DOCTORAL THESIS

# Soil contamination and plant uptake of metal pollutants released from Cu(In, Ga)$Se_2$ thin film solar panel and remediation using adsorbent derived from mineral waste material

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# Abstract

The $Cu(In,Ga)Se_2$ (CIGS) thin-film solar panels (TFSPs) are widely used in integrated photovoltaic (PV) and solar power systems because of their perfect PV characteristics and ductility. However, the semiconductor layers of these panels contain potentially toxic metals. In this study, the potential environmental pollution arisen by CIGS TFSP treated as construction trash at the end of their useful life was examined. Acid extraction was used to simulate leaching toxicity followed by burying CIGS TFSP material in different soils, namely a synthetic soil, a Mollisol, and an Oxisol, to determine whether metal pollutants might be released into the soil. A vegetable, *Brassica parachinensis* L. H. Bariley ($Veg_{Brassica}$), was selected to grow in these polluted soils to investigate the uptake of metals and their bioaccumulation.

The simulative remediation of contaminated soils was carried out using a remediation module created by the combination of activated carbon and modified mineral waste material (MMWM) in this research. The activated carbon derived from the waste biomass material was produced by an environmental friendly method, and the MMWM was obtained through a thermal dehydroxylation treatment. The physiochemical properties of MMWM, with focusing on mineral phase transformation, were related to the changes in surface morphology due to dehydroxylation occurred during the process of thermal treatment of MMWM samples, and the adsorption performances of metal (lead, Pb) and organic compound (methyl orange, MO) onto this newly modified MMWM were studied. Furthermore, an end-of-life treatment method was designed and proposed for harmless disposal of CIGS TFSP.

Various metals, including Pb, zinc (Zn), nickel (Ni), chromium (Cr), gallium (Ga), copper (Cu), indium (In) and aluminum (Al) were found to be released into the soil and caused contamination when scrapped end-of-life CIGS TFSP were buried, and the rates of metal release changed with the variations of both the amounts of CIGS TFSP material in the soil and the soil properties. The increases in concentrations of heavy metals such as Zn, Cu, Ni, Ga, Pb, In, and Cr were correlated with the amounts of CIGS TFSP material added in soils. The Pollution Index and the Nemerow Contamination Index calculated from our results confirmed that, when buried, the CIGS TFSP material polluted the soil. Plants grew well in the synthetic soil and the Mollisol, but those in the Oxisol showed prominent signs of chlorosis and died after 30 days. The bioaccumulation factor (BF) and concentration of Zn were 3.61 and 296 mg/kg, respectively in $Veg_{Brassica}$ grown in the synthetic soil with 10% (200 g to 2 kg of soil) of added CIGS TFSP, while the BF and concentration of In were 3.80 and 13.72 mg/kg, respectively in $Veg_{Brassica}$ grown in the Mollisol, indicating that bioaccumulation occurred.

The thermally treated MMWM samples showed morphological transformation mainly on surface based on the scanning electron microscopy (SEM) observations, and an increasing trend in BET specific surface area (SSA) from 120 to 500 ℃

followed by a decreasing trend up to 1000 ℃. Thermal modification had successfully improved Pb adsorption capacity up to 515 mg/g, corresponding to MMWM modified at 600 ℃ with an SSA of 6.5 $m^2/g$. The MO adsorption capacity was also improved after thermal treatment of MMWM, which performed the best adsorption of 87.6 mg/g at 400 ℃. The adsorption of Pb and MO were mainly chemisorption and monolayer coverage, as pseudo-second-order model and Langmuir equation displayed good relationships of correlation for Pb and MO adsorption data. It is therefore indicated that the newly designed soil remediation modules could significantly remove metals from the contaminated soils.

In summary, soils can be contaminated by metal pollutants released from CIGS TFSP, and considerable uptake of metals can be observed in plant with different absorption patterns. The technologies used and adsorbents produced in this work reveal their significance in potential application for remediation of contaminated soils.

**Keywords:** Biomass activated carbon, $Cu(In,Ga)Se_2$ (CIGS) thin-film solar panel, End-of-life treatment, Modified mineral waste material (MMWM), Soil remediation

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