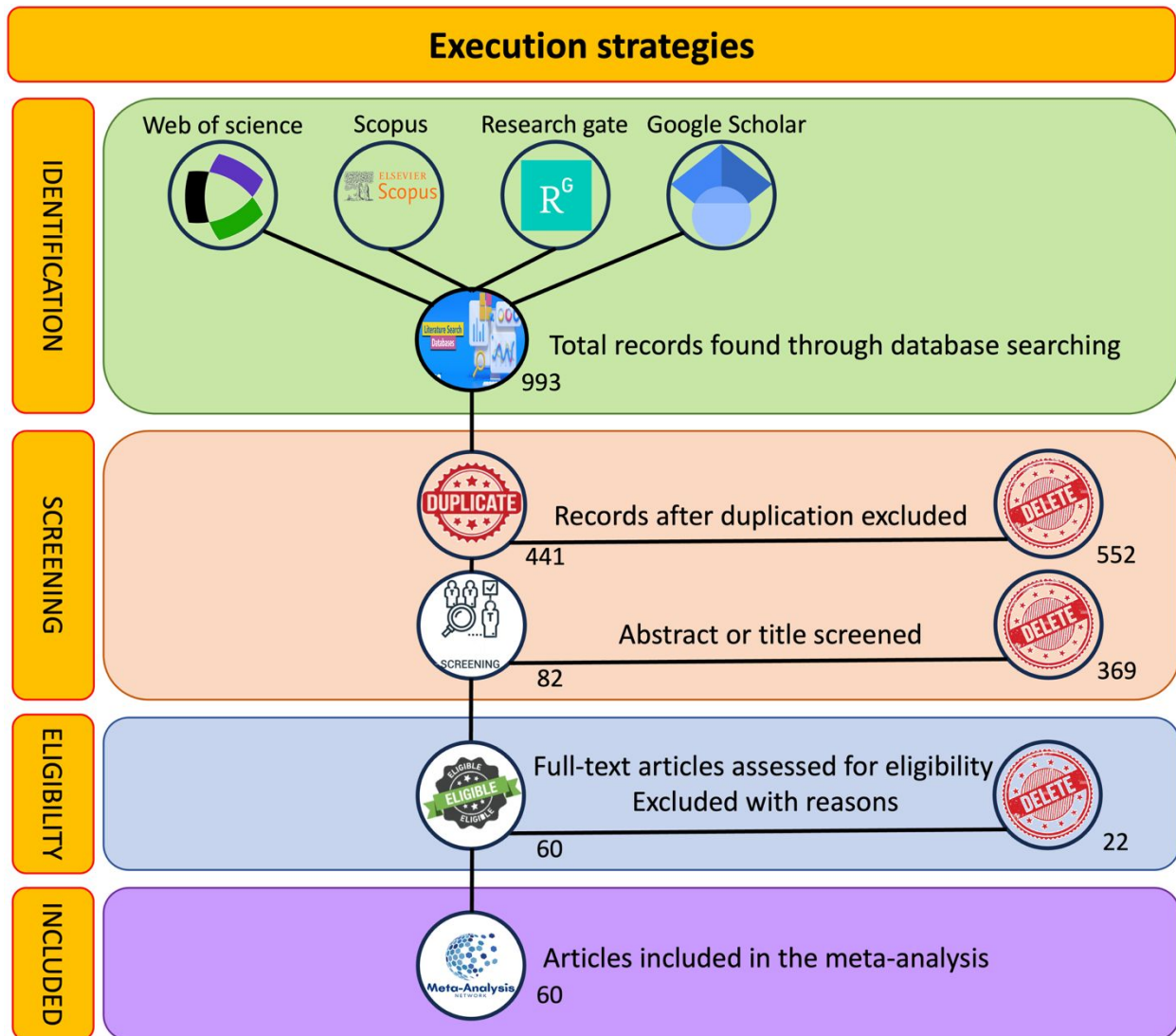
### **Microplastic-mediated modulation of Cd toxicity: evidence from a global meta-analysis**

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
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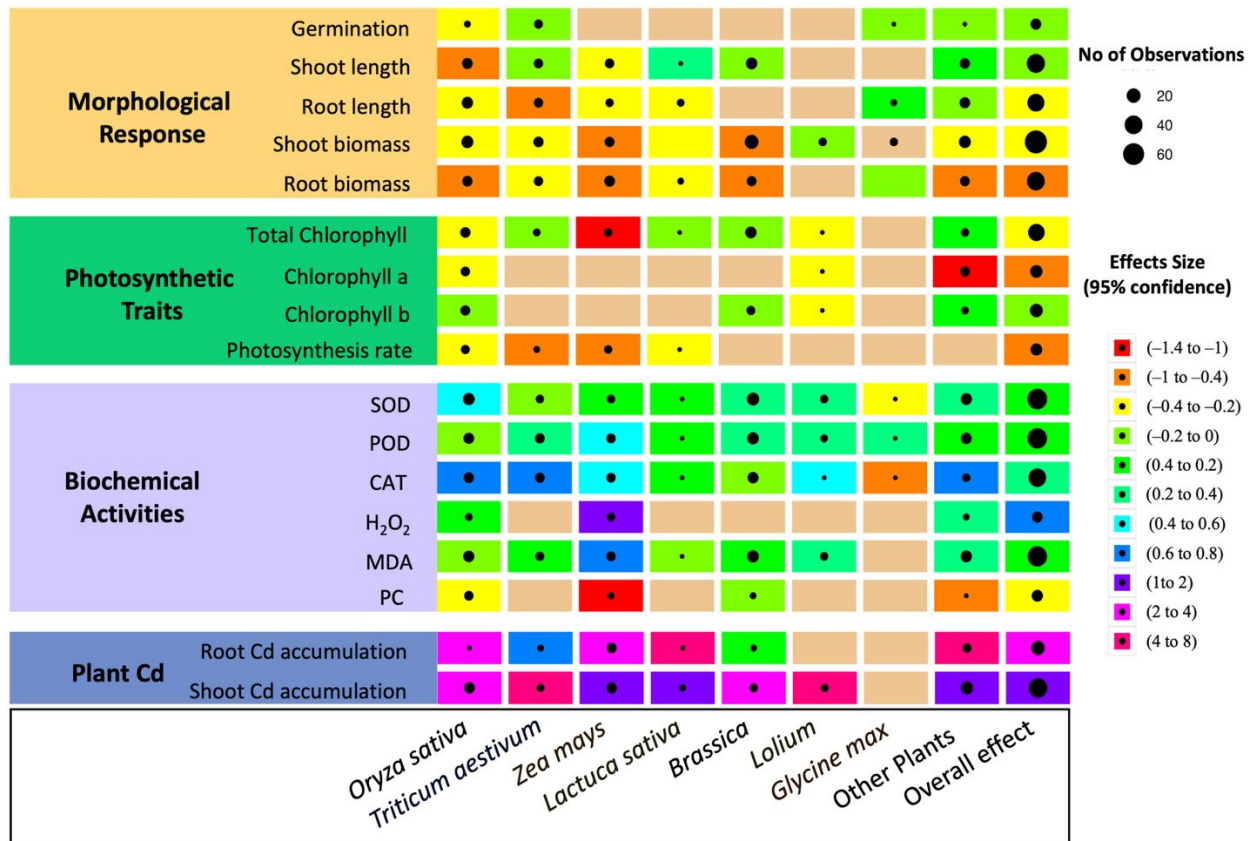
E-mail: [weiwu@hainanu.edu.cn](mailto:weiwu@hainanu.edu.cn) (W. Wu).



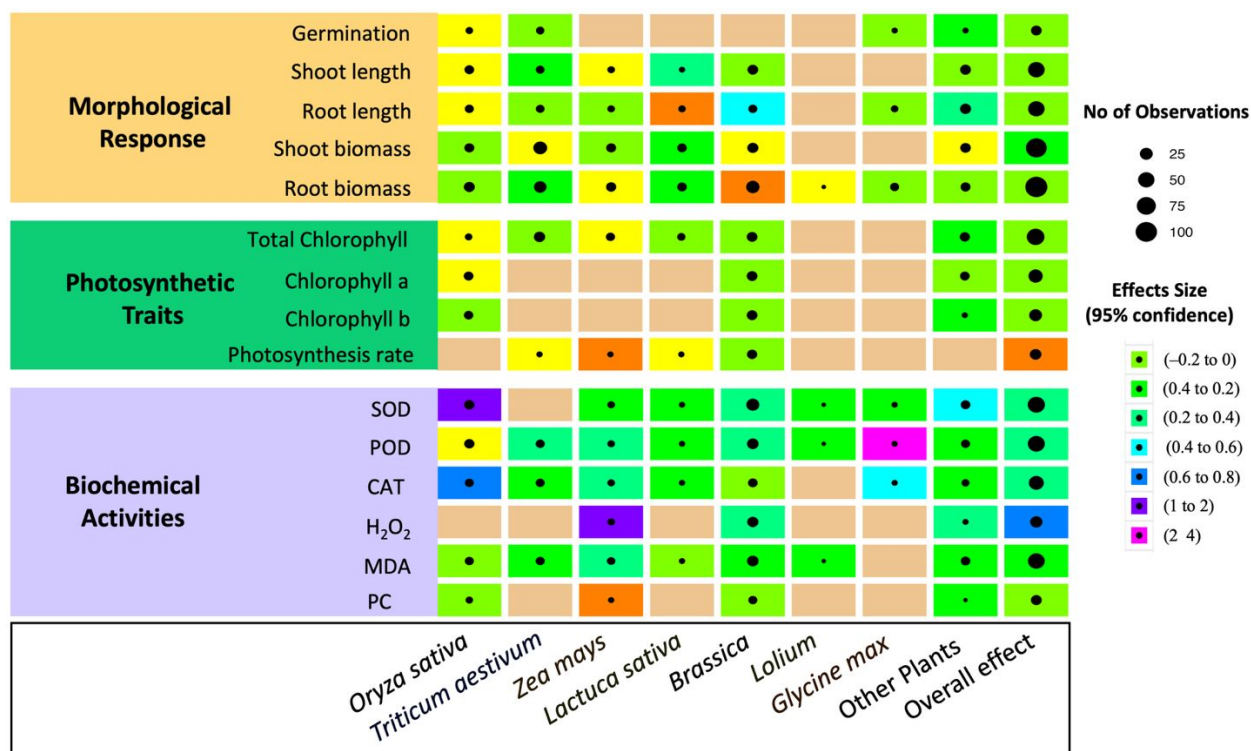
**Figure S1.** Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) Flow Chart describes the protocol for searching, identifying, and selecting publications for the current meta-analysis. The numbers represent the number of collected references.

Main Categories	Sub-Categories	Size ( $\mu\text{m}$ )	Duration (Days)	Doses ( $\text{mg L}^{-1}$ )
<b>Morphological Responses</b>	Germination	 $<100$ Size 1	 $<15$ Duration 1	$\leq 100$ Class 1 
	Shoot length			
	Root length			
	Shoot biomass			
	Root biomass			
<b>Photosynthetic Traits</b>	T. Chlorophyll	$\geq 100$ Size 2 	$15-30$ Duration 2	$>100 + \text{Cd}$ Class 3 
	Chlorophyll a			
	Chlorophyll b			
	Photosynthesis rate			
<b>Biochemical Activities</b>	SOD	$\geq 100$ Size 2 	$>30$ Duration 3 	$\leq 100 + \text{Cd}$ Class 4 
	POD			
	CAT			
	$\text{H}_2\text{O}_2$			
	MDA			
	PC			
<b>Plant Cd</b>	Root	$\geq 100$ Size 2 	$>30$ Duration 3 	$<10 + \text{MPs}$ Class 5 
	Shoot			$\geq 10 + \text{MPs}$ Class 6 

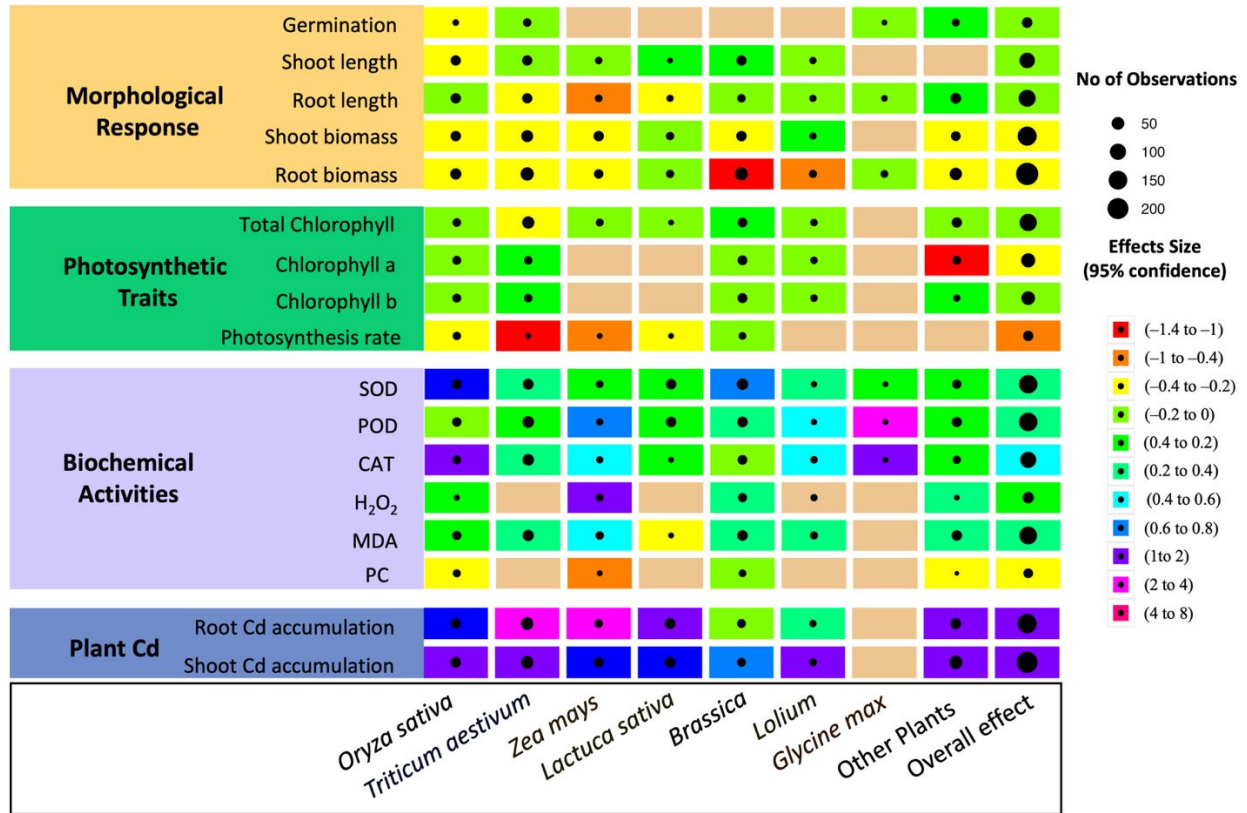
**Figure S2.** Graphical summary of the moderating variables that were retained to measure the effect of MPs and Cd on Morphological Responses, photosynthetic traits, biochemical responses, and Cd accumulations.



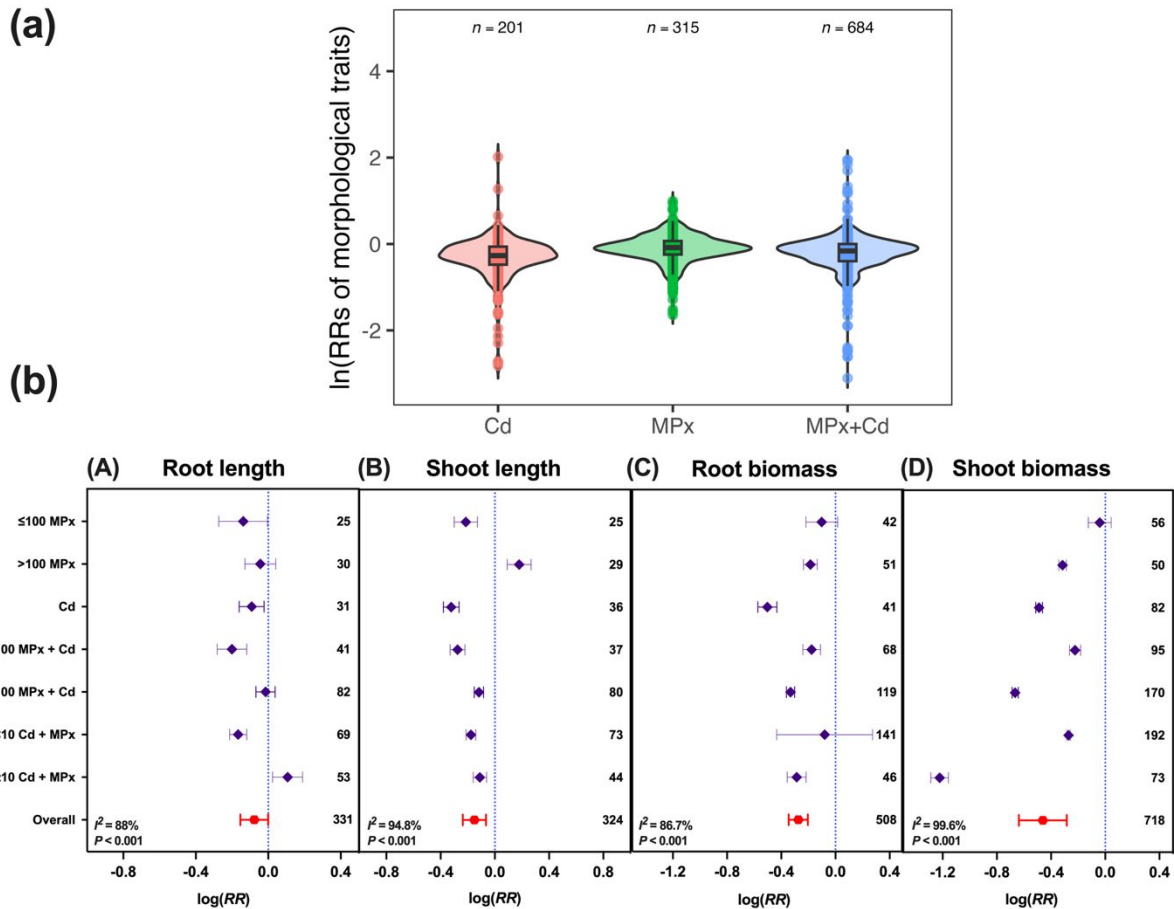
**Figure S3. The effects of Cd exposures on plant responses relative to control in terms of morphological parameters, photosynthetic traits, biochemical activities, and plant Cd accumulation.** The meta-analysis integrates responses across morphological parameters, photosynthetic traits, biochemical activities, and Cd accumulation. Rows represent specific traits, while columns correspond to plant species, family, and the overall effect. Effect sizes (±95% CI) are indicated by a color gradient, ranging from strongly inhibitory (red, -1.4 to -1) to strongly promotive (dark pink, 4 to 8). Circle size denotes the number of contributing observations, and blank cells indicate the absence of reported data.



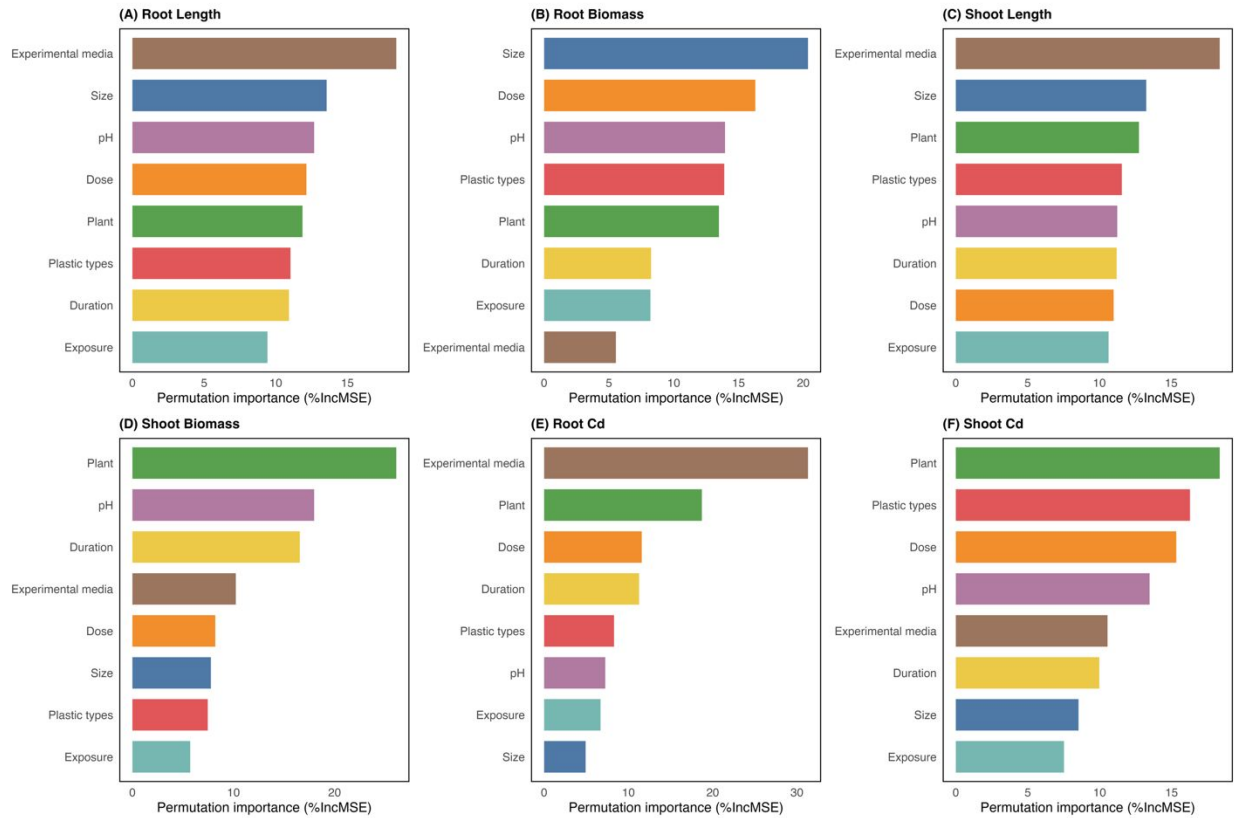
**Figure S4. The effects of MPs exposures on plant responses relative to control in terms of morphological parameters, photosynthetic traits, biochemical activities, and plant Cd accumulation.** The meta-analysis integrates responses across morphological parameters, photosynthetic traits, and biochemical activities. Rows represent specific traits, while columns correspond to plant species, family, and the overall effect. Effect sizes ( $\pm 95\%$  CI) are indicated by a color gradient, ranging from strongly inhibitory (lime green,  $-0.2$  to  $-0$ ) to strongly positive (bright pink,  $2$  to  $4$ ). Circle size denotes the number of contributing observations, and blank cells indicate the absence of reported data.



**Figure S5. The co-exposure effect of MPs and Cd on plant responses relative to control in terms of morphological parameters, photosynthetic traits, biochemical activities, and plant Cd accumulation.** The meta-analysis integrates responses across morphological parameters, photosynthetic traits, biochemical activities, and Cd accumulation. Rows represent specific traits, while columns correspond to plant species, family, and the overall effect. Effect sizes ( $\pm 95\%$  CI) are indicated by a color gradient, ranging from strongly inhibitory (red,  $-1.4$  to  $-1$ ) to strongly promotive (dark pink,  $4$  to  $8$ ). Circle size denotes the number of contributing observations, and blank cells indicate the absence of reported data.

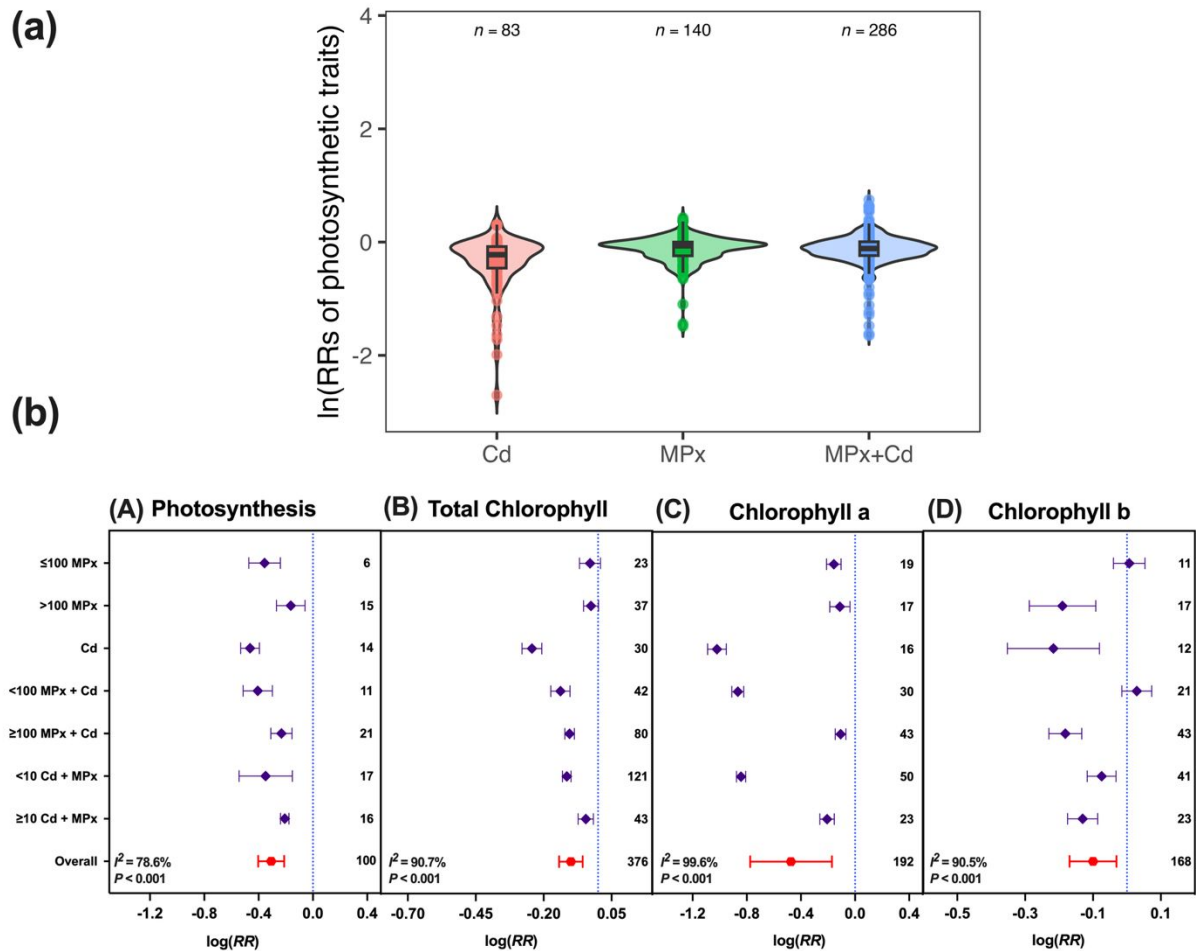


**Figure S6. The effects of MPs, Cd, and co-exposures on plant morphological traits (a).** Meta-analytical model of the single and overall effects of different doses of MPs and Cd on plant morphological responses (b). (A) root length, (B) shoot length, (C) Root biomass, and (D) shoot biomass. Values are the mean effect size  $\pm$  95% CI. The right side has a positive effect, the left side has a negative effect, and the bar overlaps zero becomes not significant for each plot. In each plot, the number associated with each data point represents the number of pairwise observations. The symbol  $\leq 100$  MPs represents microplastic concentrations less than or equal to  $100 \text{ mg kg}^{-1}$ , while  $>100$  MPs indicates concentrations greater than  $100 \text{ mg kg}^{-1}$ . Cd refers to the overall cadmium concentrations expressed in  $\text{mg kg}^{-1}$ . The notation  $<100$  MPs + Cd denotes co-exposure of less than  $100 \text{ mg kg}^{-1}$  concentration of MPs with Cd, whereas  $\geq 100$  MPs + Cd represents equal to or greater than  $100 \text{ mg kg}^{-1}$  concentration of MPs with Cd. Similarly,  $<10$  Cd + MPs refers to co-exposure of less than  $10 \text{ mg kg}^{-1}$  concentration of Cd with MPs, and  $\geq 10$  Cd + MPs indicates equal to or greater than  $10 \text{ mg kg}^{-1}$  concentration of Cd with MPs.

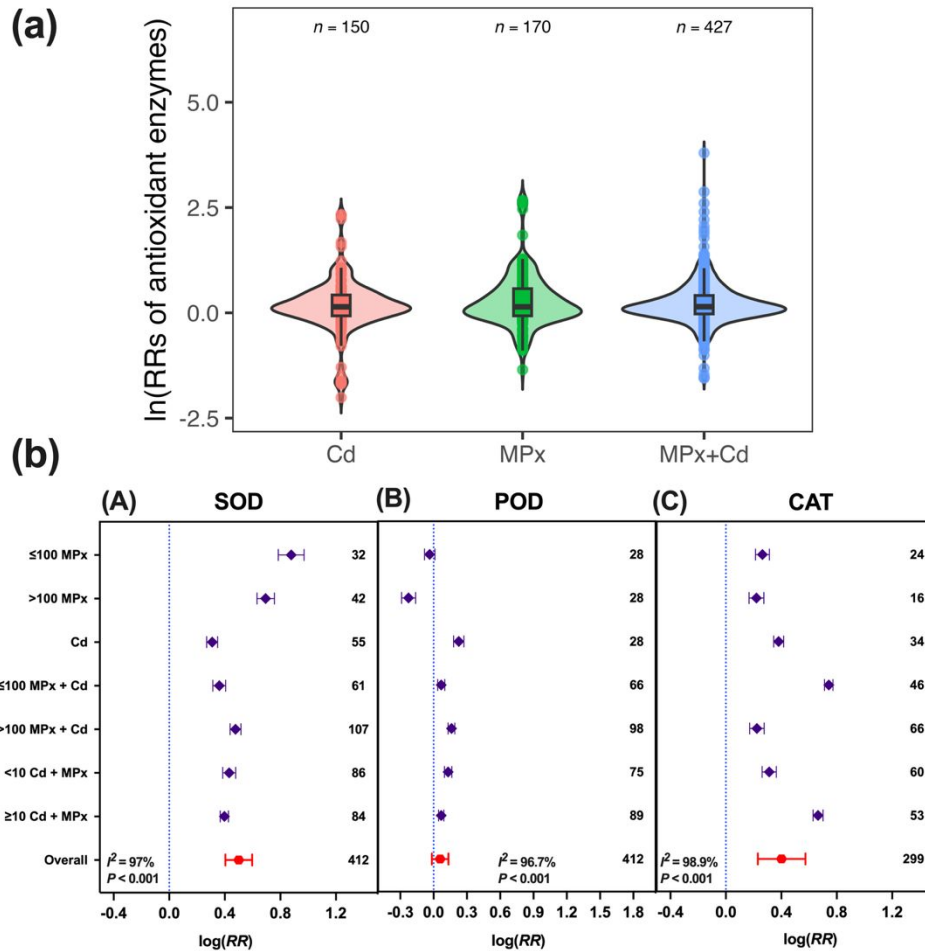


**Figure S7. Performance of the RF model and important feature contribution.**

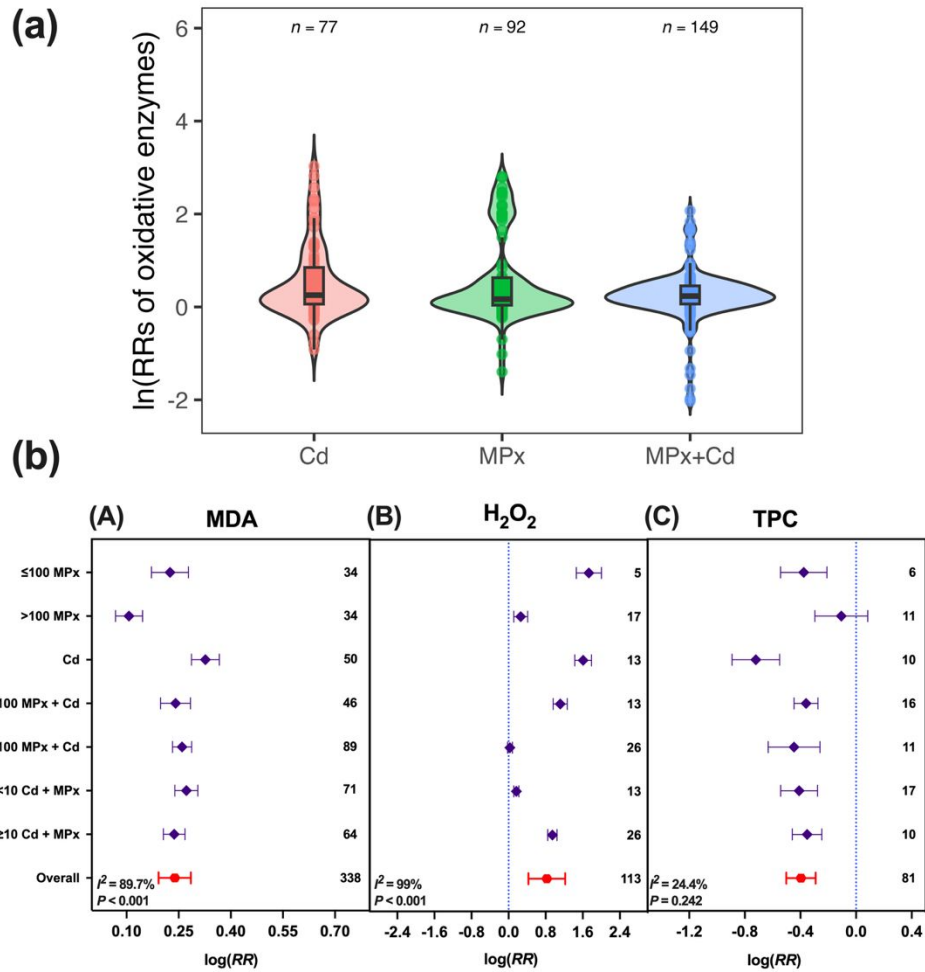
The importance of the variables used in the RF model, as well as their interactions for (A) root length, (B) root biomass, (C) shoot length, (D) shoot biomass, (E) root Cd, and (F) shoot Cd, are presented. Feature importance was assessed using the percentage increase in mean squared error (%IncMSE), enabling the identification of key drivers influencing plant responses.



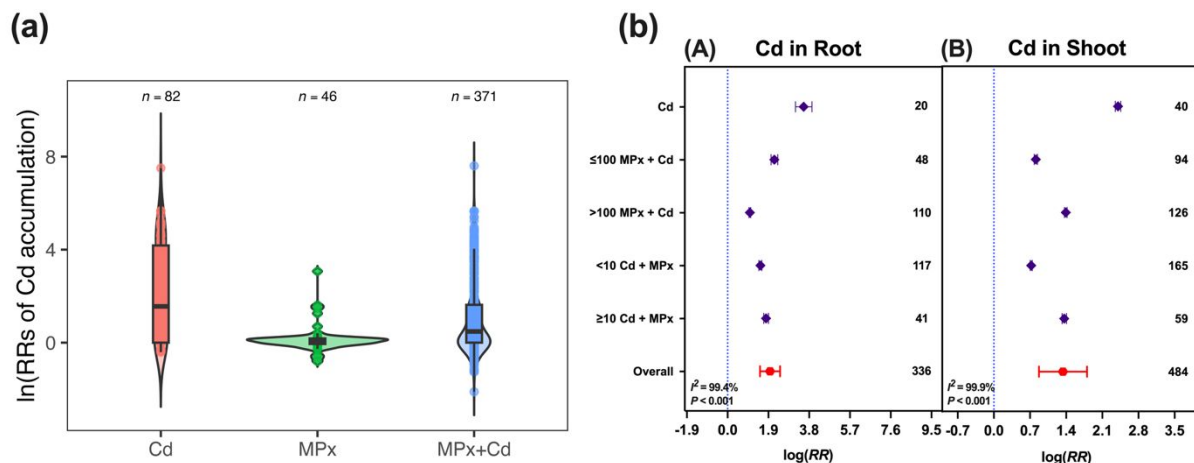
**Figure S8. Responses of plant photosynthetic traits to single and co-exposure of MPs and Cd** (a). Meta-analytical model of the single and overall effects of different doses of MPs and Cd on plant photosynthetic traits (b). (A) photosynthesis rate, (B) total chlorophyll, (C) chlorophyll a, and (D) chlorophyll b. Values are the mean effect size  $\pm$  95% CI. The right side has a positive effect, the left side has a negative effect, and the bar overlaps zero becomes not significant for each plot. In each plot, the number associated with each data point represents the number of pairwise observations. The symbol  $\leq 100$  MPs represents microplastic concentrations less than or equal to  $100 \text{ mg kg}^{-1}$ , while  $>100$  MPs indicates concentrations greater than  $100 \text{ mg kg}^{-1}$ . Cd refers to the overall cadmium concentrations expressed in  $\text{mg kg}^{-1}$ . The notation  $<100$  MPs + Cd denotes co-exposure of less than  $100 \text{ mg kg}^{-1}$  concentration of MPs with Cd, whereas  $\geq 100$  MPs + Cd represents equal to or greater than  $100 \text{ mg kg}^{-1}$  concentration of MPs with Cd. Similarly,  $<10$  Cd + MPs refers to co-exposure of less than  $10 \text{ mg kg}^{-1}$  concentration of Cd with MPs, and  $\geq 10$  Cd + MPs indicates equal to or greater than  $10 \text{ mg kg}^{-1}$  concentration of Cd with MPs.



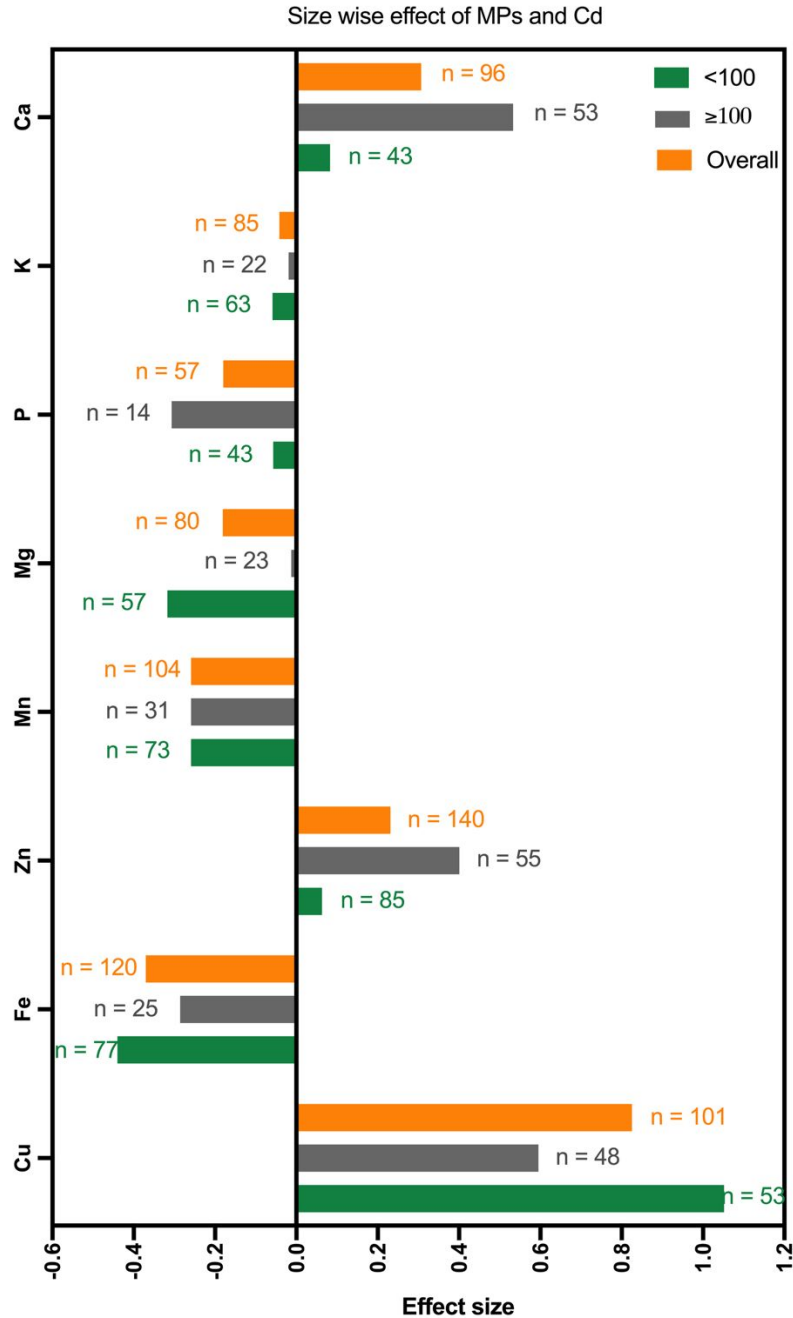
**Figure S9. Single and co-exposure of MPs and Cd modulate the antioxidant enzymatic activities (b).** Meta-analytical model of the single and overall effects of different doses of MPs and Cd on antioxidant enzymatic activities (b). (A) superoxide dismutase (SOD), (B) peroxidase (POD), and (C) catalase (CAT). Values are the mean effect size  $\pm$  95% CI. The right sidebar has a positive effect, the left side has a negative effect, and the bar overlaps zero becomes not significant for each plot. In each plot, the number associated with each data point represents the number of pairwise observations. The symbol  $\leq 100$  MPs represents microplastic concentrations less than or equal to  $100 \text{ mg kg}^{-1}$ , while  $>100$  MPs indicates concentrations greater than  $100 \text{ mg kg}^{-1}$ . Cd refers to the overall cadmium concentrations expressed in  $\text{mg kg}^{-1}$ . The notation  $\leq 100$  MPs + Cd denotes co-exposure of less than or equal to  $100 \text{ mg kg}^{-1}$  concentration of MPs with Cd, whereas  $>100$  MPs + Cd represents greater than  $100 \text{ mg kg}^{-1}$  concentration of MPs with Cd. Similarly,  $<10$  Cd + MPs refers to co-exposure of less than  $10 \text{ mg kg}^{-1}$  concentration of Cd with MPs, and  $\geq 10$  Cd + MPs indicates equal to or greater than  $10 \text{ mg kg}^{-1}$  concentration of Cd with MPs.



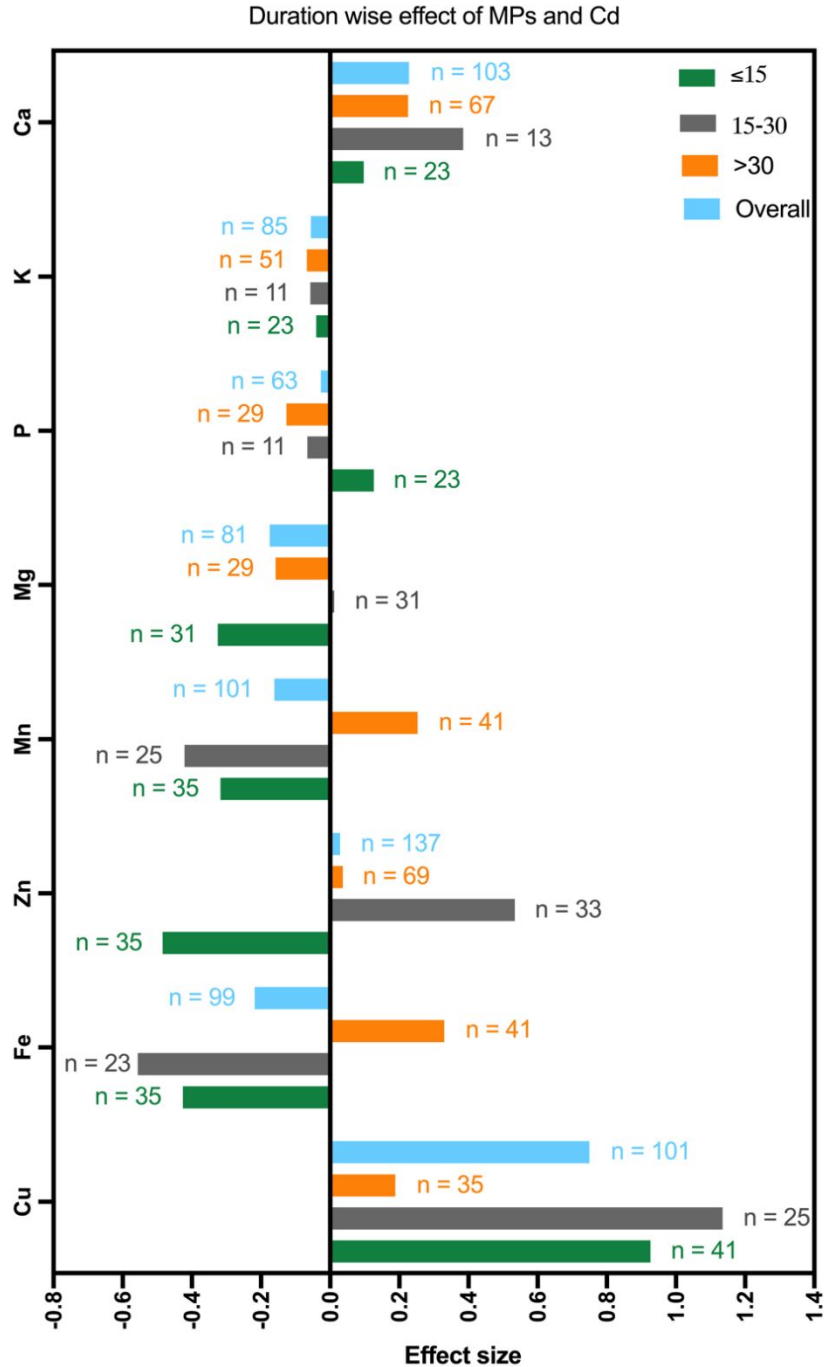
**Figure S10. Responses of oxidative enzymes to MPs, Cd, and their co-exposure (a).** Meta-analytical model of the single and overall effects of different doses of MPs and Cd on oxidative enzymatic activities and protein contents **(b)**. (A) malondialdehyde (MDA), (B) hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>), and (C) protein contents (PC). Values are the mean effect size  $\pm$  95% CI. The right sidebar has a positive effect, the left side has a negative effect, and the bar overlaps zero becomes not significant for each plot. In each plot, the number associated with each data point represents the number of pairwise observations. The symbol  $\leq 100$  MPs represents microplastic concentrations less than or equal to 100 mg kg<sup>-1</sup>, while  $>100$  MPs indicates concentrations greater than 100 mg kg<sup>-1</sup>. Cd refers to the overall cadmium concentrations expressed in mg kg<sup>-1</sup>. The notation  $\leq 100$  MPs + Cd denotes co-exposure of less than or equal to 100 mg kg<sup>-1</sup> concentration of MPs with Cd, whereas  $>100$  MPs + Cd represents greater than 100 mg kg<sup>-1</sup> concentration of MPs with Cd. Similarly,  $<10$  Cd + MPs refers to co-exposure of less than 10 mg kg<sup>-1</sup> concentration of Cd with MPs, and  $\geq 10$  Cd + MPs indicates equal to or greater than 10 mg kg<sup>-1</sup> concentration of Cd with MPs.



**Figure S11. Cd accumulation in the plant under single and co-exposure of MPs and Cd (a).** Meta-analytical model of the single and overall effects of different doses of MPs and Cd on Cd accumulation in roots and shoots (b). (A) Cd accumulation in roots and (B) Cd accumulation in shoots. Values are the mean effect size  $\pm$  95% CI. The right sidebar has a positive effect, the left side has a negative effect, and the bar overlaps zero becomes not significant for each plot. In each plot, the number associated with each data point represents the number of pairwise observations. The symbol Cd refers to the overall cadmium concentrations expressed in  $\text{mg kg}^{-1}$ . The notation  $\leq 100$  MPx + Cd denotes co-exposure of less than or equal to  $100 \text{ mg kg}^{-1}$  concentration of MPs with Cd, whereas  $> 100$  MPx + Cd represents greater than  $100 \text{ mg kg}^{-1}$  concentration of MPs with Cd. Similarly,  $< 10$  Cd + MPx refers to co-exposure of less than  $10 \text{ mg kg}^{-1}$  concentration of Cd with MPs, and  $\geq 10$  Cd + MPx indicates equal to or greater than  $10 \text{ mg kg}^{-1}$  concentration of Cd with MPs.

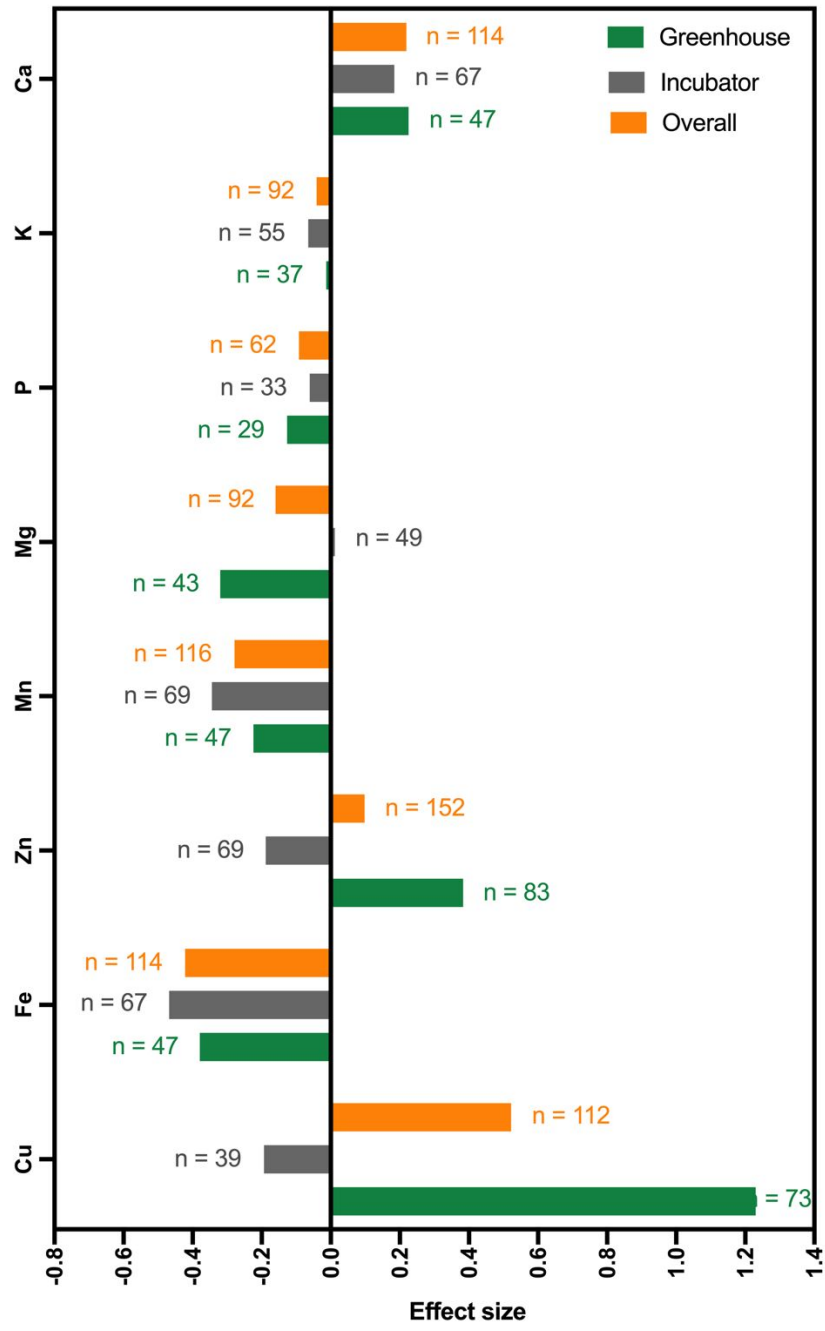


**Figure S12. Meta-analysis of MPs particle size with Cd effects on essential plant nutrient uptake.** Results are presented for eight mineral nutrients (copper (Cu), iron (Fe), zinc (Zn), manganese (Mn), magnesium (Mg), phosphorus (P), potassium (K), and calcium (Ca) under MPs less than 100  $\mu\text{m}$  particle size (<100  $\mu\text{m}$ ) (green), greater or equal to 100  $\mu\text{m}$  particle size ( $\geq 100 \mu\text{m}$ ) (gray), and overall effect (orange). Values represent the mean effect size  $\pm$  95% confidence interval (CI). Positive values (right side of the baseline) indicate enhanced nutrient uptake, while negative (left side of the baseline) values indicate inhibition. Number of each bar reflects the number of observations contributing to the estimated effect size.



**Figure S13. Meta-analysis of MPs and Cd exposure intervals on the uptake of essential plant nutrients.** Results are presented for eight mineral nutrients (copper (Cu), iron (Fe), zinc (Zn), manganese (Mn), magnesium (Mg), phosphorus (P), potassium (K), and calcium (Ca) under MPs less or equal to 15 days of exposure ( $\leq 15$ ) (green), 15-30 days of exposure (15-30) (gray), greater than 30 days of exposure ( $>30$ ) (orange), and overall effect (light blue). Values represent the mean effect size  $\pm$  95% confidence interval (CI). Positive values (right side of the baseline) indicate enhanced nutrient uptake, while negative (left side of the baseline) values indicate inhibition. Number of each bar reflects the number of observations contributing to the estimated effect size.

Experimental methods wise effect of MPs and Cd



**Figure S14. Meta-analysis of MPs and Cd exposure methods on the uptake of essential plant nutrients.** Results are presented for eight mineral nutrients (copper (Cu), iron (Fe), zinc (Zn), manganese (Mn), magnesium (Mg), phosphorus (P), potassium (K), and calcium (Ca) under greenhouse experiment (green), incubator experiment (gray), and overall effect (orange). Values represent the mean effect size  $\pm$  95% confidence interval (CI). Positive values (right side of the baseline) indicate enhanced nutrient uptake, while negative (left side of the baseline) values indicate inhibition. Number of each bar reflects the number of observations contributing to the estimated effect size.