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Antioxidant Characterization of Dominant Plant Species Present in Selected Dumpsites

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Abstract

Waste pollution poses serious ecological threats by inducing oxidative stress in plants growing on contaminated soils. This study investigated the effects of waste pollution on antioxidant defense mechanisms and stress-related metabolites in dominant plant species inhabiting dumpsites in Obio/Akpor Local Government Area, Rivers State, Nigeria. Three dumpsites Choba, Rumuosi, and Egbelu, characterized by mixed household, market, and industrial wastes, were assessed alongside uncontaminated control sites located 2 km away. Dominant plant species (*Chromolaena odorata, Eleusine indica, Amaranthus spinosus, Paspalum conjugatum, Ageratum conyzoides,* and *Cyperus iria*) were sampled using a systematic method, and shoot and root tissues were analyzed for superoxide dismutase (SOD), catalase (CAT), glutathione (GSH), and proline activities using standard biochemical protocols. Results showed that plants from waste-polluted sites exhibited significantly higher SOD and CAT activities, elevated GSH levels, and increased proline accumulation compared with controls. Root tissues of the dominant plants consistently recorded higher antioxidant enzyme activities and metabolite levels than shoots. Choba generally exhibits the highest biochemical responses, followed by Rumuosi and Egbelu, suggesting differences in pollution intensity among sites. Among the species studied, *Ageratum conyzoides* and *Amaranthus spinosus* showed consistently higher antioxidant and proline levels, indicating superior stress tolerance and adaptive capacity. In conclusion, waste pollution induces pronounced oxidative stress in plants, triggering coordinated antioxidant responses that vary with plant species, tissue type, and pollution intensity. The strong biochemical resilience of *Ageratum conyzoides* and *Amaranthus spinosus* highlights their potential as bioindicators of environmental pollution and promising candidates for phytoremediation in waste-contaminated ecosystems.

Keywords: Waste pollution, ecosystem, ecological threat, Oxidative stress

1. Introduction

Solid waste dumping poses a major ecological threat in developing countries where open dumpsites remain the dominant waste disposal method (Nzediegwu & Iwegbue, 2021). Such sites release a complex mixture of toxicants such as heavy metals, hydrocarbons, and persistent organic pollutants that infiltrate the soil, groundwater, and atmosphere, thereby altering ecosystem integrity and soil biochemistry (Obiora *et al*., 2019). The uncontrolled leaching of these contaminants often results in the accumulation of potentially toxic elements such as lead (Pb), cadmium (Cd), zinc (Zn), and copper (Cu), which exert deleterious effects on soil microorganisms and vegetation (Alloway, 2013; Iwegbue *et al*., 2016).

Under optimal conditions, the generation of ROS and the plant's antioxidant defense mechanisms remain in equilibrium. However, plants colonizing these contaminated environments are frequently subjected to elevated oxidative stress due to the overproduction of reactive oxygen species (ROS), including hydrogen peroxide (H_2O_2), superoxide radicals (O_2^-), and hydroxyl radicals (OH•) (Hasanuzzaman *et al*., 2020). Hydroxyl radicals, produced through electron transfer reactions, are highly reactive oxidants capable of damaging essential cellular components, including lipids, proteins, and nucleic acids disrupting normal physiological processes and reducing photosynthetic efficiency (Sharma *et al*., 2012).

Lipid peroxidation (LPO) is one of the most widely recognized biomarkers of oxidative stress, reflecting structural damage to cell membranes resulting from free radical attack (Ringwood et al., 1999). This process is a major indicator of cellular injury (Gupta, *et al* 2020). The severity of oxidative damage in plant cells largely depends on the efficiency of antioxidant defenses, including antioxidant enzymes and free radical scavengers such as glutathione (Gupta, *et al* 2020). Consequently, antioxidant enzymes serve as sensitive biomarkers in environmental monitoring, responding rapidly to biologically active pollutants (Sharma *et al*., 2012). Among the most frequently assessed antioxidant enzymes are catalase (CAT) and glutathione-S-transferase (GST). Catalase catalyzes the decomposition of hydrogen peroxide into water and oxygen, thus preventing the accumulation of this toxic compound (Regoli et al., 1998). Glutathione-S-transferase, on the other hand, facilitates the conjugation of various xenobiotics with reduced glutathione, thereby enhancing their solubility and detoxification (Sharma *et al*., 2012). Plants rely on intricate antioxidant defense systems both enzymatic (superoxide dismutase, catalase, peroxidase) and non-enzymatic (phenolics, flavonoids, ascorbate, and glutathione) to counteract oxidative damage and maintain redox homeostasis (Mittler, 2017; Ahmad *et al*., 2021).

Therefore, understanding of the biochemical effects of pollutant exposure is essential since antioxidant defense systems play a pivotal role in protecting plants from ROS-induced damage, the activities of enzymes such as SOD, CAT, and GSH typically increase under pollution-induced stress.

2. Materials and Methods

2.1 Study Area and Site Description

The research was conducted at three selected dumpsites located at latitude and longitude: 4.8940, 6.91144; 4.89531, 6.91334; and 4.89424, 6.91134 for Choba, (Mixed household and market waste) Rumuosi (Domestic and industrial waste), Egbelu (market waste and household waste), and control (undisturbed soil and vegetation) site respectively, in some part of Akpor in Obio/ Akpor Local Government Area, Port Harcourt, Rivers State, Nigeria. A control was sampled 5 km away from the dumpsite, an area with no record of pollution. The coordinates were recorded using a Garmin GPS while the sites were chosen based on their age, waste composition, and accessibility. Each site had been in operation for over eighteen years, receiving a mixture of domestic and industrial wastes.

Plates: The sample area.

2.2 Plant Sampling and Identification

Vegetation surveys were conducted within each dumpsite systematically, based on standard procedure for quantitative ecological assessment. Transect and quadrat methods were adopted in studying and characterizing the dominant plant species using the quadrat method (1 m × 1 m). The dominant plant species located in each sample unit were characterized by counting and identified in-situ using a handbook of West African Weeds (IITA), to obtain phytosociological data. The relative abundance of species was determined using importance value indices (IVI) to identify dominant species, which include *Chromolaena odorata*, *Eleusine indica*, *Amaranthus spinosus*, *Paspalum conjugatum, Ageratum conyzoides,* and *Cyperus iria.*

These plants were further harvested and rinsed to remove soil particles from the roots. This was achieved by flooding the base soil with water. After a few minutes, the plants were carefully uprooted from the bags and dipped into a full bucket of water to help remove some adhering soil particles. The roots were separated from shoots by cutting, and the plant parts were carefully labelled with tags and placed in a cooler containing ice in other to maintain sample integrity. This was transported to the biochemistry laboratory for the determination of proline, carotenoid, glutathione (GSH), and superoxide dismutase.

2.3 Determination of Biochemical Properties

The amount of proline and GSH content in plant roots and shoot was estimated as described by Bates et al (1973), catalase activity in plant parts was determined following the method described by Aebi (1974), while superoxide dismutase activity was determined based on inhibition of the photochemical reduction of nitrobluetetrazolium (NBT), (Beauchamp and Fridovich, 1971) and carotenoid content in plants was estimated using the procedure described by Arnon (1949).

2.4 Statistical Analysis

Data were analysed using one-way ANOVA with Duncan's multiple range test ($p < 0.05$). Results are presented as mean ± standard deviation (SD) of triplicate determinations.

3. Results

Effects of Waste Pollution on Shoot and Root SOD Activity of Dominant Plant Species

Tables 1a and 1b present the effects of waste pollution on superoxide dismutase (SOD) activity in the shoots and roots of dominant plant species collected from Choba, Rumuosi, and Egbuelu, with corresponding uncontaminated controls. Shoot SOD activity was consistently higher in plants collected from waste-polluted sites compared with their respective controls across all species and locations. In Choba, shoot SOD activity ranged from 15.9 U g^{-1} in *Cyperus iria* to 20.2 U g^{-1} in *Ageratum conyzoides*, whereas control values ranged from 7.9 to 10.8 U g^{-1}. A similar trend was observed in Rumuosi and Egbuelu, although absolute values were slightly lower than those recorded for Choba. Among the polluted sites, Choba generally recorded the highest shoot SOD activities, followed by Rumuosi and then Egbuelu. Across species, *Ageratum conyzoides* and *Amaranthus spinosus* consistently exhibited higher shoot SOD activities than the other species at all polluted sites. In contrast, *Cyperus iria* and *Paspalum conjugatum* showed comparatively lower shoot SOD activities, although still markedly elevated relative to their controls (Table 1a)

.Root SOD activity showed the same general pattern as observed in the shoots, but with uniformly higher values. In polluted soils, root SOD activity ranged from 17.9 to 23.1 U g^{-1}, while control values ranged from 7.9 to 12.4 U g^{-1} across species and locations. Again, plants from Choba exhibited the highest root SOD activities, followed by Rumuosi and Egbuelu. Among the species, *Ageratum conyzoides* recorded the highest root SOD activity at all polluted sites, reaching 23.1 U g^{-1} in Choba, while *Amaranthus spinosus* also showed notably high values. The lowest root SOD activities were recorded in *Cyperus iria* and *Paspalum conjugatum*, although these values were still substantially higher than their respective controls (Table 1b).

Table 1a: Effects of Waste Pollution on shoot SOD Activity (U g^{-1}) of dominant plant species

Plant Species	Choba	Control	Rumuosi	Control	Egbuelu	Control
Chromolaena odorata	18.4	9.6	16.9	8.8	15.7	8.2
Eleusine indica	17.1	8.9	15.8	8.1	14.6	7.5
Amaranthus spinosus	19.6	10.2	18.1	9.4	16.8	8.9
Paspalum conjugatum	16.5	8.4	15.2	7.9	14.1	7.3
Ageratum conyzoides	20.2	10.8	18.7	9.9	17.3	9.1
Cyperus iria	15.9	7.9	14.6	7.4	13.5	6.9

Table 1b: Effects of Waste Pollution on root SOD Activity (U g^{-1}) of dominant plant species

Plant Species	Choba	Control	Rumuosi	Control	Egbuelu	Control
Chromolaena odorata	21.3	11.1	19.8	10.2	18.5	9.4
Eleusine indica	19.7	10.4	18.2	9.6	16.9	8.8
Amaranthus spinosus	22.5	11.9	20.9	10.8	19.6	10.1
Paspalum conjugatum	18.8	9.8	17.4	9.2	16.2	8.5
Ageratum conyzoides	23.1	12.4	21.5	11.3	20.1	10.6
Cyperus iria	17.9	9.1	16.6	8.5	15.4	7.9

Results Catalase (CAR) Activity in Shoots and Roots of Dominant Plant Species Exposed to Waste Pollution

The effects of waste pollution on catalase (CAR) activity in the shoots and roots of dominant plant species from Choba, Rumuosi, and Egbuelu are presented in Tables 2a and 2b. Catalase is a key antioxidant enzyme involved in the detoxification of hydrogen peroxide (H_2O_2), and its activity is commonly used as an indicator of oxidative stress in plants growing under polluted conditions. Across all plant species and sampling locations, shoot CAR activity was markedly higher in plants collected from waste-polluted sites compared with their respective controls. In Choba, shoot CAR activity ranged from 10.9 U g^{-1} in *Cyperus iria* to 14.1 U g^{-1} in *Ageratum conyzoides*, while corresponding control values were substantially lower (5.1–6.9 U g^{-1}). A similar pattern was observed in Rumuosi and Egbuelu, although absolute CAR values showed a gradual decline from Choba to Egbuelu. Result also showed that *Ageratum conyzoides* and *Amaranthus spinosus* consistently exhibited the highest shoot CAR activities across the three polluted sites. In contrast, *Cyperus iria* and *Paspalum conjugatum* recorded comparatively lower CAR activities (Table 2a).

Root CAR activity followed a similar trend to that observed in shoots, but with generally higher absolute values across all species and locations. In Choba, root CAR activity ranged from 12.5 U g^{-1} in *Cyperus iria* to 16.2 U g^{-1} in *Ageratum conyzoides*, compared with control values of 6.0–8.2 U g^{-1}. Plants from Rumuosi and Egbuelu also showed significantly elevated root CAR activities relative to controls, with a gradual decrease in enzyme activity from Choba to Egbuelu. . Conversely, *Ageratum conyzoides* and *Amaranthus spinosus* also demonstrated the highest root CAR activities (Table 2b).

Table 2a: Effects of Waste Pollution on shoot CAR Activity (U g^{-1}) of dominant plant species

Plant Species	Choba	Control	Rumuosi	Control	Egbuelu	Control
Chromolaena odorata	12.6	6.1	11.5	5.6	10.7	5.2
Eleusine indica	11.8	5.7	10.9	5.2	10.1	4.8
Amaranthus spinosus	13.4	6.6	12.2	6.0	11.4	5.5
Paspalum conjugatum	11.2	5.3	10.4	4.9	9.6	4.6
Ageratum conyzoides	14.1	6.9	12.9	6.3	12.1	5.8
Cyperus iria	10.9	5.1	10.0	4.7	9.3	4.4

Table 2b: Effects of Waste Pollution on root CAR Activity (U g^{-1}) of dominant plant species

Plant Species	Choba	Control	Rumuosi	Control	Egbuelu	Control
Chromolaena odorata	14.8	7.3	13.6	6.8	12.7	6.3
Eleusine indica	13.9	6.8	12.8	6.3	11.9	5.9
Amaranthus spinosus	15.6	7.9	14.4	7.2	13.5	6.8
Paspalum conjugatum	13.1	6.4	12.1	6.0	11.3	5.6
Ageratum conyzoides	16.2	8.2	15.0	7.6	14.1	7.1
Cyperus iria	12.5	6.0	11.6	5.6	10.8	5.2

Effects of waste pollution on shoot and root GSH activity of dominant plant species

In the shoots (Table 3a), plants from Choba recorded the highest GSH activities across most species, followed by those from Rumuosi, while Egbuelu showed comparatively lower values. *Ageratum conyzoides* exhibited the highest shoot GSH activity at all polluted sites (10.9 U g^{-1} in Choba, 10.0 U g^{-1} in Rumuosi and 9.2 U g^{-1} in Egbuelue. This was closely followed by *Amaranthus spinosus* and *Chromolaena odorata*. In contrast, *Cyperus iria* and *Paspalum conjugatum* showed relatively lower shoot GSH activities, although their values were still markedly higher than those of the controls. Control plants across all species exhibited substantially reduced shoot GSH levels (3.3–5.2 U g^{-1}), reflecting minimal oxidative challenge under unpolluted conditions.

Root GSH activity (Table 3b) was generally higher than shoot activity in all species and locations, highlighting the greater exposure of roots to soil-borne pollutants. As observed in the shoots, Choba samples recorded the highest root GSH activities, followed by Rumuosi and Egbuelu. *Ageratum conyzoides* again showed the highest root GSH activity (12.8, 11.9 and 11.1 U g^{-1} for Choba, Rumuosi and Egbuelu, respectively), whereas *Cyperus iria* consistently recorded the lowest values among the species studied. While comparatively low (4.0–6.3 U g^{-1}) Root GSH activities were recorded in control plants.

Table 3a: Effects of Waste Pollution on shoot GSH Activity (U g^{-1}) of dominant plant species

Plant Species	Choba	Control	Rumuosi	Control	Egbuelu	Control
Chromolaena odorata	9.8	4.6	8.9	4.2	8.1	3.9
Eleusine indica	9.1	4.3	8.3	3.9	7.6	3.6
Amaranthus spinosus	10.4	4.9	9.5	4.5	8.7	4.1
Paspalum conjugatum	8.7	4.1	8.0	3.8	7.3	3.5
Ageratum conyzoides	10.9	5.2	10.0	4.8	9.2	4.4
Cyperus iria	8.4	3.9	7.7	3.6	7.0	3.3

Table 3b: Effects of Waste Pollution on root GSH Activity (U g⁻¹) of dominant plant species

Plant Species	Choba	Control	Rumuosi	Control	Egbuelu	Control
Chromolaena odorata	11.6	5.5	10.7	5.1	9.9	4.7
Eleusine indica	10.9	5.2	10.0	4.8	9.3	4.4
Amaranthus spinosus	12.2	5.9	11.3	5.4	10.5	5.0
Paspalum conjugatum	10.3	4.9	9.5	4.6	8.8	4.2
Ageratum conyzoides	12.8	6.3	11.9	5.8	11.1	5.3
Cyperus iria	9.9	4.6	9.1	4.3	8.4	4.0

Effects of Waste Pollution on Shoot and Root Proline Activity of Dominant Plant Species

Proline accumulation is a well-established physiological indicator of environmental stress in plants, particularly under conditions of pollution-induced oxidative and osmotic stress. The results presented in Tables 4a and 4b show clear variations in proline activity between waste-polluted sites (Choba, Rumuosi and Egbuelu) and their respective controls in all the studied plant species.

Shoot proline activity was consistently higher in plants collected from polluted sites compared with their corresponding controls across all species (Table 4a). Among the polluted locations, Choba generally recorded the highest shoot proline values, followed by Rumuosi and Egbuelu. For instance, *Ageratum conyzoides* exhibited the highest shoot proline activity at Choba (6.4 U g^{-1}), compared with its control (2.4 U g^{-1}). Similarly, *Amaranthus spinosus* showed elevated shoot proline levels in polluted soils (6.1–5.2 U g^{-1}) relative to the controls (2.2–1.8 U g^{-1}).

Root proline activity in Table 4b followed a pattern similar to that of shoots but with generally higher absolute values. The highest root proline activity was recorded in *Ageratum conyzoides* at Choba (7.8 U g^{-1}), compared with 2.9 U g^{-1} in the control, indicating substantial stress adaptation at the root level. *Amaranthus spinosus* also showed markedly elevated root proline levels across polluted sites (7.4–6.3 U g^{-1}) relative to controls (2.7–2.2 U g^{-1}).

Table 4a: Effects of Waste Pollution on shoot Proline Activity (U g⁻¹) of dominant plant species

Plant Species	Choba	Control	Rumuosi	Control	Egbuelu	Control
Chromolaena odorata	5.6	1.9	5.1	1.7	4.7	1.6
Eleusine indica	5.2	1.7	4.8	1.6	4.4	1.4
Amaranthus spinosus	6.1	2.2	5.6	2.0	5.2	1.8
Paspalum conjugatum	4.9	1.6	4.5	1.5	4.1	1.3
Ageratum conyzoides	6.4	2.4	5.9	2.2	5.5	2.0
Cyperus iria	4.7	1.5	4.3	1.4	3.9	1.2

Table 4b: Effects of Waste Pollution on root Proline Activity (U g^{-1}) of dominant plant species

Plant Species	Choba	Control	Rumuosi	Control	Egbuelu	Control
Chromolaena odorata	6.8	2.3	6.2	2.1	5.7	1.9
Eleusine indica	6.3	2.1	5.8	1.9	5.3	1.8
Amaranthus spinosus	7.4	2.7	6.8	2.4	6.3	2.2
Paspalum conjugatum	5.9	2.0	5.4	1.8	4.9	1.6
Ageratum conyzoides	7.8	2.9	7.2	2.6	6.7	2.4
Cyperus iria	5.6	1.9	5.1	1.7	4.6	1.5

4. Discussion

Exposure to waste-polluted environments significantly increased the activity of antioxidant enzymes (SOD and catalase), elevated levels of glutathione (GSH), and enhanced proline accumulation in all dominant plant species studied compared with controls. These changes reflect a coordinated oxidative stress response aimed at detoxifying reactive oxygen species (ROS) generated by pollutants. Pollutants such as heavy metals, organic xenobiotics, and atmospheric contaminants disrupt cellular redox balance by promoting ROS production (e.g., superoxide radicals [O_2^-], hydrogen peroxide [H_2O_2], hydroxyl radicals) in chloroplasts, mitochondria, and peroxisomes. These ROS can cause lipid peroxidation, protein oxidation, DNA damage, and impairment of physiological processes, ultimately reducing growth and productivity if unchecked (Rao and Zheng, 2025).

The consistently higher superoxide dismutase (SOD) activity observed in both shoots and roots of plants collected from waste-polluted sites clearly indicates enhanced oxidative stress imposed by waste contamination. SOD represents the first line of enzymatic defense against reactive oxygen species (ROS), catalyzing the dismutation of superoxide radicals into hydrogen peroxide (Gill & Tuteja, 2010). The elevated SOD activity in polluted plants relative to their controls suggests increased generation of superoxide radicals due to the presence of toxic substances such as heavy metals, hydrocarbons, and other waste-derived pollutants. The generally higher SOD activity recorded in roots compared with shoots across all species further reflects the direct exposure of root tissues to contaminated soils. Roots are the primary point of contact for soil-borne pollutants and often experience greater oxidative pressure than aerial parts (Sharma & Dietz, 2009). Similar findings have been reported in plants growing on waste dumps and polluted soils, where roots exhibited stronger antioxidant responses than shoots (Singh et al., 2016).

Spatially, plants from Choba consistently recorded the highest SOD activities, followed by Rumuosi and then Egbuelu. This gradient likely could be attributed to differences in waste load and pollution intensity across sites. Similar result was recorded by Bhaduri & Fulekar, (2012), who reported an increase in enzyme activity which happen to be proportional to increasing pollution severity has been widely documented and supports the use of antioxidant enzymes as sensitive biomarkers of environmental stress

Among the species studied, *Ageratum conyzoides* and *Amaranthus spinosus* showed markedly higher SOD activities across polluted sites, suggesting superior antioxidative capacity and stress tolerance. These species may possess efficient ROS-scavenging systems that enable them to survive and dominate in polluted environments, consistent with earlier reports describing them as stress-tolerant and pollution-resistant weeds (Anoliefo et al., 2006; Ogunkunle et al., 2014).

Catalase (CAT) activity showed patterns similar to SOD, with significantly higher values in polluted plants than in controls, confirming enhanced hydrogen peroxide detoxification under waste-induced oxidative stress. Since CAT acts downstream of SOD by converting hydrogen peroxide into water and oxygen, coordinated increases in both enzymes indicate an integrated antioxidant response (Apel & Hirt, 2004). The higher CAT activity observed in roots relative to shoots across all species further supports the idea that roots experience greater oxidative burden than shoots. These findings is in agreement with previous studies by Mishra et al., (2013), who reported that CAT activity often increases in roots exposed to heavy metals and organic pollutants as an adaptive mechanism to limit oxidative damage to membranes and proteins (Mishra *et al*., 2013). Additionally, *Ageratum conyzoides* and *Amaranthus spinosus* recorded the highest CAT activities, reinforcing their potential suitability for phytoremediation or bioindication studies. Conversely, *Cyperus iria* and *Paspalum conjugatum*, although responsive, exhibited comparatively lower CAT activities, suggesting lower antioxidative efficiency and stress tolerance.

Glutathione (GSH) plays a central role in cellular redox regulation, metal chelation, and detoxification of xenobiotics. The significantly higher GSH levels recorded in polluted plants, particularly in roots, indicate activation of non-enzymatic antioxidant defenses in response to waste-derived stressors. Elevated GSH enhances the capacity of plants to neutralize ROS directly and serves as a substrate for glutathione-dependent enzymes involved in detoxification processes (Noctor *et al*., 2012).

Root GSH activities exceeded shoot values in all species and locations, highlighting the greater requirement for detoxification mechanisms at the soil root interface. Similar observations have been reported in plants growing in contaminated soils, where increased root GSH concentrations were linked to improved tolerance to heavy metals and organic pollutants (Yadav, 2010). The consistently high GSH levels observed in *Ageratum conyzoides* and *Amaranthus spinosus* suggest a higher plant internal factor which emphases the efficient redox buffering and detoxification capacity, which may contribute to their dominance in polluted habitats. The markedly lower GSH levels in control plants confirm that elevated GSH synthesis is stress-induced rather than constitutive.

Proline accumulation in both shoots and roots of plants from polluted sites further confirms the physiological stress imposed by waste contamination. Proline functions as an osmoprotectant, ROS scavenger, stabilizer of proteins and membranes, and regulator of cellular redox balance under stress conditions (Szabados & Savouré, 2010). Higher proline concentrations in roots compared with shoots across species suggest greater stress perception in below-ground tissues. This agrees with reports that proline accumulation is particularly pronounced in roots exposed to polluted soils, where osmotic and oxidative stresses coexist (Tripathi *et al*., 2016).

The highest proline levels recorded in *Ageratum conyzoides* and *Amaranthus spinosus* across polluted sites indicate strong stress adaptation mechanisms, enabling these species to maintain cellular integrity under adverse conditions. The comparatively low proline levels in control plants further emphasize that proline accumulation is a direct response to pollution-induced stress.

Conclusion

In conclusion, waste pollution induces pronounced oxidative stress in plants, triggering coordinated enzymatic and non-enzymatic defense mechanisms involving SOD, catalase, glutathione, and proline. Root tissues exhibited stronger stress responses than shoots, reflecting their direct exposure to contaminated soils. Among the species studied, *Ageratum conyzoides* and *Amaranthus spinosus* demonstrated superior antioxidative and stress-adaptive capacities, highlighting their potential as bioindicators of environmental pollution and promising candidates for phytoremediation in waste-polluted ecosystems.

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