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Exposure characteristics and human health risk of various heavy metal(loid)s in urine of occupational workers for different activities of E-waste recycling

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ABSTRACT

To reach sustainability, e-waste is dismantled and precious materials are extracted for reuse. However, e-waste dismantling poses substantial heavy metal(loid) exposure risks to workers and nearby residents, but process-specific mechanisms and combined risk characteristics remain unclear. We aim to address this gap by studying internal exposure characteristics and human health risk of 14 typical metal(loid)s in urine of e-waste dismantling workers ($n = 173$) from a recycling industrial park and nearby residents ($n = 228$). Principal component analysis, job-specific comparisons, partial correlation analysis, and health risk were integrated to clarify exposure characteristics, influencing factors, risks, and uncertainty. Results showed distinct population-specific distributions: workers had higher levels of Zn (405 μg/L), Cu (15.7 μg/L), Pb (5.85 μg/L), Ni (14.1 μg/L), Sb (0.170 μg/L), Sn (1.68 μg/L), and V (0.550 μg/L), while residents had elevated levels of Cr (2.05 μg/L), Mn (1.76 μg/L), and Co (0.360 μg/L). Sn, Sb, Pb, Co, and Ni were identified as candidate biomarkers tentatively associated with occupational exposure in baking settings. Cr was potentially indicative of exposure to feeding dust, while V and Mn showed preliminary associations with both baking and smelting activities. Employment duration (positive for Ni, Cd, and Pb), smoking status, gender, age, body mass index, and alcohol consumption jointly regulated concentrations of these urinary metal(loid)s. High non-carcinogenic risks were identified for Cu (95.5%), Pb (75.7%), Zn (45.0%), and Ni (25.7%) in workers, with Cu (50.5%) and Pb (35.4%) contributing most to hazard index variance. Monte Carlo simulation integrated with sensitivity analysis confirmed the robustness of the risk assessment outcomes and identified urinary metal(loid) concentration as the predominant driver of HI uncertainty. This study identifies candidate biomarkers tentatively associated with specific dismantling processes and reveals elevated non-carcinogenic risks in workers, providing a preliminary scientific basis for targeted occupational health protection in e-waste recycling.

1. Introduction

Globally, large quantities of valuable materials are discarded as electronic waste (e-waste). E-waste recycling can help to supply them to vulnerable industrial chain. However, substantial and continuous increase in the global e-waste has emerged as a considerable challenge (Baldé et al., 2024), due to massive hazardous substances being released along with recycling precious metals and electronic components (Wang et al., 2024). The public health burden associated with heavy metal exposure constitutes a critical global health challenge, particularly in regions with intensive e-waste recycling activities. Besides various organics (Tang et al., 2023; Yue et al., 2022), substantial hazardous elements including Hg, Pb, Ni, As, and Cd are also released (Fu et al., 2018). These metal(loid)s often persist in various environmental media, posing serious threats to environmental and human health (Adnan et al., 2025; Gangwar et al., 2019), and hindering circular-economy goal of "closing the loop" for critical metals. For instance, Pb affects people's behavior, learning abilities, and cardiac dysfunction; Cu causes liver damage; Ni

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causes allergies and cancer; and long-term exposure to Cd increases risks of lung cancer and kidney damage (Arfaeinia et al., 2022; Chen et al., 2021). Independent regional environmental studies have consistently documented the widespread co-occurrence of heavy metals across diverse natural media—including soil, water, and rainwater—and have rigorously assessed their associated ecological risks and adverse human health outcomes (Hosseinpoor et al., 2024a; Hosseinpoor et al., 2024b; Nemati-Mansour et al., 2025). Therefore, achieving health co-benefits necessitates a transition toward sustainable e-waste valorization pathways that concurrently maximize metal recovery and reduce toxic emissions.

To address this, China has taken various efforts, including ban on importing foreign e-waste and establishment of ecological industrial parks to realize formal e-waste dismantling and centralize waste air and water treatment (Fu et al., 2018; Yang et al., 2023). However, heavy metal(loid) emissions still occur even in formal e-waste dismantling plants (Cai et al., 2025; Wang et al., 2022). The potential sources of these heavy metals are diverse and can be broadly categorized into three primary pathways: (i) intrinsic metals in e-waste (e.g., Pb and Sn in solder, Cd in batteries); (ii) emissions from different recycling operations (e.g., manual dismantling, crushing, and baking); and (iii) secondary contamination from leaching of residual materials (Alabi et al., 2021; Arya et al., 2021; Takyi et al., 2021; Yang et al., 2023). For instance, in a typical standardized dismantling plant, Cr, Mn, Cu, As, Cd, Pb, and Hg (ND–1.91 $\times$ 10^4 mg/kg) are detected in dust with both maximum non-carcinogenic and carcinogenic risk exceeding respective risk thresholds (Cai et al., 2025). Noteworthily, environmental monitoring indicators (e.g., concentrations) cannot accurately represent internal dose in human body, as significant variations of bioavailability, metabolic transformation and elimination exist among individuals (Martinez-Morata et al., 2023). Generally, urine is widely employed as a non-invasive biological matrix for biomonitoring human exposure to metals (Liao et al., 2024), because many metals are naturally excreted through urines (Zeng et al., 2015; Zhang et al., 2019). Urinary metal concentrations reflect recent exposure integrated over hours to days (Zhang et al., 2019). Therefore, this study measured urinary metal(loid) concentrations to assess the impact of e-waste recycling activities on occupational metal exposure among workers and to evaluate the effectiveness of cleaner production retrofits aimed at sustainable e-waste recycling.

Previously, most studies focus on urinary heavy metal characteristics in informal e-waste recycling workers (Dai et al., 2019; Takyi et al., 2021), while only limited studies focus on the formal ones. For example, in three Sweden formal e-waste recycling plants, urinary Cr, Co, Pb, and Hg concentrations in e-waste dismantling workers are significantly higher than those in office workers (Julander et al., 2014). Similarly, in Hong Kong China, urinary Li, Mn, Ni, Cu, Zn, Sr, Tl and Pb in workers are significantly higher than those in office workers (Liao et al., 2024). However, as a population with high-frequency exposure, workers in formal e-waste recycling plants urgently require in-depth research on characteristics of their urinary heavy metal internal exposure, exposure differences across occupational categories, and accurate risks.

Therefore, this study sampled urine from workers of different occupations at a typical formal e-waste recycling industrial park, and aims to: (1) clarify internal exposure characteristics of target urinary heavy metals of workers across different occupational categories; (2) assess non-carcinogenic risks based on internal exposure data; (3) quantify uncertainty of key parameters using Monte Carlo simulation, and accurately predict distribution range and probability density of hazard quotient (HQ). This study can enrich basic database of heavy metal internal exposure of formal e-waste dismantling, and promote green and sustainable development of the e-waste recycling industry.

2. Materials and methods

2.1. Sample collection

Urine (30 mL each) was sampled in the morning from November 2018 to January 2021 from 401 individuals (173 workers in a formal e-waste recycling industrial park and 228 nearby residents South China). Samples were transferred into polypropylene bottles and stored at −20 °C for analysis. Notably, all subjects were informed objectives of the study and signed informed consent. Each participant was requested to fill out a questionnaire, and demographic details and questionnaire responses are summarized in Table S1. The study protocol received ethical approval from the Ethics Committee of Guangdong University of Technology.

2.2. Sample preparation and analysis

Urine samples for heavy metals analysis were processed (Wu et al., 2025). Urine was selected as the unified biological matrix for all target metal(loid)s. Although blood Pb and Cd concentrations better reflect chronic systemic body burden, urine offers practical advantages for large-scale studies (including non-invasive sampling, high participant acceptability, and analytical comparability across all 14 metal (loid)s), and urinary Pb and Cd concentrations validly distinguish occupational from residential exposure levels. Detailed information is provided in Text S1 and chemical materials are presented in Table S2.

Simultaneous analysis of 14 urinary metal(loid)s (Cr, V, Co, Mn, Cu, Zn, Ni, As, Se, Cd, Sn, Sb, Tl, and Pb) was conducted with ICP-MS (iCAP RQ, Thermo Fisher, Germany) (Wu et al., 2025). Matrix drift in ICP-MS is meticulously corrected using internal standards (yttrium, scandium, indium, and bismuth).

2.3. Quality assurance and quality control

To ensure the accuracy and reliability of heavy metal analysis in urine, quality assurance and quality control were performed asdescribed in Text S2. The spiked recovery rates, limits of detection (LOD), limits of quantification (LOQ), and method detection limits (MDL) for all targeted metals are explicitly tabulated in Table S3.

2.4. Health risk assessment and statistical analysis

Health risks associated with heavy metal exposure among workers and nearby residents were evaluated by calculating the estimated daily intake, HQ, and hazard index (HI) (Kuang et al., 2023; Sáez et al., 2021). In this study, the HQ calculation was performed using a deterministic modeling approach with fixed input parameters. HQ $>$ 1 indicates a significant potential risk. HI represents sum of HQ for all elements. HI $>$ 1 indicates an overall potential non-carcinogenic risk. We only assessed HQ of Mn, Co, Ni, Cu, Zn, Se, Sb, and Pb, due to absence of biomonitoring equivalent values and daily intake guidance values for other elements. The detailed procedure is described in Text S3. Urinary excretion factors and health-based reference values of elements used for health risk assessment are listed in Table S4. Furthermore, stochastic model based on Monte Carlo simulation was utilized to analyze uncertainty and characterize the probability distribution of health risk outcomes (details in Text S4). Statistical analysis was further performed as described in Text S5.

3. Results and discussion

3.1. Concentrations and distribution patterns of heavy metal(loid)s in human urine

To clarify the impact of e-waste dismantling activities on human exposure, urinary levels of 14 heavy metal(loid)s were determined in

173 workers and 228 surrounding residents from an e-waste dismantling area. Detection frequency of most heavy metal(loid)s exceeded 93.0% for both populations, except for Sb (89.0%) among workers as well as Sb (82.5%) and Sn (87.3%) among surrounding residents (Table S5). This high detection rate demonstrates that workers and surrounding residents in an e-waste dismantling area are universally exposed to heavy metal(loid)s, reflecting the pervasiveness of exposure scenarios in the region.

Regarding distribution characteristics, significant disparities were noted in urinary heavy metal(loid) concentrations between workers and residents (Fig. 1 and Table S5). Specifically, workers' urinary concentrations of V, Ni, Cu, Zn, Sn, Sb, and Pb were 1.13 to 3.50 times higher than those of residents ($p < 0.01$). Among these elements, the most significant difference was Sn (1.68 μg/L in workers vs. 0.480 μg/L in residents). In workers' urine, the median concentration ranking followed Zn > Cu > Ni > Pb > V > Sb > Sn, with Zn showing the highest median concentration (405 μg/L), followed by Cu (15.7 μg/L), Ni (14.1 μg/L), and Pb (5.85 μg/L). The median concentrations of V and Sb ranged from 0.170 to 0.550 μg/L. In residents' urine, dominated heavy metal(loid)s were Cr, Mn, and Co, with medians of 2.05, 1.76, and 0.360 μg/L respectively. Additionally, no statistically significant differences were found in urinary concentrations of As, Cd, and Tl between two populations ($p > 0.05$). As was 1.21 and 1.15 μg/L in workers and residents; Cd was 1.46 and 1.32 μg/L; and Tl was 0.03 and 0.02 μg/L, respectively.

These disparities in concentration distribution are closely related to pollution emission characteristics of e-waste dismantling activities and population-specific exposure pathways. E-waste, especially printed circuit boards (PCBs) and chip components, is replete with metals including Zn, Cu, Ni, Pb, Sn, Sb, and V. During dismantling, which encompasses high-temperature welding (200 °C–300 °C) and mechanical crushing, these metals can extensively release and present in air with particle sizes < 10 μm or fall on ground as dust (Khanna et al., 2020). Further, they can transport to adjacent area. As reported, dust in PCB dismantling workshops and adjacent streets is rich in heavy metals, with average concentrations of Pb, Cu, Zn, and Ni in workshop dust up to 1.10×10^5, 8.36×10^3, 4.42×10^3, and 1.50×10^3 mg/kg, respectively, corresponding 2.26×10^4, 6.17×10^3, 2.37×10^3, and 304 mg/kg in adjacent street dust (Leung et al., 2008). Occupational workers are exposed to them for 8–10 h daily, and their employment duration exhibits a significant positive correlation with urinary concentrations of Ni, Cd, and Pb ($r = 0.162$–0.214, $p < 0.05$; this study, see Table S6). That is, high pollution of environmental media and the cumulative effect of employment duration collectively contribute to the elevated urinary concentrations of these metals in workers. In contrast, nearby residents showed relatively higher urinary concentrations of Cr, Mn, and Co, suggesting that their exposure may originate from both e-waste and non-e-waste pollution. For instance, regional traffic (Cr in diesel vehicle exhaust particles (Liati et al., 2013)) and agricultural activities (Mn and Co as chemical fertilizer additives (Brennan and Bolland, 2004)) are potential sources (Lee et al., 2026). However, the specific pollution sources of these elements among surrounding residents remain unclear, and correlation analyses between metal concentrations in environmental media (soil, dust, ambient air, and food) and urinary metal concentrations remain insufficient. Further verification is required to improve the explanation of the factors underlying the urinary concentration distribution patterns.

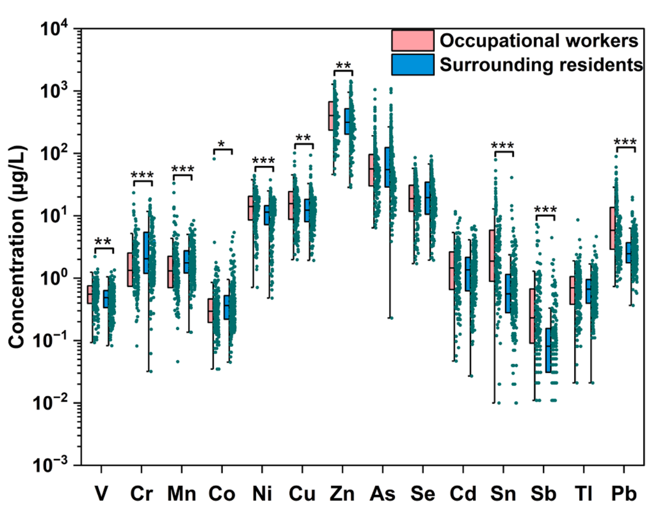

Fig. 1. Concentrations of heavy metal(loid)s in human urine samples from different exposed populations (Mann-Whitney U tests were used; *** $p < 0.001$ (2-tailed); ** $p < 0.01$ (2-tailed); * $p < 0.05$ (2-tailed)).

Overall, distribution of urinary heavy metal(loid) concentrations in populations within e-waste dismantling areas exhibited significant population-specificity. Workers were dominated by Zn, Cu, Ni, Pb, Sn, Sb, and V as the main high-exposure elements, which are closely related to pollution emission from e-waste dismantling activities and cumulative effect of employment duration. In contrast, Cr, Mn, and Co were the predominant elements in nearby residents, potentially influenced by other pollution sources. Additionally, no significant difference in As, Cd, and Tl concentrations was observed between two populations, reflecting balance in exposure pathways or effectiveness of regionally uniform pollution control measures. These distribution characteristics provide a scientific basis for identifying characteristic exposure biomarkers of populations in e-waste dismantling areas and formulating targeted pollution prevention and control strategies.

3.2. Profiling of urinary heavy metal(loid)s in workers for different recycling activities: PCA and job-specific comparisons

E-waste dismantling in this region is primarily focused on processing PCBs and waste e-equipment with manual disassembly, baking, sorting, feeding, and pyrometallurgical smelting. Different dismantling techniques may release unique group of heavy metal(loid)s, which may link unique urinary heavy metal(loid) profiles to specific occupational exposure pathways.

First, unique urinary heavy metal(loid) profiles of workers were investigated by performing PCA on elemental concentrations. PCA extracted five principal components collectively accounting for 67.1% of total variance (Figs. S1 and S2) and provided a framework for source identification. PC1, explaining 19.5% of variance, was characterized by Cu, Zn, As, Se, and Cd. PC2, accounting for 16.8% of variance, was dominated by Sn, Sb, and Pb. PC3 was defined by V and Mn, while PC4 was characterized by Cr and Tl, and PC5 by Co and Ni. This grouping of elements is consistent with various dismantling processes in the region, laying a foundation for subsequent exposure analysis targeting different occupational categories.

Workers were categorized into six groups based on occupational categories: five direct exposure subgroups (manual disassembly, baking, sorting, feeding, and pyrometallurgical smelting) and one indirect exposure group (administrative and production management personnel). Workers in direct exposure subgroups are involved in workflows with direct contact with e-waste, whereas those in the indirect exposure group are primarily exposed to pollutants through contaminated air and dust. Median urinary concentrations of Ni (16.3 μg/L), Sn (1.95 μg/L), Sb (0.200 μg/L), and Pb (7.22 μg/L) in direct exposure workers were 1.18–1.96 times higher than those in indirect ones. Statistically significant differences were obtained for Ni and Pb ($p < 0.01$) (Fig. S3). This finding strongly indicates that exposure to Ni and Pb is associated with PCB dismantling, because approximately 30% of total e-waste is PCBs and approximately 28%–30% of PCBs is metals (Cu: 10%–20%; Pb: 1%–5%; Ni: 1%–3%) (De Souza et al., 2018). Further, high levels of Pb (1.10×10^5 mg/kg) and Ni (1.50×10^3 mg/kg) are detected in surface dust of PCB recycling workshops in this region

(Leung et al., 2008), confirming PCB dismantling as a critical exposure source.

In contrast, median urinary Mn (2.05 μg/L) and As (108 μg/L) concentrations in indirect exposure workers were significantly higher than those in direct ones (Mn: 1.02 μg/L; As: 52.2 μg/L) ($p < 0.01$). Moreover, median urinary Mn concentration in indirect exposure workers was comparable to that of local residents (1.76 μg/L), while urinary As concentration was substantially higher than that of local residents (55.0 μg/L) (Fig. S3 and Table S5). This discrepancy may be attributed to multiple factors, including lack of personal protection among indirect exposure workers, dietary differences, and variations in metabolic capacity across groups. Seafood consumption is also a well-documented source of urinary As (Julander et al., 2014), indicating that this population is concurrently exposed to As from e-waste-related and dietary sources since this area is near the sea. For V, Cr, Co, Cu, Zn, Se, Cd, and Tl, median urinary concentrations in direct exposure workers (0.560, 1.13, 0.290, 14.76, 385, 17.5, 1.59, and 0.680 μg/L, respectively) were comparable to or slightly lower than those in indirect exposure workers (0.550, 1.44, 0.300, 16.7, 443, 21.0, 1.62, and 0.850 μg/L, respectively). This suggests presence of complex exposure mechanisms and potential non-occupational exposure sources among indirect exposure group. Overall, direct occupational exposure does not necessarily lead to higher metal concentrations, highlighting necessity of source apportionment tailored to specific process flows.

Workers engaged in feeding, pyrometallurgical smelting, management, manual disassembly, and baking had the highest median urinary concentrations of Cu (20.5 μg/L), Zn (445 μg/L), As (108 μg/L), Se (21.7 μg/L), and Cd (1.95 μg/L) in PC1 (Fig. 2). This indicates that these elements are comprehensively influenced by multiple occupational processes, which is consistent with the industrial characteristics of the region focusing on PCBs and cathode ray tubes, both of which contain Cu, Zn, As, Cd, and Se as major hazardous components (Fujimori et al., 2012). A statistically significant difference in urinary As concentration was observed only between general managers and feeding workers ($p < 0.01$), and the extremely high As levels in general managers warrant further investigation into unknown exposure pathways. Collectively, Cu, Zn, As, Se, and Cd in PC1 primarily originate from the combined effects of feeding, pyrometallurgical smelting, manual disassembly, and baking processes.

Besides elements in PC1, elements in PC2 and PC5 also showed distinct characteristics related to specific occupational processes. Baking workers exhibited the highest median urinary Sn (9.76 μg/L), Sb (0.730 μg/L), Pb (19.1 μg/L), Co (0.340 μg/L), and Ni (20.5 μg/L) concentrations in PC2 and PC5 (Fig. 2). Baking involves thermal dismantling of PCBs using electric tin melting furnaces (operating temperature > 220 °C) to separate e-components. Sn and Pb are key components of PCB solder (Kumari and Yadav, 2023), while Sb is used as a functional dopant in semiconductor devices and critical flame retardant synergist in circuit boards of e-equipment (Bi et al., 2011). Consistent with this, median concentrations of Sn (9.76 *vs.* 1.70 μg/L), Sb (0.730 *vs.* 0.0910 μg/L), and Pb (19.1 *vs.* 5.77 μg/L) in baking workers were significantly higher than those in manual disassembly workers ($p < 0.05$), which were 2.15 to 7.28 times higher than those in general managers ($p < 0.05$) (Fig. 2). Additionally, urinary Sb concentration in pyrometallurgical smelting workers (0.331 μg/L) was 3.64 times higher than that of manual disassembly workers ($p < 0.05$). It may be attributed to high-temperature volatilization of Sb during smelting, complex chemical reactions, and more difficulty in using personal protective equipment than manual disassembly. Therefore, PC2 (Sn, Sb, Pb) and PC5 (Co, Ni) were closely associated with baking-related activities. These associations suggest that Sn, Sb, Pb, Co, and Ni hold promise as candidate exposure biomarkers for characterizing occupational exposures in this setting.

For urinary V, a key element in PC3, the highest median

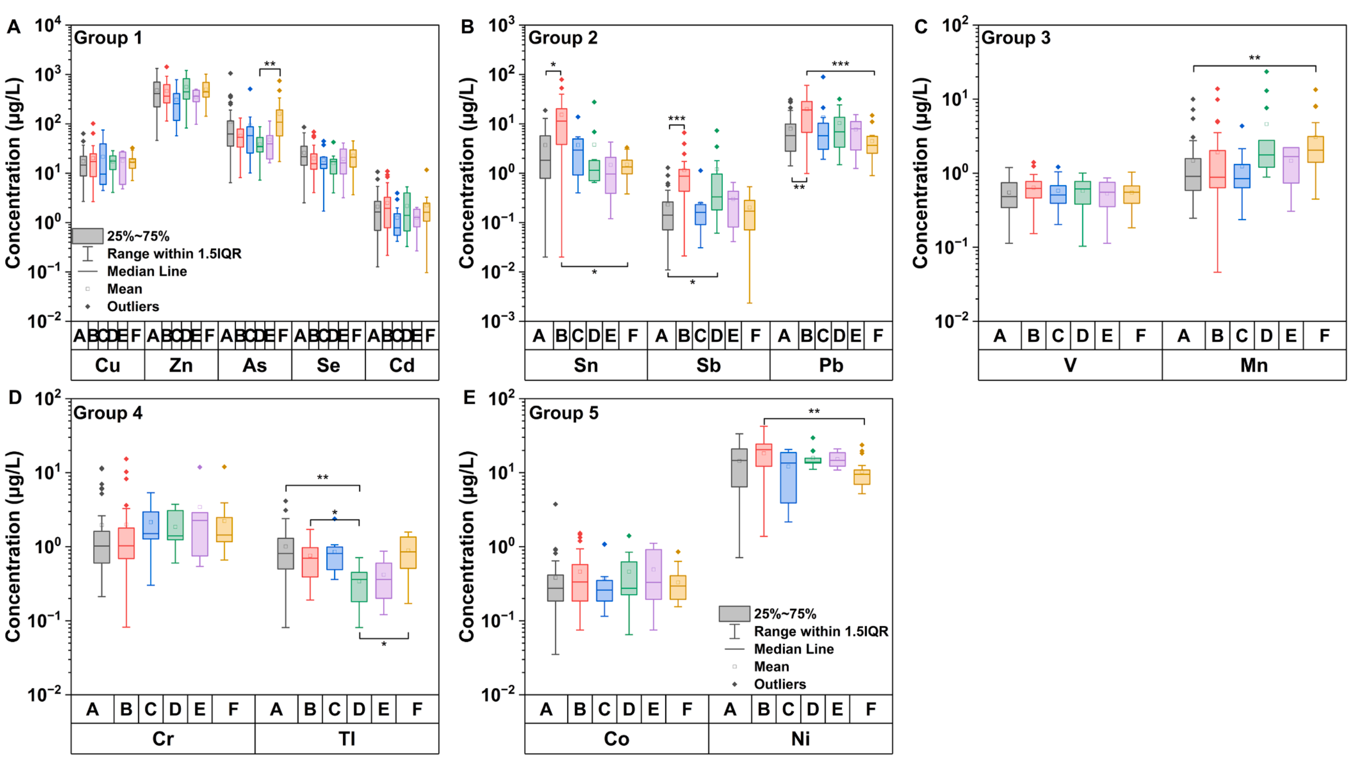

Fig. 2. Urinary concentrations of heavy metals and metalloids in exposed workers from different occupation subgroups with specified sample sizes: A. Manual disassembly (n = 53), B. Baking (n = 39), C. Sorting (n = 12), D. Feeding (n = 13), E. Pyrometallurgical smelting (n = 6), and F. General management personnel (Administrative staff and production management personnel, n = 21). Group 1 included Cu, Zn, As, Se, and Cd, characterized by PC1; Group 2 included Sn, Sb, and Pb, characterized by PC2; Group 3 included V and Mn, characterized by PC3; Group 4 included Cr and Tl, characterized by PC4; Group 5 included Co and Ni, characterized by PC5. (Kruskal-Wallis H tests were used; *** $p < 0.001$ (2-tailed); ** $p < 0.01$ (2-tailed); * $p < 0.05$ (2-tailed)).

concentration was observed in baking (0.623 μg/L) and pyrometallurgical smelting workers (0.613 μg/L) (Fig. 2), indicating widespread occupational exposure sources of V in workshops of this study, despite no statistically significant differences between groups. In contrast, general managers had the highest median urinary Mn concentration (2.05 μg/L), which was 2.29 times higher than that of manual disassembly workers (0.896 μg/L) ($p < 0.05$) (Fig. 2). Urinary Mn levels in pyrometallurgical smelting workers (1.77 μg/L) and feeding workers (1.68 μg/L) were comparable, approximately twice those of manual disassembly, baking, and sorting workers. These results preliminarily indicate that V exposure tends to relate to baking and pyrometallurgical smelting processes. For the indirect exposure crowd, elevated Mn levels may be linked to non-occupational factors such as ambient air pollution, while definite environmental supporting evidence still needs further verification. This preliminarily suggests that V and Mn in PC3 are likely related to board baking and pyrometallurgical smelting activities, and Mn may also stem from non-occupational exposure sources.

Additionally, elements in PC4 presented distinct distribution patterns and sources. Feeding workers had the highest median urinary Cr concentration (2.27 μg/L), which was 2.22 times higher than that of manual disassembly and baking workers (1.02 μg/L), and 1.51 to 1.62 times higher than that of pyrometallurgical smelting (1.40 μg/L) and sorting workers (1.50 μg/L) (Fig. 2). This suggests that Cr (core element of PC4) is primarily associated with feeding. For urinary Tl, another element in PC4, concentration was comparable among manual disassembly workers (0.811 μg/L), sorting workers (0.811 μg/L), and general managers (0.851 μg/L), slightly higher than those in baking workers (0.701 μg/L), and 1.94 to 2.36 times higher than those in pyrometallurgical smelting workers ($p < 0.05$) (Fig. 2). These indicate that Tl originates from multiple sources including manual disassembly, board baking, and sorting. Collectively, Cr in PC4 is primarily from feeding, while Tl is from various processes.

In sum, Cu, Zn, Se, Cd, Sn, Sb, Pb, V, Mn, Cr, Tl, Co, and Ni were primarily from direct occupational exposure during e-waste dismantling. Specifically, Cd, Sn, Sb, Pb, Co, and Ni were linked to baking, and the rest were associated with feeding, pyrometallurgical smelting, sorting, and manual disassembly. Notably, As exposure was related to both e-waste source and dietary factors (e.g., seafood consumption). These findings identify candidate biomarkers tentatively associated with specific occupational exposures (e.g., Sn, Sb, and Pb for board baking process; Cr for feeding process). They offer a scientific basis for formulating targeted occupational health protection and pollution control measures for the field of e-waste dismantling activities.

3.3. Associations between work-related factors and urinary heavy metal (loid) concentrations, and control of confounding factors

Besides occupational exposure associated with e-waste, individual characteristics and habits (e.g. smoking status, alcohol consumption, gender, age, body mass index (BMI), and employment duration) may also affect urinary concentrations of heavy metal(loid)s in workers. For instance, smoking is a major source of Cd, Ni, and Cr (Badea et al., 2018). In this study, significant differences in urinary heavy metal (loid) levels were observed between smokers and non-smokers ($p < 0.05$) (Fig. S4). Specifically, smokers had significantly higher concentrations of urinary Mn (1.50 μg/L), Zn (483 μg/L), Se (21.4 μg/L), and Cd (1.68 μg/L) than non-smokers, with fold changes ranging from 1.30 to 1.59 ($p < 0.05$). Spearman correlation analysis further confirmed significant positive correlations between smoking status and these four elements ($r = 0.157$–0.278, $p < 0.01$) (Table S7). Given this, smokers were excluded from occupational and resident groups in subsequent study. As Fig. S5 demonstrates, significant differences in urinary heavy metal(loid) levels between occupational and resident groups remained evident among non-smokers ($p < 0.05$). Concentrations of urinary V, Ni, Sn, Sb, and Pb in workers were 1.19 to 3.33 times higher than those in residents ($p < 0.01$), strongly supporting e-waste dismantling being the primary driver of elevated urinary heavy metal(loid)s in worker.

After adjustment for smoking status as a confounding variable, partial correlation analysis identified associations between gender, BMI, and urinary heavy metal(loid) concentrations (Table S6): gender was significantly positively correlated with Zn ($r = 0.194$), As ($r = 0.182$), and Se ($r = 0.206$), and significantly negatively correlated with Pb ($r = -0.172$) (all $p < 0.05$). It is because gender is a key determinant of element exposure and metabolism, due to their inherent disparities in lifestyle, dietary habits, and physiological traits. Females are more susceptible to micronutrient deficiencies, which can enhance gastrointestinal absorption of toxic metal(loid)s like As, whereas males typically have superior nutritional status, potentially contributing to higher levels of essential elements including Zn and Se (Berglund et al., 2011). Further, in this study, BMI was significantly negatively correlated with As ($r = -0.206$) and Sn ($r = -0.266$) (both $p < 0.01$). We assume that As and Sn exposure may perturb normal physiological metabolism, thereby potentially affecting weight status of workers. As reported, exposure to some metal(loid)s can induce weight loss in children (Shao et al., 2017).

Furthermore, significant associations of age and employment duration, two factors closely linked to cumulative exposure, with urinary heavy metal(loid) concentrations were observed (Table S6): Age was significantly negatively correlated with Se ($r = -0.209$, $p < 0.01$) and significantly positively correlated with Cd ($r = 0.179$, $p < 0.05$). This is consistent with metabolic accumulation characteristics of Cd, and kidney, as the primary organ for Cd storage, exhibits a progressive increase in Cd content with advancing age (Berglund et al., 2011). Chronic exposure to Cd-containing waste among workers further exacerbates this age-related accumulation. Meanwhile, Se and Cd exhibit antagonistic relationship (Li et al., 2019); as age and internal Cd burden increase, more Se is mobilized to participate in Cd detoxification, resulting in reduced urinary Se excretion. This mechanism can well explain negative correlation between age and urinary Se levels in this study. In addition, employment duration was significantly positively correlated with concentrations of urinary Ni, Cd, and Pb ($r = 0.162$–0.214, all $p < 0.05$), confirming cumulative occupational exposure effect of e-waste dismantling on workers (Wang et al., 2011). Together, these results highlight that physiological aging and prolonged occupational exposure contribute to accumulation of heavy metal(loid)s (e.g., Cd, Pb) in workers.

Alcohol consumption was also significantly associated with urinary Cd ($r = -0.213$, $p < 0.01$) and BMI ($r = 0.24$, $p < 0.01$) (Table S6). This inverse alcohol-Cd association aligns with experimental evidence that ethanol enhances Cd urinary excretion while reducing its accumulation in blood and soft tissues (Brzóska et al., 2013). In a rat model to simulate long-term human exposure, ethanol co-administration increases gastrointestinal Cd retention and urinary output, consequently lowering blood Cd and tissue burdens. The positive alcohol-BMI correlation likely reflects ethanol's inhibition of fat oxidation (Yeomans et al., 2003). While these findings suggest alcohol may modulate Cd body turnover through altered absorption and renal excretion, we acknowledge that causal inference from this cross-sectional observation requires further validation.

These findings clarify effects of work-related factors and various confounding variables on urinary heavy metal(loid) concentrations in workers, and emphasize importance of controlling confounding factors including smoking status and alcohol consumption in exposure assessment. They provide a key basis for understanding characteristics of heavy metal(loid) exposure in this high-risk population and scientific support for developing targeted health intervention strategies (e.g., Se supplementation, lifestyle modifications, and long-term occupational health monitoring).

3.4. Human exposure and health risk assessment

3.4.1. Non-carcinogenic risk

Based on urinary heavy metal(loid) concentrations, health risks associated with heavy metal(loid) exposure for these populations were quantified following the risk assessment framework described in Section 2.4. Biomonitoring equivalents and threshold values adopted for data conversion were sourced from published authoritative studies, and all calculation parameters are summarized in Table S4.

As Fig. 3 presents, for single-element HQ, non-carcinogenic risks of workers were significantly higher than those of surrounding residents, with statistical significance verified by two-tailed Mann-Whitney U test. Specifically, except for Se (HQ < 1 in both groups, no significant difference), HQ of Mn, Co, Ni, Cu, Zn, Sb, and Pb differed significantly between two populations ($p < 0.01$). Proportions of workers with HQ $>$ 1 were as follows: Ni (31.2%), Zn (46.2%), Cu (96.5%), and Pb (75.1%). In contrast, corresponding proportions among residents were substantially lower: Ni (6.58%), Zn (33.8%), Cu (96.9%), and Pb (42.5%). This discrepancy is associated with distinct exposure characteristics of two groups. Workers are chronically exposed to characteristic heavy metal (loid)s in e-waste (e.g., Cu in PCBs, Pb in welding materials, and Ni in alloys) via inhalation, dermal contact, and ingestion. Sustained exposure elevates their body burden, thereby increasing associated health risks. Although residents have no direct occupational exposure, they remain at risk due to pollution of regional environmental media (e.g., dust and vegetables). Notably, high-risk proportion of Cu among residents (96.9%) was comparable to that of workers, potentially attributed to high environmental mobility of Cu (e.g., uptake via atmospheric dust or drinking water). These finding highlights need to address environmental exposure risks in non-occupational populations.

For overall HI, median HI of workers reached 10.1, significantly exceeding the safety threshold of "HI $= 1$" and 1.52 times higher than that of surrounding residents (median HI $= 6.66$) ($p < 0.001$). This indicates that workers face significant non-carcinogenic risks from multi-element accumulation. Meanwhile, although risk for residents was lower, their overall HI still exceeded 1. Therefore, it is necessary to be vigilant against the cumulative effect of combined exposure.

To further understand risk factors, an in-depth analysis of heavy metal contributions to non-carcinogenic risks in exposure populations was conducted (Fig. 3). Cu and Pb were the core contributors to HI of both populations. Median HQ of urinary Cu and Pb of workers were 4.65 and 2.06, respectively, being 1.27- and 2.37-fold higher than those of residents (Cu: 3.65; Pb: 0.87) ($p < 0.01$). In total HI of workers, Cu accounted for 53.0% and Pb for 23.0%, with a combined contribution $>$ 75%. This high contribution of Cu and Pb to the HI is not coincidental. It is directly associated with high release levels of them during e-waste dismantling. It is because Cu and Pb in PCBs account for 20%–30% and 15% of total metal(loid) content, respectively (De Souza et al., 2018), and high concentrations of Cu and Pb are detected in floor dust and air in formal PCB dismantling workshops (Song et al., 2015). Therefore, long-term exposure to the polluted environment generated by such high releases is likely to pose certain health risks.

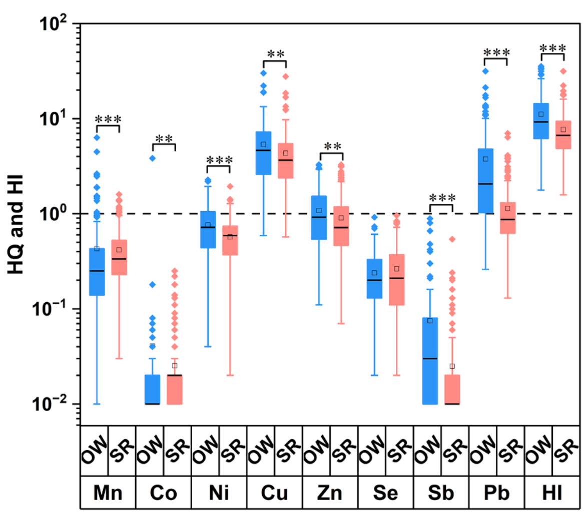

Fig. 3. HQ and HI of heavy metal(loid)s estimated from the concentrations of heavy metal(loid)s in human urine of occupational workers and surrounding residents (Mann–Whitney U tests were used; *** $p < 0.001$ (2-tailed); ** $p < 0.01$ (2-tailed)).

Notably, although surrounding residents have no occupational exposure, proportion of individuals with HQ > 1 for Pb remained high (42.5%). This may be associated with "multi-media exposure" of Pb in environment, and Pb can enter human body through "soil-crop-diet" pathway. Further, both populations exhibited high risks of Cu exposure (workers: 96.5%; residents: 96.9%), primarily related to e-waste recycling activities.

In sum, workers face significantly higher non-carcinogenic risks than residents due to direct occupational exposure and long-term cumulation, with Cu and Pb as the core risk factors. Although residents had no occupational exposure, they still bore non-negligible combined risks affected by environmental media pollution. Considering distinct risk profiles of workers and residents identified here, targeted prevention and control measures are warranted. For workers, priority should be given to strengthening source control of Cu and Pb exposure. Monitoring frequency should be optimized based on years of service; for instance, workers with more than five years of service should undergo quarterly urinary Cu and Pb testing. For residents, emphasis should be placed on preventing and controlling Pb pollution in environmental media including soil remediation and regular cleaning of indoor dust. Dietary guidance should also be provided to reduce consumption of locally grown crops with high Pb content.

3.4.2. *Uncertainty analysis in non-carcinogenic risk*

To quantify the uncertainty of non-carcinogenic risk assessment model, discrepancies between the calculated and simulated results were compared (Fig. 4). Median HQ of various elements derived from Monte Carlo simulations (Mn: 0.240; Co: 0.0100; Ni: 0.730; Cu: 4.21; Zn: 0.920; Se: 0.190; Sb: 0.0100; Pb: 2.05) were generally consistent with the calculated median HQ (Mn: 0.250; Co: 0.0140; Ni: 0.720; Cu: 4.65; Zn: 0.920; Se: 0.200; Sb: 0.0200; Pb: 2.06). This indicates that the uncertainty associated with health risk assessment affects its reliability and stability (Thompson et al., 1992).

Further, Monte Carlo simulations predicted that workers exceeding HQ $= 1$ accounted for 25.7% (Ni), 45.0% (Zn), 95.5% (Cu), and 75.7% (Pb), respectively, suggesting potential non-carcinogenic risks associated with these heavy metals. These risk proportion data were closely aligned with the calculated results, confirming that model bias is minimal. Such consistency further supports robustness of our assessment framework, as small discrepancies between simulated and calculated values suggest that potential errors from parameter assumptions do not significantly alter risk characterization (Kerr et al., 2015).

To identify the most influential parameters driving non-carcinogenic risks and prioritize risk mitigation strategies, sensitivity analysis was conducted using Monte Carlo simulation (Fig. S6). Heavy metal(loid) concentrations were the dominant factor affecting non-carcinogenic risks in occupational setting. Specifically, Cu and Pb concentrations contributed the most to HI variance, accounting for 50.5% and 35.4% of total variance, respectively. Prominent contribution of Cu and Pb concentrations underscores need for targeted control measures (e.g., improved personal protective equipment, process optimization) to reduce exposure to these two elements, which would effectively lower overall non-carcinogenic risk burden for workers.

4. Conclusions

This study systematically investigated heavy metal(loid) exposure characteristics, sources, influencing factors, and health risks of workers and nearby residents in a typical e-waste recycling industrial park. E-waste dismantling significantly elevated workers' urinary heavy metal

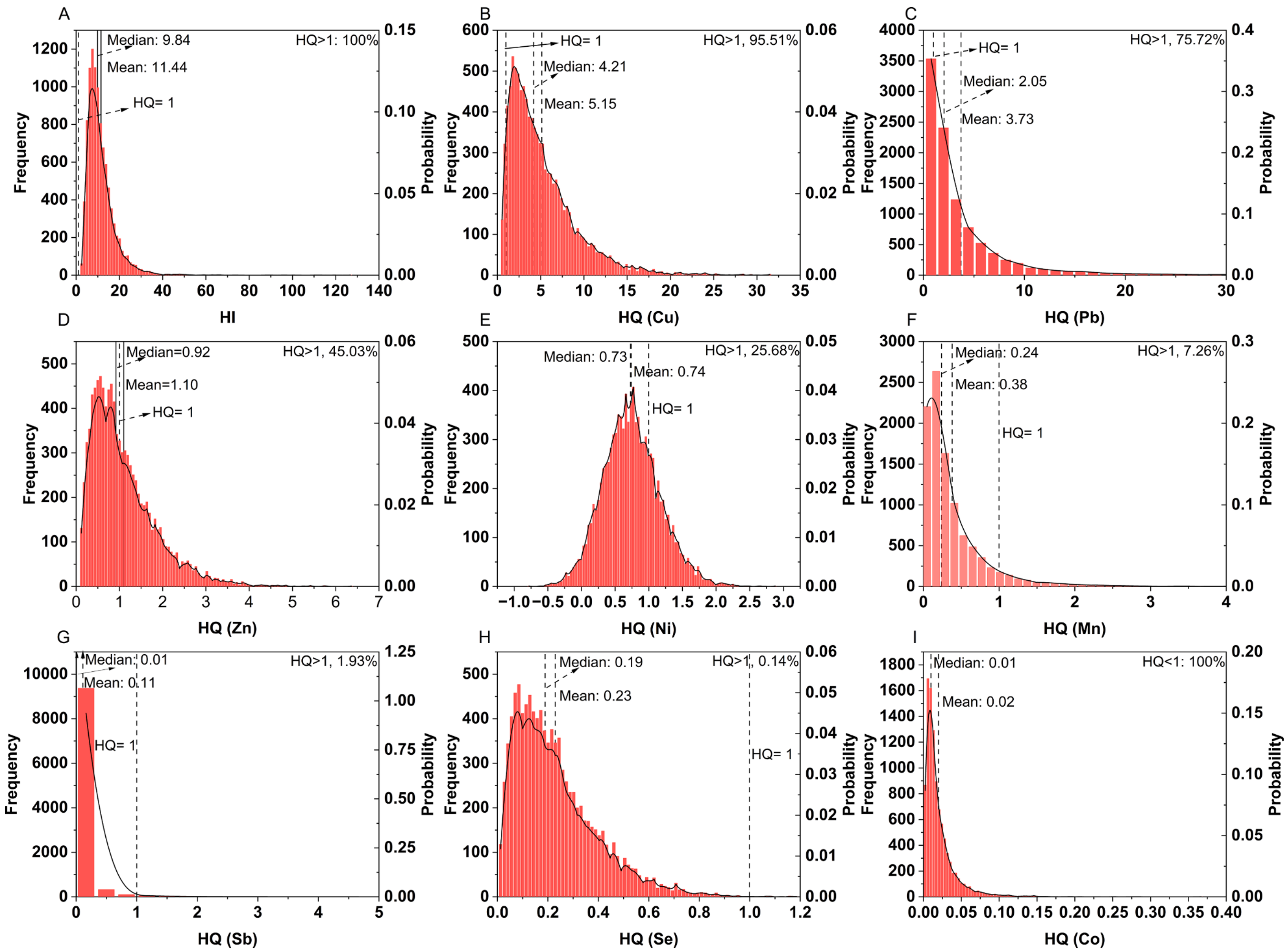

Fig. 4. Monte Carlo simulation results of non-carcinogenic health risks for occupational workers. Panels (A) - (I) represent: (A) hazard index (HI); and hazard quotient (HQ) of (B) Cu, (C) Pb, (D) Zn, (E) Ni, (F) Mn, (G) Sb, (H) Se, and (I) Co.

(loid) concentrations (especially Zn), showing distinct population-specific exposure patterns: workers had higher levels of e-waste-related metals (Zn, Cu, Ni, Pb, Sn, Sb, V), whereas residents exhibited elevated levels of conventionally sourced metals (Cr, Mn, Co). This reflects a combined exposure pattern of "e-waste-specific pollution and conventional source exposure". PCA and job-specific comparisons revealed preliminary associations between elements and occupational activities, informing candidate biomarker identification. Occupational exposure was confirmed as the dominant factor regulating urinary concentrations after adjusting for confounding factors (e.g., employment duration, smoking status, gender, BMI, age, alcohol consumption). Cu, Pb, Zn, and Ni were identified as high-priority contributors to non-carcinogenic risk. This study clarifies the "process-behavior-physiology" exposure regulation mechanism and provides critical scientific support for targeted environmental management and occupational health protection.

Author statement

This work has received approval for research ethics from Guangdong University of Technology and a proof/certificate of approval is available upon request.

CRediT authorship contribution statement

Shixing Ren: Writing – original draft, Visualization, Writing – review & editing, Formal analysis, Methodology, Investigation. **Weixin Weng:** Methodology, Investigation. **Congcong Yue:** Methodology, Investigation. **Yingjun Wu:** Methodology, Investigation. **Jian Tang:** Methodology, Investigation. **Guiying Li:** Writing – review & editing, Supervision. **Taicheng An:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.horiz.2026.100202.

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