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Mercury transportation in soil via using gypsum from flue gas desulfurization unit in coal-fired power plant

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Abstract

The mercury flux in soils was investigated, which were amended by gyspums from flue gas desulphurization (FGD) units of coal-fired power plants. Studies have been carried out in confined greenhouses using FGD gypsum treated soils. Major research focus is uptakes of mercury by plants, and emission of mercury into the atmosphere under varying application rates of FGD gypsum, simulating rainfall irrigations, soils, and plants types. Higher FGD gypsum application rates generally led to higher mercury concentrations in the soils, the increased mercury emissions into the atmosphere, and the increased mercury contents in plants (especially in roots and leaves). Soil properties and plant species can play important roles in mercury transports. Some plants, such as tall fescue, were able to prevent mercury from atmospheric emission and infiltration in the soil. Mercury concentration in the stem of plants was found to be increased and then leveled off upon increasing FGD gypsum application. However, mercury in roots and leaves was generally increased upon increasing FGD gypsum application rates. Some mercury was likely absorbed by leaves of plants from emitted mercury in the atmosphere.

Key words: flue gas desulphurization; gyspums; soils; mercury emissions; mercury uptakes; mercury infiltration; greenhouse tests

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Introduction

Coal is a major fossil fuel which is burned for heat and power generation. Approximately 45% of the U.S. electrical supply in 2010 was generated from coal combustion. Coal combustion leads to many environmental pollutant issues, such as acid rains, emissions of toxic heavy metals, and CO₂ as greenhouse gases. In 1990, the U.S. Clean Air Act enacted regulations on sulfur dioxide emissions (SO₂) from coal combustion, which forced coal-fired power plants to install flue gas desulphurization (FGD) scrubbers in order to lower sulfur emissions. In a wet scrubber, crushed lime or limestone in water is used as the reagent to capture SO₂ and generate calcium sulfite (CaSO₃·0.5H₂O). This unstable by-product is further oxidized by oxygen and stabilized as calcium sulfate (CaSO₄·2H₂O), which refers to FGD gypsum. Its initial beneficial utilization was for wall board manufacturing and raw materials for cement production. With the increasing installation of FGD facilities and increased usage of high sulfur coal, a large amount of FGD gyspums was produced. According to a report of the American Coal Ash Association, approximately 33 million metric tons of FGD gypsum was produced in 2007. Currently, FGD gypsum has been over-supplied for wall board and cement manufacturing, leading to increased pressure for alternative usage of gypsum from coal-fired power plants. A promising large scale user of FGD gypsum is in agriculture land application. This attractive practice has been extended to direct soil amendment. Previous field studies indicated that FGD gypsum may improve soil quality by altering the chemical and physical characteristics of soil, such as decreases in acidity and increases of availabilities of phosphorus and nitrogen (Clark et al., 1999, 2001; Chen, 2010). Thus, increases in plant yields was expected by the application of FGD gypsum into soil (Wolkowski, 2010)

However, concerns about the release of hazardous elements, especially mercury in gypsum from coal-fired power plants, have inhibited this direct beneficial usage in soils. Mercury in FGD gypsum amended soil may evaporate into the atmosphere, infiltrate into underground water, and be absorbed by plants. The objective of this study is to investigate the mercury transport from FGD gypsum treated soil.

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1 Materials and methods

1.1 Materials

Two types of soil samples were used in these experiments. One soil was collected from Heritage farm in local Bowling Green, KY, which is rich in clay and thus higher pH. The other soil sample was purchased from Supermarket (WalMart, commercial brand: Earthgro), which is rich in organic matters. The Earthgro soil is in lower pH and sour. Because of more mercury bonding to organic matters, thus higher mercury content was found in Earthgro soil. Mercury content of the local soil sample was 20–25 μg/kg, while that of the organic Earthgro soil sample was averaged at 32 μg/kg. The FGD gypsum sample was from a regional coal-fired power plant in Kentucky, and its mercury concentration was approximately 300 μg/kg. Type II de-ionized water (15 MΩ) was used for irrigating the plants, and its mercury concentration was below the detection limit. Three plant species were selected in this study, including tall fescue, cherry radish and Lamium amplexicaule. Tall fescue is the most common grass in Kentucky. L. amplexicaule is a widely-grown natural grass. Seeds of tall fescue and L. amplexicaule were on the top of the plants, whereas that of the cherry radish was under the soil.

1.2 Setup of the greenhouse system

The greenhouse system was made of the acrylic plastic board approximately 6 mm thick. The system has three chambers, each with a sectional area of 30.5 cm² and 76 cm tall. The configuration of this greenhouse system is shown in Fig. 1. Drainage valves were in the bottom of each chamber. Two holes on the top of greenhouse were used for samplings of air, into and out of the chamber, respectively. Permeable plastic material was placed in the bottom of each chamber to hold the soil in place, and also allow for drainage of moisture. In this study, after consulting with agriculture experts, we decided to apply for different solar radiation and time periods for different plants in the tall fescue study (study 1) and cherry radish and L. amplexicaule study (study 2), which are beneficial for plant growths. Two sunlight systems (Sunlight Supply Inc., USA, SS-7 MH 400 and SS-7 HPS 600) were located on the top of each greenhouse for providing the simulating solar radiations. The irrigation system was installed at the top of each greenhouse chamber. There were two similar greenhouses used in this study with totally six chambers.

1.3 Sample collection, handling and preservation

Soils were sampled by a self-made probe, with which different layers of soil samples along depth could be separated. The soil samples belonging to the same layer and the same chamber were mixed prior to analysis. Samples were air dried at 40°C for 72 hr in order to reduce moisture content and then crushed prior to analysis. Plants (tall fescue, cherry radish and L. amplexicaule) were taken out gently from the soils in order to prevent breakage in the root system. Plants were then washed with de-ionized water and air-dried at 40°C for 72 hr. Plant samples were further segregated into different parts including leaves, stems and roots for crushing and analysis. The infiltration waters were collected at the bottom of the greenhouse system and stored in 125 mL polypropylene screw bottles. The mercury from the air in the greenhouse system was collected using activated carbon traps at the end of each experimental period, which was generally 33 days.

1.4 Analytical methods

It has been revised as follows: plants, soil, infiltration water and plants were analyzed using the LECO AMA 254 (LECO Corporation, USA) and the Leeman Hydra C (Leledyne Leeman Labs, USA). Activated carbon traps were analyzed by the Ohio Lumex (OhioLumex Co., USA). These instruments were operated by the cold-vapor atomic absorbance spectrometry techniques, which are based on EPA Method 7473. Because mercury concentration of the samples was normally at the parts per billion level (μg/kg), check standards were routinely performed every 10 samples loaded to analytical instrument to ensure accuracy of data.

Fig. 1 Schematic description of greenhouse chamber.
Standard reference material, NIST 2682b (National Institute of Standards and Technology, USA), was used as a check standard, whose mercury concentration is 108 ng/g. When samples of soil, plants and water in low mercury contents were analyzed, smaller mass of NIST 2682b was used (0.2 g). When samples of soils in higher mercury contents were analyzed, larger mass of NIST 2682b was used (0.8 g).

### 1.5 Greenhouse studies

Three series of laboratory studies were carried out in the greenhouses, including (1) the mercury transport in tall fescue grew in the soil with varying amounts of FGD gypsum; (2) the mercury transport in cherry radish and _L. amplexicaule_ grew in the soil with varying amounts of FGD gypsum; (3) the mercury transport in the soil with varying different rainfall. Studies were carried out in duplicate.

The objective of the tall fescue study was to determine the effect of varying amounts of FGD gypsum on mercury transport. Initially 15 kg of Pembroke soil (25 µg/kg Hg) was added into the bottom of each greenhouse chamber, this was followed-up by the addition of 1 kg of well-mixed top soil, varying amounts of FGD gypsum (300 µg/kg Hg), 0.1 kg chicken waste (17 µg/kg Hg), and 5 g tall fescue seeds (65 µg/kg Hg). The three levels of applied gypsum were 0 kg (Chamber 1), 0.5 kg (Chamber 2), and 1 kg (Chamber 3). The chicken waste was used as a source for plant nutrients. Around 3 L of water was added to moisten the dry soil for preparation of the crop growth. Solar radiation was 5 hours per day. Soil samples were collected at the beginning and end of the study (initial soil and final soil). For a given chamber, the soil was sampled in triplicate. Each soil sample was segregated into four parts (based on depth). The segregated samples were labeled as Layer 1 (top), Layer 2, Layer 3, and Layer 4 (bottom). Tall fescue samples and infiltration water samples were collected at the end of the study.

Studies of cherry radish and _L. amplexicaule_ were conducted to understand the effect of plant species on mercury uptake, as a comparison to tall fescue. Initially 10 kg of dry soil (21 µg/kg Hg) was added to each chamber, followed by the addition of 350 mL of deionized water. Application amounts of FGD gypsum were administered more at 6 levels (level 1: control 0 kg; level 2: 0.01 kg; level 3: 0.05 kg; level 4: 0.1 kg; level 5: 0.5 kg; and level 6: 1 kg). After collecting the initial soil samples, ten seeds were planted in each row, approximately 2 cm deep. Solar radiation was increased to 12 hr each day for this test. Chambers were watered on an “as needed” basis, with a total amount of 2300 mL of de-ionized water per chamber. Investigation of mercury emissions into the atmosphere was added. Activated carbon traps (EPA Appendix K, 30B) were used for this purpose. Figure 2 shows the experimental setup for measuring the emission of mercury into the atmosphere.
2 Results and discussion

2.1 Tall fescue study

The results of the mercury concentration in varying depths of soil are listed in Table 2. Because FGD gypsum was applied only to the surface of the soil in each greenhouse chamber, the mercury concentration in the topsoil (Layer 1) was found to be higher than the soils of increasing depth (Layer 2 to Layer 4). The sum of the top two layers decreased 15% in the 0.5 kg rate and 19% in the 1.0 kg rate, respectively. There was negligible change in the bottom two layers over the 6 week trial. The structure of soils may impact mercury mobility and penetration inside soils. In this study, all soil samples were compacted, and thus, likely inhibited applied FGD gypsum and mercury penetrating further down to Layer 3 and Layer 4 soils. The lack of mobility for the mercury appears independent on the application amounts of gypsums. It means plants can keep mercury in the topsoil. This is agreeable to conclusion of Millhollen (2006) on mercury accumulation in plant roots. The decrease of mercury in the top two layers of soil may be attributed to plant uptake of the mercury in the tall fescue and/or mercury emissions into atmosphere.

Table 2 gives the yields of harvested tall fescue and the corresponding mercury concentrations. The yield of tall fescue without gypsum averaged 168 g for each chamber. The application of 0.5 kg gypsum decreased the yield of tall fescue by 9%, which averaged 153 g. Increasing the application of gypsum to 1 kg decreased the yield 42% to 98 g. By comparison, the mercury uptake of tall fescue at different gypsum applications, shows that at a critical level the root system of the tall fescue appears poisoned by the concentration of mercury (likely other elements in applied gypsum). This phenomenon is demonstrated by the lower yield and decreased concentration of mercury within the tall fescue at the 1.0 kg rate, as compared to the 0.5 kg. This study indicated that FGD gypsum applied at significant levels may inhibit the growth of tall fescue, and mercury (likely other elements in gypsum) may be preferentially uptaken by tall fescue but finally impacted by slow growth. FGD gypsum is normally applied to soils at the 5000 pounds/acre rate in some field studies, which would be equivalent to a 0.01 kg FGD gypsum in the greenhouse study. Therefore, the current applied levels of gypsum (0.5–1.0 kg gypsum) should be considered extreme levels, which resulted in a negative effect on the growth of plants, at least for the tall fescue. Mercury concentration in infiltration water is listed in Table 3. Only minimal mercury was found in the infiltration water, which was in good agreement to the mercury concentrations in bottom two levels of soils. Table 3 shows the overall recovery of the average total mercury for each chamber.

2.2 Cherry radish and L. amplexicaule study

Figure 4 shows the mercury concentrations in soils at different depths before and after FGD gypsum application at varying levels for the case of cherry radish and L. amplexicaule, similar to the case of tall fescue, the applications of FGD gypsum appeared to stay in the upper levels of the soil.

In the case of cherry radish, mercury emissions into the
atmosphere were included in the study. Table 4 shows the mercury emissions to atmosphere using the carbon trap method for an experimental period of 33 days. The mercury data of trap Section 1 indicates the majority of mercury emitted into the atmosphere. Section 2 checks a breakthrough portion to validate the measurement system. In all tests, low mercury mass was observed in Section 2, which demonstrates the validity of the measurement. Data presented that with increasing applications of FGD gypsum a corresponding increases in mercury emissions into the atmosphere were measured. One possible explanation for the increased mercury emissions may be attributed to the vaporization of irrigated water, which is supported by the following moisture study. Mercury in FGD gypsum was likely in ionic forms (Cheng, 2009) and increases of dissolved mercury species were expected when gypsum was increasingly applied. Utilizing water evaporation as a mode of transportation, mercury was released from the soils.

It has been reported that different plant species have different mercury uptake capabilities (Chen, 1964; Molina et al., 2006). This study further investigated the mercury uptakes or distributions in different parts of plants. Table 5 presents mercury concentrations in roots, leaves and stems for two selected plants including L. amplexicaule and cherry radish. The overall mercury concentration within the plants increased with corresponding increases of applied FGD gypsum. For L. amplexicaule, mercury concentrations in leaves and roots followed similar trends and increased upon increases in the application of FGD gypsum. The mercury concentration of the stem stopped to increase after the application levels increased to 0.1 kg gypsum, meaning that a saturation level for the mercury uptake of L. amplexicaule was obtained. Logically, the stems should not be able to transport mercury from the roots to the leaves, and thus increased mercury accumulation in leaves. However, this was not agreeable to the fact that the mercury concentrations in the leaves continuously increased with gypsum application levels over 0.1 kg. This may imply that more mercury accumulation may be from the gas atmosphere. Mercury concentrations in the roots of cherry radish increased with increasing applications levels of FGD gypsum, but large fluctuations were found in the leaves and stems of cherry radish. The variation may be attributed to inconsistent sampling procedures in the combination, not individual separation, of leaves and stems for analysis of cherry radish. However, a good mercury balance was still obtained, as shown in Table 6.

2.3 Water irrigation study

In previous single and multiple rainfall experiments (Song and van Heyst, 2005), a single heavy rainfall could lead to an increase in mercury emissions into atmosphere. In multiple rainfall experiments, only the first rain leads to an increase in mercury emissions, whereas the following two rainfalls did not produce the expected additional mercury emissions. Thus, it was concluded that rainfall can contribute to mercury emissions in dry soils, but only to a certain limit. In this study, the effects of soil moisture on mercury emissions were simulated by controlled water irrigation. Table 7 shows results of the mercury emissions under two water irrigation modes. For Mode 1, the mercury concentration in Layer 1 soil was not significantly decreased as expected, and the mercury in Layer 2 soil was also not significantly increased, with the application of a single water irrigation in large amount (3 L of deionized water). It is apparent that large amounts of water did not significantly change mercury retentions in the soil, therefore responding to near zero mercury emissions to the atmosphere or penetration into the soil. For Mode 2, mercury concentrations in the topsoil (Layer 1) decreased by about 15%, but there were no obvious mercury increases in the Layer 2 soils. This result was independent

<table>
<thead>
<tr>
<th>FGD gypsum mass (kg)</th>
<th>Mercury concentration (ppb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before adding FGD gypsum</td>
<td>0</td>
</tr>
<tr>
<td>After adding FGD gypsum</td>
<td>0</td>
</tr>
<tr>
<td>Soil adjacent to root</td>
<td>0</td>
</tr>
</tbody>
</table>

Fig. 4 Mercury concentrations in soil versus applied FGD gypsum mass.
Table 6  Mercury mass balance under applied FGD gypsums (case of cherry radish)

<table>
<thead>
<tr>
<th>Grass (ng)</th>
<th>Soil mixture (ng)</th>
<th>Carbon trap (ng)</th>
<th>Infiltrated water (ng)</th>
<th>Final mercury (ng)</th>
<th>Initial mercury (ng)</th>
<th>Recovery (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>24</td>
<td>207000</td>
<td>19</td>
<td>N.D.</td>
<td>207043</td>
<td>210000</td>
</tr>
<tr>
<td>0.01 kg</td>
<td>138</td>
<td>210000</td>
<td>30</td>
<td>N.D.</td>
<td>210168</td>
<td>213000</td>
</tr>
<tr>
<td>0.05 kg</td>
<td>99</td>
<td>214000</td>
<td>469</td>
<td>N.D.</td>
<td>214568</td>
<td>225000</td>
</tr>
<tr>
<td>0.1 kg</td>
<td>218</td>
<td>235000</td>
<td>709</td>
<td>N.D.</td>
<td>235927</td>
<td>240000</td>
</tr>
<tr>
<td>0.5 kg</td>
<td>69</td>
<td>346500</td>
<td>928</td>
<td>N.D.</td>
<td>347497</td>
<td>360000</td>
</tr>
<tr>
<td>1.0 kg</td>
<td>133</td>
<td>441500</td>
<td>1591</td>
<td>N.D.</td>
<td>443224</td>
<td>510000</td>
</tr>
</tbody>
</table>

N.D.: not detected.

Table 7  Effect of single large rainfall

<table>
<thead>
<tr>
<th>Chamber</th>
<th>Irrigation rate (mL/day)</th>
<th>Initial (µg/kg)</th>
<th>Final (µg/kg)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control Layer 1 (non gypsum)</td>
<td>29 ± 1</td>
<td>27 ± 2</td>
<td>–6.9</td>
<td></td>
</tr>
<tr>
<td>Control Layer 2 (non gypsum)</td>
<td>25 ± 2</td>
<td>27 ± 1</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>0.05 kg FGD gypsum Layer 1</td>
<td>32 ± 0</td>
<td>30 ± 1</td>
<td>–6.3</td>
<td></td>
</tr>
<tr>
<td>0.05 kg FGD gypsum Layer 2</td>
<td>26 ± 1</td>
<td>26 ± 0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>0.1 kg FGD gypsum Layer 1</td>
<td>39 ± 1</td>
<td>32 ± 1</td>
<td>–17.9</td>
<td></td>
</tr>
<tr>
<td>0.1 kg FGD gypsum Layer 2</td>
<td>26 ± 0</td>
<td>26 ± 1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Mode 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water irrigation 1 Layer 1</td>
<td>130</td>
<td>42 ± 1</td>
<td>35 ± 0</td>
<td></td>
</tr>
<tr>
<td>Water irrigation 1 Layer 2</td>
<td>130</td>
<td>33 ± 2</td>
<td>33 ± 1</td>
<td></td>
</tr>
<tr>
<td>Water irrigation 2 Layer 1</td>
<td>260</td>
<td>43 ± 0</td>
<td>34 ± 1</td>
<td></td>
</tr>
<tr>
<td>Water irrigation 2 Layer 2</td>
<td>260</td>
<td>32 ± 0</td>
<td>33 ± 1</td>
<td></td>
</tr>
<tr>
<td>Water irrigation 3 Layer 1</td>
<td>520</td>
<td>42 ± 1</td>
<td>36 ± 1</td>
<td></td>
</tr>
<tr>
<td>Water irrigation 3 Layer 2</td>
<td>520</td>
<td>36 ± 1</td>
<td>34 ± 1</td>
<td></td>
</tr>
</tbody>
</table>

on water irrigation amounts that were increased from 130 to 520 mL/day. Therefore, increasing the water irrigation likely increased mercury emissions into atmosphere, but not mercury penetration into the soil. This was comparable to the single larger water irrigation, that application did not help in the transportation of mercury in topsoils either to the bottom soils or emission into the atmosphere.

3 Conclusions

The greenhouse system was applied for understanding occurrence and transportation of mercury in the gypsum-amended soils. Major conclusions were obtained as followed: The increases of FGD gypsum application amounts, as expected, resulted in the increases of mercury concentrations in the topsoils. Consequently, mercury concentrations in some plants and air emissions increased, but the bottom soils and underground water did not increase. Plants could assist in keeping mercury in the soils and prevent mercury infiltration into the ground water. Air emissions were not only irrigation-dependent, also relative to application rates of FGD gypsum. A water irrigation study indicated that the mercury emissions into atmosphere were only relative to water irrigation with a smaller amount, and then leveled off with continuously increase of irrigation. Mercury intakes by grown plants were dependent on plant species, and distributions of mercury contents in plants were varied. Roots of plants and surrounding soil generally accumulated mercury. Mercury on leaves of plants were not only from mercury intake in plants, but also likely deposited from mercury in the atmosphere.

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References

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