

# Upcycling CNT-BASED Spent Catalysts into ML-Integrated Handheld Electrochemical Sensors for Toxic Heavy Metal Detection

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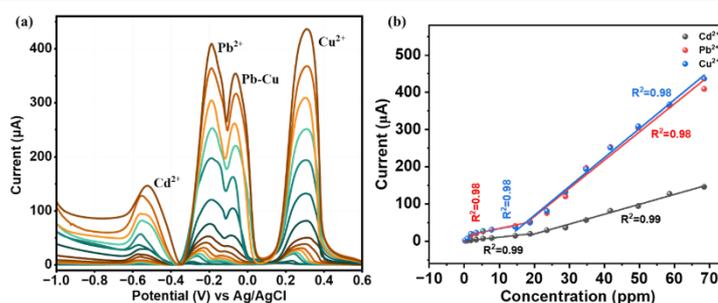
## Abstract

Heavy metal ions (HMIs) such as cadmium ( $\text{Cd}^{2+}$ ), lead ( $\text{Pb}^{2+}$ ), and copper ( $\text{Cu}^{2+}$ ) pose significant environmental and public health risks due to their toxicity, persistence, and bioaccumulative nature. Even trace-level exposure can lead to severe damage to the kidneys, liver, nervous system, and cardiovascular system. Although spectroscopic techniques offer high sensitivity and accuracy for HMI detection, their widespread application is constrained by expensive instrumentation, complex sample preparation, and limited on-site accessibility. In this work, we report a portable electrochemical sensing platform based on square wave anodic stripping voltammetry (SWASV) for the sensitive and selective detection of  $\text{Cd}^{2+}$ ,  $\text{Pb}^{2+}$ , and  $\text{Cu}^{2+}$ . Carbon nanotube-based spent catalyst, recovered from the catalytic decomposition of methane (CDM), was utilized as a sustainable and cost-effective working electrode material. The recovered material exhibited high electrical conductivity and an enhanced electroactive surface area, leading to improved stripping responses. The modified electrode produced distinct, well-resolved stripping peaks with high sensitivities and low limits of detection. Interference and mixed-ion studies further confirmed the selectivity and practical applicability of the sensing platform. To enhance analytical robustness and enable automated interpretation, supervised machine learning algorithms were integrated for peak-feature extraction, metal ion classification, and concentration regression. The classification model demonstrated high predictive accuracy, while regression models achieved coefficients of determination ( $R^2$ ) exceeding 0.95. Overall, the integration of sustainable electrode materials, advanced electrochemical detection, and embedded machine learning into a handheld architecture establishes a reliable and scalable platform for rapid qualitative and quantitative heavy metal ion analysis, offering a promising solution for real-time environmental monitoring and point-of-care applications.

## References

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## Figures



**Figure 1:** (a) The SWASV current response and (b) linear calibration plot in presence of  $\text{Cd}^{2+}$ ,  $\text{Pb}^{2+}$ , and  $\text{Cu}^{2+}$  ions