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Effect of Heavy Metals on Insect Health and Their Detection through Artificial Intelligence

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SUMMARY

As the most prevalent group on the planet, insects play a crucial role in biodiversity and provide vital ecological services. However, various heavy metals such as arsenic, copper, zinc, cadmium, mercury and lead act as environmental pollutants, posing significant threats to insect health. The release of these toxic metals into the environment leads to severe adverse effects on both terrestrial and aquatic organisms. Certain insects, including dragonflies, mayflies, and caddisflies serve as potential bioindicators of heavy metal pollution. In some cases, these toxic metals enter into the food chain, accumulating in insects' bodies and causing harmful effects. Advances in Artificial Intelligence (AI) and the Internet of Things (IoT) have introduced innovative technologies for developing sensors that can also detect and monitor the impact of heavy metals on bioindicator insect health. Therefore, this article aims to evaluate the influence of heavy metals on insect health as well as explore recent advancements in AI, sensors, and IoT for monitoring and detection.

INTRODUCTION

Heavy metals constitute a diverse group of elements with varying chemical compositions and biological roles. The term "heavy metals" typically refers to elements having density greater than 5 g/cm³. Due to their high toxicity, they are widely recognized as hazardous pollutants affecting both humans and bioindicators (Raikwar *et al.*, 2008). Certain heavy metals, such as lead, mercury, and cadmium, act as cumulative poisons, persisting in the environment without breaking down easily. These metals enter the food chain due to their high toxicity level (Singh *et al.*, 2022) and accumulate in insect bodies through ingestion or inhalation, leading to severe adverse effects (Mildvan and Albert 1970). The release of heavy metals into the environment is driven by anthropogenic activities such as metal mining, smelting, and pollution (Singh *et al.*, 2022). Heavy metal contamination affects all aspects of terrestrial ecosystems, posing significant health risks to both humans and insects, including physiological damage such as nervous system impairment, metabolic disturbances, and biochemical imbalances (Skaldina and Sorvari 2019).

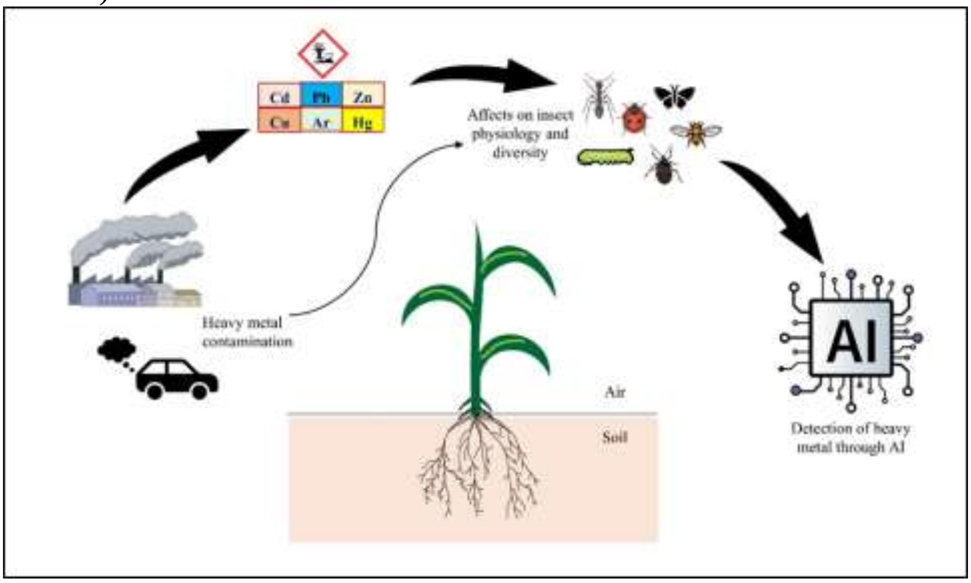

Fig 1: Overview of source of heavy metal and detections

Additionally, pollinators such as bees, ants, wasps, butterflies are also losing their biodiversity. The integration of advanced artificial intelligence technologies, including sensor systems, satellite imaging, and sophisticated AI models, has revolutionized the way we monitor the effects of heavy metals on insect health by providing precise, scalable, and real-time solutions. One such innovation is hyperspectral imaging, which has proven to be an effective tool for detecting subtle morphological changes in insects resulting from heavy metal exposure (Mittal *et al.,* 2020). Devices such as the Specim IQ and Headwall Photonics Hyperspectral Sensors capture detailed spectral data, revealing alterations in colour, surface texture, and structural deformities—early indicators of metal toxicity (Fig 1). Additionally, the development of wearable biosensors and microfluidic devices (lab-on-a-chip systems) has significantly enhanced the ability to monitor key physiological parameters such as enzyme activity, metabolic rates, and body temperature directly from insects in their natural habitat (Bi *et al*., 2021). These portable technologies enable non-invasive, continuous health monitoring while providing real-time data for analysis.

Impact of heavy metals on insect health:

2.1 Physiological damage: The harmful impact of heavy metal stress on insect growth and development suggests that exposure to these metals adversely affects their reproduction, feeding habits, and overall growth (Jiang *et al.*, 2011). Heavy metals interfere with insect physiology by disrupting crucial biological functions. One of the major consequences is oxidative stress, where the accumulation of reactive oxygen species (ROS) leads to cellular and tissue damage (Ramos, 2024). This disruption impairs metabolic activities, affecting energy production and enzyme functionality (Table 1). Moreover, heavy metals cause neurotoxicity, leading to compromised motor functions, altered feeding behaviour, and reduced responsiveness. Hormonal disruptions may also occur, resulting in developmental abnormalities, stunted growth, and decreased reproductive efficiency. Additionally, the immune system is weakened, making insects more prone to infections and environmental stress. Overall, these physiological impairments pose a significant threat to insect populations, ultimately affecting their survival and ecological stability.

2.2 Metabolic disruptions: Energy metabolism and the immune system are crucial for the proper functioning of insects' bodies. However, the accumulation of heavy metals disrupts metabolic pathways, affecting the production of carbohydrates, proteins, and lipids, which are essential energy sources (Du *et al.*, 2019). These macronutrients are vital for various physiological functions, including nerve signalling, growth, phospholipid production, sexual development, and egg laying (Oslon *et al.*, 2000). The insect immune system is essential for defense against environmental stress, but exposure to heavy metals can impair immune responses, increasing vulnerability to external threats (Hogervost *et al* 2007). Additionally, heavy metals can disturb the balance of metabolic hormones, affecting processes like nutrient absorption, detoxification, and homeostasis. For example, disruptions in lipid metabolism can damage cell membrane integrity, affecting cell function and communication. Over time, such metabolic disturbances hinder the insect's ability to adapt to environmental changes, make them more susceptible.

2.3 Neurological damage**:** The deposition of heavy metals in particular tissues, including the nervous system and muscles, affects the metabolism of excitable cells, disrupting their normal functioning (Tylko *et al.*, 2005). Heavy metals significantly affect the insect nervous system, causing serious physiological and behavioural disturbances. These toxic substances disrupt neurotransmission by altering the balance of vital ions such as calcium, sodium, and potassium, which are essential for proper nerve signal transmission. As a result, neurotoxicity develops, leading to impaired motor functions, decreased coordination, and weakened reflexes. Moreover, heavy metals can harm neural tissues, causing cognitive impairments, disorientation, and diminished sensory perception. The disruption of neural pathways also affects feeding behaviour, reducing foraging efficiency and food consumption. Prolonged exposure may lead to paralysis or even death due to severe neural damage. Ultimately, the harmful effects of heavy metals on the nervous system weaken insect populations, compromising their survival and ecological roles.

2.4 Biochemical imbalance**:** Exposure to high levels of heavy metals Enhances the generation of reactive oxygen species (ROS), resulting in oxidative stress that damages DNA structure (EL-Samad *et al.*, 2015) and ultimately results in cell deterioration. Insects subjected to heavy metal contamination often experience disruptions in antioxidant enzyme activity, such as superoxide dismutase (SOD) and catalase (CAT), as their bodies attempt to mitigate oxidative damage. Moreover, heavy metals can interfere with neurotransmitter function, causing nervous system impairments, reduced mobility, and behavioural changes. Metal toxicity also disrupts hormonal balance, moulting, and reproductive processes, ultimately lowering insect survival rates and threatening population stability.

3. Remote sensing base health monitoring system:

At a larger environmental scale **satellite-based remote sensing** provides critical data on the presence and distribution of heavy metals in ecosystems. **Sentinel-2** (operated by the European Space Agency) and **Landsat 8** (by NASA) supply high-resolution multispectral imagery, that enabling the detection of heavy metal contamination in soils, water bodies and vegetation (Ebert *et al.*, 2024). Such environmental pollutants indirectly affect insect populations through bioaccumulation and habitat degradation (Sharma *et al*., 2019). Additionally, **drones equipped with multispectral and hyperspectral cameras**, such as the *DJI Matrice 300 RTK* paired with the *Micasense RedEdge-MX sensor*, allow for localized and high-precision monitoring. These drones can capture environmental data and insect population health in hard-to-reach or hazardous areas by enhancing the granularity of monitoring efforts (Byrne *et al.*, 2018).

3.1 Impact of CNNs in detection of heavy metal on insect health:

The data collected from these technologies is processed using cutting-edge AI models tailored for specific analytical tasks. Convolutional Neural Networks (CNNs) particularly architectures like EfficientNet and ResNet, excel in analyzing hyperspectral images to identify morphological anomalies such as discoloration, deformities and abnormal structural growths in insects (Fig 2). For more complex datasets that involve behavioural or environmental relationships Graph Neural Networks (GNNs) are highly effective (Choi *et al.*, 2021). GNNs can map how insect behaviour (such as movement patterns or population dynamics) changes in response to varying levels of heavy metal contamination in their environment.

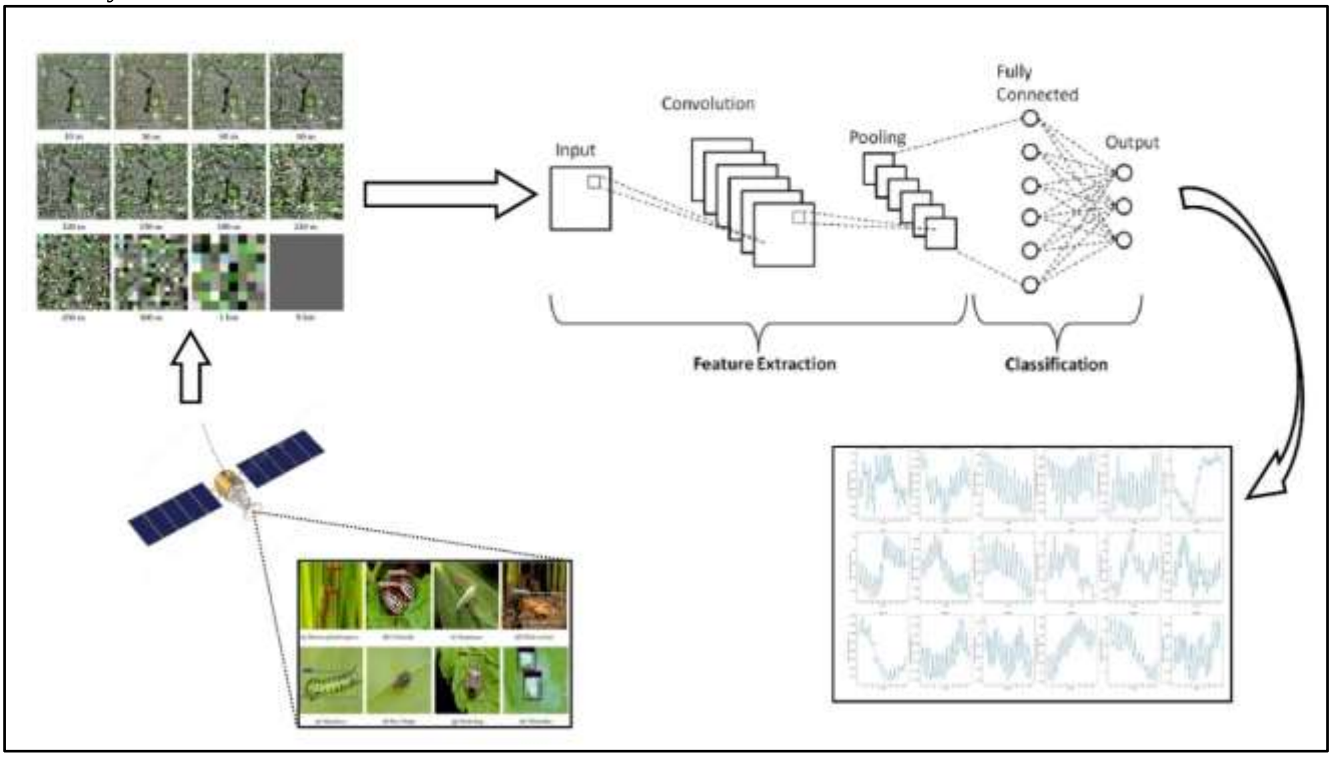

Fig 2: CNN-based heavy metal analysing by hyper spectral image processing for insects

3.2 Vision transformers (ViT):

Advanced AI models enhance the detection of heavy metal impacts on insect health. Vision Transformers (ViTs), initially developed for natural language processing, now outperform traditional CNNs in identifying subtle morphological changes in insect images (Beijbom *et al.*, 2012). Variational Autoencoders (VAEs) specialize in detecting physiological anomalies like irregular enzyme levels or metabolic disruptions, providing probabilistic insights into heavy metal exposure severity (Dogjani *et al*., 2019). To ensure accurate, privacy-preserving analysis across multiple monitoring sites, Federated Learning allows AI models to be trained on decentralized data without sharing sensitive environmental information (Zhang *et al.*, 2019*)*. This approach enhances adaptability, allowing AI-driven systems to assess insect health across diverse ecosystems. These advancements make AI a powerful tool for early detection and mitigation of heavy metal contamination, supporting environmental conservation and agricultural stability.

Table 1: Effect of heavy metals in insect physiology

Heavy metal	Particle size	Type of toxicity	Enzyme activity reduction (%)	Increased oxidative stress (%)	Behavioural changes observed	Reported in insect species
Lead (Pb)	<0.1 µm	Highest	30	50	Effect on respiratory system and reduced movement, feeding	*Tenebrio molitor* (Meyer *et al.*, 2021)
Mercury (Hg)	0.1–10 µm	Moderate	45	65	Neurological dysfunction and loss of coordination	Black soldier fly larvae (Purschke *et al.*, 2017)
Cadmium (Cd)	>10 µm	Lower	35	55	Effect the digestive system and delayed larval development	Yellow mealworm, superworms, grasshoppers, locusts, termites and black soldier fly larvae (Mlček *et al.*, 2017; Lange and Nakamura, 2021)

CONCLUSION:

Heavy metal contamination threatens the insect health, disrupting ecosystems, agriculture, and public health. As vital pollinators and pest regulators, insect declines due to metal toxicity can lead to significant economic and ecological losses. Early detection is crucial to mitigating these effects and ensuring environmental stability. AI-driven technologies, including hyperspectral imaging, biosensors, remote sensing, and advanced AI models, provide real-time, cost-effective solutions for monitoring insect health. These innovations enhance accuracy, reduce operational costs, and enable large-scale environmental assessments. Beyond ecosystem protection, AI-based monitoring also safeguards public health by identifying contamination risks and minimizing human exposure to toxic metals. Additionally, its adoption is driving economic growth and innovation in the environmental technology sector. Ultimately, AI-powered detection of heavy metal effects on insects offers a sustainable approach to preserving biodiversity, agriculture, and public well-being, ensuring proactive environmental conservation.

REFERENCES:

Purschke, B., Scheibelberger, R., Axmann, S., Adler, A., & Jäger, H. (2017). Impact of substrate contamination with mycotoxins, heavy metals and pesticides on the growth performance and composition of black soldier fly larvae (*Hermetia illucens*) for use in the feed and food value chain. *Food Additives & Contaminants: Part A*, 34 (8): 1410–1420.

Meyer, A.M., Meijer, N., Hoek-Van den Hil, E.F. & Van der Fels-Klerx, H.J. (2021). Chemical food safety hazards of insects reared for food and feed. *Journal of Insects as Food and Feed*, 7(5): 823–831.

Mlček, J., Adámek, M., Adámková, A., Borkovcová, M., Bednářová, M. & Skácel, J. (2017). Detection of selected heavy metals and micronutrients in edible insects and their dependency on the feed using XRF spectrometry. Potravinarstvo Slovak Journal of Food Sciences, 11(1): 725–730.

Beijbom, O., Edmunds, P. J., Kline, D. I., Mitchell, B. G., & Kriegman, D. (2012). Automated annotation of coral reef survey images. *2009 IEEE Conference on Computer Vision and Pattern Recognition*, 1170–1177.

Bi, D., Almpanis, A., Noel, A., Deng, Y., & Schober, R. (2021). A Survey of Molecular Communication in Cell Biology: Establishing a new hierarchy for interdisciplinary applications. *IEEE Communications Surveys & Tutorials*, 23(3): 1494–1545.

Byrne, G., Dimitrov, D., Monostori, L., Teti, R., Van Houten, F., & Wertheim, R. (2018). Biologicalisation: Biological transformation in manufacturing. *CIRP Journal of Manufacturing Science and Technology*, 21: 1–32.

Choi, K., Yi, J., Park, C., & Yoon, S. (2021). Deep Learning for Anomaly Detection in Time-Series Data: Review, analysis, and guidelines. *IEEE Access*, *9*, 120043–120065.

Dogjani, A., Haxhirexha, K., Kurihara, H., Mesquita, C., La Greca, A., Zago, M., Gjata, A., Celiku, E., Draçini, X., Dibra, A., Mistuk, S., Hoxha, F. T., Pevec, T., Alimehmeti, R., Xhumari, A., Saygili, B., Seferi, A., Lame, A., Bajrami, I., . . . Hasalla, E. (2019). ACTES 2019 - Abstracts Book; The 3rd Albanian Congress of Trauma and Emergency Surgery. *Albanian Journal of Trauma and Emergency Surgery*, *3*(2.3), 1–124.

Lange, K.W., Nakamura, Y., 2021. Edible insects as future food: chances and challenges. *Journal of Future Foods*, 1 (1): 38–46.

Du, C., Wu, J., Bashir, M. H., Shaukat, M., & Ali, S. (2019). Heavy metals transported through a multi-trophic food chain influence the energy metabolism and immune responses of Cryptolaemus montrouzieri. *Ecotoxicology*, 28: 422-428.

Ebert, D., Weng, B., Wang, C., Bedle, H., Xu, M., Hu, X., Crowell, S., Koch, J., Danala, G., Kayakan, E., Honeycutt, W., Wang, Q., Liu, C., Suriamin, M., Moreno-Ward, A., Hyppolite, B., & Connelly, S. (2024). *Multi-Scale Integrated Monitoring System for Enhancing Methane Emission Detection, Quantification & Prediction*.

EL-Samad, L. M., Mokhamer, E., Osman, W., Ali, A., & Shonouda, M. L. (2015). The ground beetle, Blaps polycresta (Coleoptera: Tenebrionidae) as bioindicator of heavy metals soil pollution. *Journal of Advances in Biology*, 7: 1153-1160.

Hogervorst, P. A., Wäckers, F. L., & Romeis, J. (2007). Effects of honeydew sugar composition on the longevity of *Aphidius ervi*. *Entomologia Experimentalis et Applicata*, 122(3): 223-232.

Jiang, D., Tan, M., Guo, Q., & Yan, S. (2021). Transfer of heavy metal along food chain: a mini-review on insect susceptibility to entomopathogenic microorganisms under heavy metal stress. *Pest Management Science*, 77(3): 1115-1120.

Mildvan, A. S. (1970). 9 Metals in Enzyme Catalsis. In *The enzymes* (Vol. 2, pp. 445-536). Academic Press.

Mittal, D., Kaur, G., Singh, P., Yadav, K., & Ali, S. A. (2020). Nanoparticle-Based Sustainable Agriculture and Food Science: Recent advances and Future Outlook. *Frontiers in Nanotechnology*, *2*.

Olson, D. A. W. N. M., Fadamiro, H., Lundgren, J. N. G., & Heimpel, G. E. (2000). Effects of sugar feeding on carbohydrate and lipid metabolism in a parasitoid wasp. *Physiological Entomology*, 25(1): 17-26.

Raikwar, M. K., Kumar, P., Singh, M., & Singh, A. (2008). Toxic effect of heavy metals in livestock health. *Veterinary world*, 1(1), 28.

Ramos, L. C., Rodríguez-García, A., Castagnini, J. M., Salgado-Ramos, M., Martínez-Culebras, P. V., Barba, F. J., & Pallarés, N. (2024). HPLC-MS/MS and ICP-MS for Evaluation of Mycotoxins and Heavy Metals in Edible Insects and Their Defatted Cakes Resulting from Supercritical Fluid Extraction. *Foods*, 13(20): 3233.

Sharma, A., Kumar, V., Shahzad, B., Tanveer, M., Sidhu, G. P. S., Handa, N., Kohli, S. K., Yadav, P., Bali, A. S., Parihar, R. D., Dar, O. I., Singh, K., Jasrotia, S., Bakshi, P., Ramakrishnan, M., Kumar, S., Bhardwaj, R., & Thukral, A. K. (2019). Worldwide pesticide usage and its impacts on ecosystem. *SN Applied Sciences*, 1(11).

Singh, S., Mahajan, E., & Sohal, S. K. (2022). Effect of heavy metals on insects. In *Appraisal of Metal (loids) in the Ecosystem* (pp. 361-390). Elsevier.

Skaldina, O., & Sorvari, J. (2019). Ecotoxicological effects of heavy metal pollution on economically important terrestrial insects. *Networking of mutagens in environmental toxicology*, 137-144.

Tylko, G., Banach, Z., Borowska, J., Niklińska, M., & Pyza, E. (2005). Elemental changes in the brain, muscle, and gut cells of the housefly, Musca domestica, exposed to heavy metals. *Microscopy Research and Technique*, 66(5): 239-247.

Zhang, C., Patras, P., & Haddadi, H. (2019). Deep learning in mobile and wireless Networking: a survey. *IEEE Communications Surveys & Tutorials*, 21(3): 2224–2287.

Singh, S., Mahajan, E., & Sohal, S. K. (2022). Effect of heavy metals on insects. In Appraisal of Metal (loids) in the Ecosystem (pp. 361-390). Elsevier.