Anatomical changes due to uptake and accumulation of Zn and Cd in Indian mustard (*Brassica juncea*)

B.B. Maruthi Sridhar a,b, S.V. Diehl a, F.X. Han c, D.L. Monts b,c, Y. Su b,*

a Department of Forest Products, Mississippi State University, Mississippi State, MS 39762, USA
b Diagnostic Instrumentation and Analysis Laboratory (DIAL), Mississippi State University, Mississippi State, MS 39762, USA
c Department of Physics and Astronomy, Mississippi State University, Mississippi State, MS 39762, USA

Accepted 21 June 2004

Abstract

Anatomical and physiological changes in Indian mustard (*Brassica juncea*) plants due to uptake and accumulation of Zn and Cd were investigated. Potted plants were exposed to metal treatments of Zn and Cd for 15 and 16 days, respectively. Leaves, stems and roots were harvested for studying anatomy and analyzing metal accumulation. Anatomical changes were documented using light microscopy, scanning, and transmission electron microscopy. Accumulation of Zn and Cd in all parts of the plant increased significantly with an increase in applied metal concentration. Microscopic studies revealed clotted depositions in roots and stems, break down of parenchyma cells, and a decrease in starch content in leaves of plants treated with high concentrations of Zn. Physiological and morphological changes of Zn-treated plants included a significant decrease in relative water content, dry weight and plant height. Cd at higher concentrations resulted in structural changes only in stems and roots. Mustard plants accumulated significant amounts of Zn and Cd without exhibiting symptoms of phytotoxicity. However, higher Zn (ZnT3 and ZnT4) and Cd (CdT4) concentrations resulted in structural changes in roots, stems and leaves and altered physiological and morphological characteristics. Our results systematically illustrate the physiological implications of structural alterations caused by Zn and Cd at higher concentrations.

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Keywords: Anatomy, *Brassica juncea*, Cadmium, Microscopy, Phytoremediation, Zinc

1. Introduction

Over many years, Zn and Cd contamination has built up in the environment from industrial activities, such as mining and smelting of metalliferous ores, electroplating, fertilizers and pesticides (Raskin and Ensley, 2000). Zn is widely used in the paint, rubber, dye and wood preservative industries (ATSDR, 1994) while Cd is mainly used in batteries, metal coatings and plastic industries (Raskin and Ensley, 2000; ATSDR, 1999). Both Zn and Cd often combine with other elements at hazardous waste sites to form compounds of chlorides,
Phytoremediation is a cleanup alternative where plants are used to degrade, extract, contain or immobilize contaminants from soils and water (Raskin and Enslow, 2000). For effective phytoremediation of metals they must be translocated and accumulated in the aerial parts of the plant. Progress of metal phytoextraction is limited by metal uptake and translocation efficiency within different plant parts. In non-hyperaccumulator plants, Zn accumulation is localized as globules in roots of *Deschampsia caespitosa* (Van Steveninck et al., 1990), As, electron dense granules in roots of *Betula pendula* (Denny and Wilkins, 1987) and as globules in leaves of *Lemna minor* (Van Steveninck et al., 1990). Among hyperaccumulators Zn is localized as globular crystals in the roots and leaves of *Thlaspi caerulescens* (Vazquez et al., 1994, 1992a, Kupper et al., 1999; Keller et al., 2000). Accumulation and localization of Cd occurred as electron dense granules in roots of *Agrostis gigantea* and *Zea mays* (Rausser and Ackerley, 1987), as cell wall deposition in roots of *Z. mays* (Khan et al., 1984) and in roots of bush bean plants (Vazquez et al., 1992a).

Uptake and accumulation of metals at higher concentrations can be cytotoxic in some plant species, causing structural and ultrastructural changes affecting the growth and physiological well being of the plants (Barcelo et al., 1988; Zhao et al., 2000; Vazquez et al., 1992a; Han et al., 2004). Zn hyperaccumulation results in a decrease in mesophyll cell size in *Arabidopsis hal-leri* (Zhao et al., 2000) while Cd accumulation causes a break down of chloroplasts in bush bean plants (Barcelo et al., 1988) and decreases plant growth in *Z. mays* (Vazquez et al., 1994, 1992a; Kupper et al., 1999; Keller et al., 2000). Accumulation and localization of Cd occurred as electron dense granules in roots of *Agrostis gigantea* and *Zea mays* (Rausser and Ackerley, 1987), as cell wall deposition in roots of *Z. mays* (Khan et al., 1984) and in roots of bush bean plants (Vazquez et al., 1992a).

Indian mustard has been identified as a high biomass producing plant with the capacity to accumulate Zn and Cd at higher concentrations in plant cells (Kumar et al., 1995; Sah et al., 1995). With in this context, the physiology, morphology and anatomical characteristics of mustard plants are important. It is also important to study the structural changes in different plant parts to understand the overall process of phytoremediation. Hence in this study the physiological, morphological and anatomical characters of mustard plants were evaluated with reference to their Zn and Cd phytoextraction potential. The main objective of our study was to identify the structural and ultrastructural changes caused by Zn and Cd accumulation in leaves, stems and roots of mustard plants; and to correlate the metal accumulation with anatomical, physiological and morphological changes.

2. Materials and methods
2.1. Plant culture and phytoremediation experimental design

The mustard seeds were a commercial variety obtained locally. The soil used for the pot study was Miracle-Gro Potting Mix from Miracle-Gro Lawn Products Inc. (Marysville, OH). The seeds were sown in plastic pots, each containing approximately 2.0 kg of potting mix. The plants were kept outdoors in an enclosed area except during extreme weather conditions. The seedlings were thinned to two plants per pot at the 2–3-leaf stage. Modified Hoaglands Nutrient solution (Hoagland and Arnon, 1950) was supplied to the plants daily, after the plants attained 4 days earlier because of severe phytotoxicity symptoms. Since large number of samples were collected for microscopic study, the Cd treated groups...
were harvested 16 days after the start of metal treatment (1 day later than most of the Zn treated groups).

2.2. Procedure for microscopic study

Stem and root samples of 5 mm length were excised from 2 cm above and 2 cm below the stem–root intersection, respectively. Leaf samples of 5 mm length were excised from the middle portion of the third leaf (lower leaf) from the base of the plant. The leaf, stem and root samples were prepared for light microscopy (LM), scanning electron microscopy (SEM), and transmission electron microscopy (TEM). All the samples were excised and quickly immersed in H$_2$S saturated water as pretreatment for 30 min at room temperature to precipitate Cd and Zn (Khan et al., 1984). The samples were immediately fixed in formaldehyde acetic acid (FAA) saturated with H$_2$S water for LM and in glutaraldehyde for SEM and TEM studies.

2.2.1. Light microscopy (LM)

The plant samples were alcohol dehydrated, paraffin embedded, ultramicrotomed and subjected to different stains including sulfide-silver to localize the Cd and Zn in stem samples and with potassium iodide (KI) to visualize the starch content (Sass, 1958) in leaf samples. For the sulfide–silver method, the LM stem sections embedded in paraffin were microtomed to obtain four microsections, placed on glass slides, cleaned in citri-solve, and dehydrated in an ethanol series. The sections were then treated in developer solution in the dark at 22°C for 1 h. Finally they were washed in an ethanol series, counter stained with 2% safranin and then dehydrated and mounted (Pearse, 1972).

2.2.2. Scanning electron microscopy (SEM)

Leaf, stem and root samples were also prepared for scanning electron microscopy (SEM). Stem samples of approximately 5 mm length were collected from 2 cm above the stem–root intersection. The procedures for collection of leaf and root samples remain the same as described for light microscopy. All the samples were immediately fixed in 2.5% glutaraldehyde in 0.05 M potassium phosphate buffer (pH 7.1) for 8 h, and post fixed with OsO$_4$. The samples were dehydrated in an ethanol series and embedded in Spurrs epoxy resin. Ultrathin sections were obtained using an ultramicrotome and stained with uranyl acetate and basic lead citrate for observation under JEOL TEM (Johansen, 1940).

2.2.3. Transmission electron microscopy (TEM)

Stem and root segments of approximately 3 mm length were collected for transmission electron microscopy (TEM). The samples were fixed in 2.5% glutaraldehyde in 0.05 M potassium phosphate buffer (pH 7.1) for 8 h, and post fixed with OsO$_4$. The samples were dehydrated in an ethanol series and embedded in Spurrs epoxy resin. Ultrathin sections were obtained using an ultramicrotome and stained with uranyl acetate and basic lead citrate for observation under JEOL TEM (Johansen, 1940).

2.3. Chemical analysis

The plants were cut about 2 cm above the soil level, upper leaves, lower leaves, stems and roots were harvested, and the roots were washed with de-ionized water and the samples were dried at 80°C for 48 h for chemical analysis. Among the total 6–7 leaves of the plant, the first three leaves counting from the base of the plant were considered as lower leaves and the rest as upper leaves when collecting leaves for chemical analysis. Dry leaves, stems and roots were then ground and weighed. Plant samples (approximately 0.5 g) were digested with concentrated HNO$_3$ and H$_2$O$_2$ (Jackson, 1958). The digested solution was filtered and then analyzed for Zn and Cd concentration using inductively coupled plasma atomic emission spectrometry (ICP-AES) (Han and Banin, 1997).

2.4. Measurements and statistical analysis

The plant heights from the root–stem intersection to the growing tip of the stem were measured at the end of the experiment. The fresh weights and dry weights of the upper leaves, lower leaves and stems were obtained using an electronic balance. The relative water content (RWC) of the plants were obtained using the formula (Fresh weight–Dry weight)/Fresh weight. Statistical analysis was conducted with SAS statistical software (SAS Institute Inc. NC). The GLM procedure was used for the analysis of different metal treatments, with means separated by Duncans multiple range test at $p < 0.05$. The CORR procedure was used for correlation.
analysis with means separated at p < 0.05. Least significant difference (LSD) was used for comparisons between the treatment means.

3. Results

3.1. Effect of Zn and Cd accumulation on plant growth

Mustard plants grew steadily in all of the Zn- and Cd-treated groups and chlorosis was not visually observed during the treatment process except in higher Zn-treatment groups (ZnT3 and ZnT4) towards the end of the experiment. General side effects of metal treatment included stunted growth with an increase in metal concentration. The Zn accumulation in leaves, stems and roots increased significantly with an increase in applied metal solution concentration (Table 1). Zn accumulation increased almost linearly in all plant parts, resulting in high Zn concentration in roots followed by stems, lower leaves and upper leaves (Table 1). The dry weight, relative water content (RWC), and plant height significantly decreased for ZnT4-treated plants (Table 1). Cd also accumulated significantly in leaves, stems and roots with higher applied metal concentrations (CdT3 and CdT4) (Table 2). The Cd accumulation in leaves and stems are close to the accumulation in roots in the CdT1- and CdT2-treated groups (Table 2) whereas the CdT3- and CdT4-treated groups showed a higher concentration in roots followed by lower leaves, upper leaves and stems. The dry weight and plant height decreased for CdT4-treated plants compared to control plants – T0 (Table 2). The metal accumulations listed in Tables 1 and 2 was based on the dry weight basis of harvested plant material.

Pearson's correlation coefficients were calculated to identify the effect of metal accumulation on the physiological and morphological characters of the plant. Zn accumulation showed significant (p < 0.01) negative correlation with plant dry weight and highly significant (p < 0.001) negative correlation with RWC and plant height (Table 3). Among the different plant parts analyzed, Zn accumulation in stem was significantly negatively correlated to the RWC (r = −0.94 *** ) and plant height (r = −0.74 *** ). Cd-treated plants showed (p < 0.01) negative correlations with only plant dry weight (Table 4).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Upper leaf concentration (mg kg⁻¹)</th>
<th>Lower leaf concentration (mg kg⁻¹)</th>
<th>Stem concentration (mg kg⁻¹)</th>
<th>Root concentration (mg kg⁻¹)</th>
<th>Dry weight (g)</th>
<th>RWC (%)</th>
<th>Height (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T0</td>
<td>3.8 c</td>
<td>76 a</td>
<td>91 c</td>
<td>72 c</td>
<td>111.2 a</td>
<td>91.7 a</td>
<td>12.7 b</td>
</tr>
<tr>
<td>ZnT1</td>
<td>326 c</td>
<td>348 c</td>
<td>437 c</td>
<td>318 c</td>
<td>12.8 a</td>
<td>89.1 a</td>
<td>18.2 a</td>
</tr>
<tr>
<td>ZnT2</td>
<td>1073 cb</td>
<td>1311 c</td>
<td>1790 c</td>
<td>1541 c</td>
<td>11.9 a</td>
<td>90.2 a</td>
<td>15 b</td>
</tr>
<tr>
<td>ZnT3</td>
<td>3022 b</td>
<td>4386 b</td>
<td>10523 b</td>
<td>10953 b</td>
<td>12.1 a</td>
<td>85.6 b</td>
<td>11 c</td>
</tr>
<tr>
<td>ZnT4</td>
<td>7280 a</td>
<td>8190 a</td>
<td>15077 a</td>
<td>16482 a</td>
<td>5.9 b</td>
<td>81.3 b</td>
<td>6.7 d</td>
</tr>
</tbody>
</table>

Means followed by different letters are significantly different at the 0.05 probability level, grouped into classes a, b, c and d.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Upper leaf concentration (mg kg⁻¹)</th>
<th>Lower leaf concentration (mg kg⁻¹)</th>
<th>Stem concentration (mg kg⁻¹)</th>
<th>Root concentration (mg kg⁻¹)</th>
<th>Dry weight (g)</th>
<th>RWC (%)</th>
<th>Height (cm)</th>
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</thead>
<tbody>
<tr>
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<td>3.8 c</td>
<td>76 a</td>
<td>91 c</td>
<td>72 c</td>
<td>111.2 a</td>
<td>91.7 a</td>
<td>12.7 b</td>
</tr>
<tr>
<td>CdT1</td>
<td>24 c</td>
<td>55 b</td>
<td>32 c</td>
<td>32 b</td>
<td>12.3 a</td>
<td>90.0 a</td>
<td>13.2 a</td>
</tr>
<tr>
<td>CdT2</td>
<td>90 bc</td>
<td>163 b</td>
<td>145 c</td>
<td>134 b</td>
<td>13.4 a</td>
<td>91.3 a</td>
<td>14.2 a</td>
</tr>
<tr>
<td>CdT3</td>
<td>271 b</td>
<td>512 b</td>
<td>303 b</td>
<td>520 b</td>
<td>10.7 a</td>
<td>91.5 a</td>
<td>13.3 a</td>
</tr>
<tr>
<td>CdT4</td>
<td>1037 a</td>
<td>1850 a</td>
<td>1125 a</td>
<td>4530 a</td>
<td>8.1 a</td>
<td>90.6 a</td>
<td>10.8 a</td>
</tr>
</tbody>
</table>

Means followed by different letters are significantly different at the 0.05 probability level, grouped into classes a, b and c.

* Not significantly different at the 0.05 probability level.
Table 3
Correlation coefficients between Zn concentrations in root, stem, lower leaf and upper leaf (in mg kg\(^{-1}\) dry weight) and plant characters: dry weight, relative water content (RWC) and plant height (\(n = 6\))

<table>
<thead>
<tr>
<th>Plant characters</th>
<th>Root concentration</th>
<th>Stem concentration</th>
<th>Lower leaf concentration</th>
<th>Upper leaf concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>RWC</td>
<td>-0.91***</td>
<td>-0.94***</td>
<td>-0.87***</td>
<td>-0.83***</td>
</tr>
<tr>
<td>Dry weight</td>
<td>-0.42**</td>
<td>-0.50**</td>
<td>-0.45**</td>
<td>-0.39**</td>
</tr>
<tr>
<td>Plant height</td>
<td>-0.64***</td>
<td>-0.74***</td>
<td>-0.66***</td>
<td>-0.64***</td>
</tr>
</tbody>
</table>

** Significant at <0.01 probability level.
*** Significant at <0.001 probability level.

Table 4
Correlation coefficients between Cd concentrations in root, stem, lower leaf and upper leaf (in mg kg\(^{-1}\) dry weight) and plant characters: dry weight, relative water content (RWC) and plant height (\(n = 6\))

<table>
<thead>
<tr>
<th>Plant characters</th>
<th>Root concentration</th>
<th>Stem concentration</th>
<th>Lower leaf concentration</th>
<th>Upper leaf concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>RWC</td>
<td>-0.06</td>
<td>0.04</td>
<td>-0.11</td>
<td>0.07</td>
</tr>
<tr>
<td>Dry weight</td>
<td>-0.45**</td>
<td>-0.46**</td>
<td>-0.52***</td>
<td>-0.41</td>
</tr>
<tr>
<td>Plant height</td>
<td>-0.44</td>
<td>-0.38</td>
<td>-0.54***</td>
<td>-0.28</td>
</tr>
</tbody>
</table>

** Significant at <0.01 probability level.
*** Significant at <0.001 probability level.

Fig. 1. SEM micrographs showing the transverse section of lower leaves of control (A and C), ZnT4-(B) and CdT4-(D) treated plants. The leaves of ZnT4-treated plants show the breakdown of epidermal, palisade and spongy parenchyma cells resulting in a decrease in intercellular spaces compared to the control (T0) plants (A) by 11th day of metal treatment. The changes in CdT4-treated (D) leaves were less significant compared to control (T0) leaves by 16th day of metal treatment. Note: ZnT4-treated plants were harvested 5 days earlier than Cd-treated plants, hence different controls (T0) were used here.
3.2. Effect of Zn and Cd accumulation on plant structural changes

The Zn-treated plants showed gradual changes in leaf structure with an increase in metal concentration. The ZnT3 and ZnT4 groups showed significant foliar structural changes compared to the control group (T0). The SEM micrographs of leaf samples showed a reduction in the palisade and epidermal cells of the ZnT4 group (Fig. 1B) compared to the control group (Fig. 1A) by 11th day of metal treatment. The leaves of ZnT4-treated plants also show a breakdown of spongy and palisade parenchyma cells (Fig. 1B) followed by further loss of cell shape and decrease in intercellular spaces compared to the control group (Fig. 1A).

For Cd-treated plants (Fig. 1D), the changes in epidermal and mesophyll cells were not significant compared to the control (Fig. 1C) by 16th day of metal treatment. The ZnT4-treated plants also show a decrease in starch content by seventh day (Fig. 2B) of metal treatment compared to the control plants (Fig. 2A). The starch content appears as black to dark brown spots in the transverse section of leaves stained with potassium iodide. The starch content was significantly reduced by the 12th day of the treatment (Fig. 2D) compared to the control group (Fig. 2C), indicating an inhibition in the formation and accumulation of starch with uptake of Zn at higher concentrations. The starch content was compared qualitatively based on microscopic observations only.
Fig. 3. Light micrographs showing the transverse section of stems of control (A and C), ZnT4 (B) and CdT4 (D) treated plants sampled on the last day of metal treatment and stained with sulfide–silver for localization of Zn and Cd. The Zn (B) and Cd (D) precipitates were seen as black deposits along the walls of xylem and phloem vessels compared to clean control-T0 (A and B) stems. Also note the increased black depositions in ZnT4 (B) treated stems compared to CdT4 (D) treated stems. Note: ZnT4-treated plants were harvested 5 days earlier than Cd-treated plants, hence different controls (T0) were used here.

Light micrographs of ZnT4 – (Fig. 3B) and CdT4 – (Fig. 3D) treated stems showed Zn and Cd precipitates as black deposits along the walls of xylem and phloem vessels compared to their respective controls (Fig. 3A,C) by 11th and 16th day, respectively. The transverse section of the stems were pretreated with H2S to precipitate metal contents and stained with sulfide–silver for localization of Zn and Cd. The metal precipitates were seen as black deposits on the safranin background. The ZnT4-treated stems showed thick black depositions along the walls of xylem and phloem vessels (Fig. 3B). In CdT4-treated stems (Fig. 3D), the black depositions were not uniform, but were seen along the walls of vascular bundles.

The SEM micrographs of sulfide fixed root samples from ZnT3 – (Fig. 4B), ZnT4 – (Fig. 4C) and CdT4 – (Fig. 4D) treated groups show precipitates binding all along the cell walls of vascular bundles compared to the control (T0) group (Fig. 4A) by the end of metal treatment period. These clotted depositions increase from ZnT3 – (Fig. 4B) to ZnT4 – (Fig. 4C) treated plants. The precipitates were more intense in Zn-treated plants (ZnT3 and ZnT4) compared to CdT4-treated plants (Fig. 4D). In control group (Fig. 4A), the clotted depositions were not observed along the cell walls of the vascular bundles. TEM observations of the sulfide fixed root sections showed black electron dense depositions along the cell walls of ZnT4-treated plants (Fig. 5B). The black depositions were not observed in the cell walls (Fig. 5A) of the roots of control group (T0). The roots of CdT4-treated plants show an increase in the number of vacuoles (Fig. 5C) and precipitation along the cell walls, when compared to the cross sections of control roots (Fig. 5A). The increase in number of...
vacuoles is seen in both epidermal and cortex cells of CdT4-treated plants.

The stems of ZnT4-treated plants (Fig. 6B) show thickened cell walls in both xylem and phloem vessels, which were not seen in control group (Fig. 6A) by the end of metal treatment period. The TEM micrographs of the sulfide fixed stems of ZnT4-treated plants show electron dense depositions along the cell walls of xylem and phloem vessels (Fig. 6C). These depositions, intensively stained with uranyl acetate and lead citrate, were seen deposited along the phloem vessels (Fig. 6D). All the plant sections were treated with H₂S to precipitate their respective metal contents.

4. Discussion

Our study shows that Zn treatments at higher concentrations results in a linear increase in metal accumulation in roots followed by stems, lower leaves and upper leaves. Since Zn acts as a growth promoting micronutrient at lower concentrations, the ZnT1- and ZnT2-treated groups show no significant changes in dry weight, RWC, and increase in plant height compared to the control (T0) group, suggesting that mustard has a high tolerance and uptake ability for Zn. Kumar et al. (1995) suggested that 100 mg l⁻¹ of Zn concentration was not phytotoxic to B. juncea when added to a soil mixture. However, at higher concentrations (ZnT3 and ZnT4), the plants show significant changes in physiological and morphological characters, such as reduction in RWC, dry weight and plant height (Table 1).

Apart from these physiological and morphological changes, Zn accumulation also results in structural changes in leaves, stems and roots. Structural changes in leaves include shrinkage of epidermal, palisade and spongy parenchyma cells and a decrease in starch content and RWC. The Zn accumulation in stems of ZnT4-treated plants were seen as depositions in light micrographs and as electron dense depositions along the walls of vascular bundles in TEM micrographs. Similar electron dense depositions were also observed all along the cell walls in TEM micrographs of their roots.
Fig. 5. TEM micrographs of transverse section of roots of ZnT4 (B), CdT4 (C) treated plants along with control-T0 (A) sampled on the last day of metal treatment. Electron dense depositions are seen along the walls of root cells in ZnT4 (B) treated plants compared to control (A). The roots of CdT4 (C) treated plants and depositions showed vacuoles and depositions along the cell walls.

Several studies verified these precipitations and depositions as compounds of Zn or large organic molecules such as proteins and carbohydrates complexes with Zn.

Most of these studies did not correlate the metal accumulation or structural changes to physiological and morphological changes. In our study, we found that at higher Zn concentrations (ZnT3 and ZnT4) an excess deposition of Zn resulted in decreased translocation or uptake of metals and water from roots and stems to leaves. This is confirmed by the significant decrease in RWC (Table 1) and by the high negative correlation of RWC with Zn accumulation in the stems ($r = -0.94^{**}$) and roots of Zn-treated plants ($r = -0.91^{***}$).

In the case of Cd-treated plants at higher concentrations, metal accumulation was higher in roots followed by lower leaves, stems and upper leaves. No significant changes in RWC, dry weight, and plant height at lower concentrations for Cd-treatment groups (CdT1, CdT2 and CdT3) suggest the applied levels of Cd were within the tolerance limit. This is consistent with mustard being a Cd accumulator (Kumar et al., 1995; Salt et al., 1995). However, due to significant metal accumulation in the CdT4-treated plants, the cross sections of roots showed precipitation and an increase in the number of vacuoles in TEM micrographs of roots (Fig. 5) and as black depositions in light micrographs of stems (Fig. 3). The Cd accumulation also results in a decrease in dry weight and plant height in CdT4-treated plants, confirming again that Cd affects the growth of plants at higher concentrations. This is in accordance with the studies of Haag-Kerwer et al. (1999) that Cd accumulation resulted in a decrease in growth rate and reduction in transpiration of mustard plants.

Mustard plants can accumulate significant amounts of Zn and Cd without showing phytotoxicity or reduction in plant growth when the environmental metal concentrations are relatively low. However, higher Zn and Cd concentrations will result in structural changes in roots, stems and leaves and altered physiological and morphological characters. Our study presented here documented some of the physiological implications of structural alterations caused by Zn and Cd due to metal uptake, translocation and accumulation. We believe that our results on the localization patterns and their effect on plant structural, morphological and physiological characteris-
tics will contribute to understand and optimize the processes of phyto remediation of Zn and Cd by mustard plants.

Acknowledgements

We acknowledge Mr. Dharmendra K. Singh, Mr. Cheng Wang, Mr. Shyam S. Balasubramaniam, and Mr. Thomas W. Hallmark, for their contributions to data collection and plant culture activities. The authors thank Ms. Yunju Xia, Mr. Dean Patterson, and Dr. Thomas Meaker of DIAL for their help in chemical analysis. We also thank Mr. Richard F. Kulinski, Mr. William A. Monroe, Ms. Kay N. Milam for expert assistance in microscopy; Ms. Amanda M. Lawrence for help in sample processing, providing Micromtome and other accessories; and Dr. Gary W. Lawrence for providing the knife holder. This work was supported by funding from U.S. Department of Energy through Cooperative Agreement DE-FC26-98FT-40395.

References


Fig. 6. SEM micrographs of transverse section of stems of ZnT4-treated plants (B) showed thickened cell walls compared to control-T0 (A). TEM micrographs of ZnT4-treated plants showed electron dense depositions along the walls of vascular bundles (C) in transverse section of stem and along phloem vessels (D) in longitudinal section of the stem. The plants were sampled on the last day of metal treatment.
I. Under saturated conditions. Water Air Soil Pollut. 95, 399–423.


