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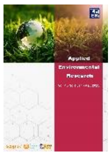

Research Article

Health Risk Assessment of Copper Exposure through Hand-to-Mouth Activities in the Lithium-ion Battery Manufacturing Industry

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Abstract

This study aims to evaluate the occupational exposure levels of copper (Cu) among workers in a battery manufacturing facility by analyzing the Cu concentrations on hand surfaces at three distinct time periods: before work (BW), before lunch (BL), and after work (AW). A total of 30 workers involved in 13 different workstations or tasks—such as battery cell preparation, spot welding, soldering, and labeling—were included in the study to reflect diverse exposure scenarios. Surface wipe sampling was conducted according to NIOSH Method 9102, and the Cu concentrations were quantified via inductively coupled plasma–mass spectrometry (ICP–MS). Additionally, the hazard quotient (HQ) was calculated to assess potential noncarcinogenic health risks. The results indicate a progressive increase in the Cu concentration throughout the workday, with the highest levels observed during the AW period. However, all HQ values remained below 1, suggesting that acute noncancer health risks are negligible. However, the potential for long-term Cu accumulation warrants continuous monitoring. This study highlights the necessity of preventive measures, such as the use of personal protective equipment (PPE), improved ventilation systems, and regular handwashing, to minimize Cu exposure and reduce unintentional ingestion risks in occupational settings.

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Introduction

The increasing global concern over climate change, driven primarily by fossil fuel emissions, has accelerated the adoption of electric vehicles (EVs) as a more sustainable mode of transportation [1–2]. Lithium-ion batteries are central to EV technology; however, their production processes involve the use of several hazardous substances, posing potential risks to both the environment and worker health [3].

A critical component of lithium-ion battery systems is the battery management system (BMS), which ensures battery safety and performance by monitoring and controlling the voltage, current, temperature, and state of charge (SOC) [4]. The assembly of the BMS, particularly the preparation of BMS cables, heavily relies on copper (Cu) because of its superior electrical conductivity. As a result, copper is extensively handled by workers, especially during cable preparation, soldering, and testing tasks.

This study focuses specifically on Cu exposure, not only because copper is among the most frequently encountered metals in the BMS assembly process but also because of its known toxicological properties, long environmental half-life [5], and potential to bioaccumulate. Although other metals are also present in the production line, Cu was selected as the primary focus because of its high frequency of direct contact by workers, making it a highly relevant target for occupational risk assessment in this industrial setting.

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In occupational environments, Cu exposure can occur through several pathways, including hand-to-mouth ingestion of surface residues, inhalation of airborne Cu dust, and dermal absorption. In this study, Cu is most commonly encountered in the form of fine particulate matter and surface dust, particularly in workers' hands. This physical form of exposure is critical, as hand-to-mouth activities represent a significant and often underestimated route for unintentional ingestion.

Chronic exposure to high levels of Cu can result in a range of adverse health effects, including liver and kidney damage, neurotoxicity, and hemolytic anemia due to red blood cell destruction [6–9]. These health effects underscore the importance of targeted monitoring and comprehensive risk assessments to protect worker health.

While several studies have evaluated Cu exposure in the mining, metallurgy, and e-waste recycling industries, limited research has been conducted on Cu exposure risks specific to lithium-ion battery manufacturing [10–11]. Moreover, few studies have quantitatively assessed exposure at the task level in relation to specific work activities, such as BMS cable preparation or spot welding. Research has shown that workers in industrial settings are at risk of exposure to various hazardous chemicals, such as Cu. These substances are commonly used in manufacturing environments and pose significant health threats if proper safety protocols are not followed. These findings underscore the importance of cultivating a strong safety culture within workplaces to effectively prevent occupational hazards and mitigate long-term health risks [12].

The novelty of this study lies in its task-specific approach to evaluating Cu exposure and risk in a modern lithium-ion battery production environment. This study measures residual Cu levels in workers' hands and applies the hazard quotient (HQ) method [13–15] to assess noncarcinogenic health risks through unintentional ingestion. The findings can be used to inform targeted preventive strategies such as PPE use, hygiene practices, and workplace design to reduce health risks and improve occupational safety standards in this growing industry.

Materials and methods

1) Population and sampling area

The inclusion criteria stipulated that participants must be employed in either the lithium battery manufacturing area (exposure group, n = 26) or the document management office (control group, n = 4) not exposed to Cu-related tasks. Among these, 20 were male, and 10 were female. The selection focused on workers who were actively engaged in specific job tasks within the production process. The production workflow at this facility is subdivided into multiple task-specific operations, such as cell sorting, spot welding, cable preparation, and quality control, reflecting distinct stages in the battery manufacturing line. Each task was analyzed individually to assess differences in Cu contamination across job types. Additionally, employees were required to be available for sample collection during the specified time periods. The inclusion criteria required participants to be full-time employees working in production or quality control areas directly involved in the lithium battery manufacturing process, aged between 18 and 60 years, free from serious skin diseases or open wounds on their hands during the sampling period, and able to voluntarily provide informed consent and participate in hand sampling at designated time points (before work (BW), before lunch (BL), and after work (AW)). The exclusion criteria included employees who were on leave, sick leave, or long-term absence during the sampling period and those who declined or were unable to provide informed consent. Ethical approval for this study was granted by the Human Research Ethics Committee, Suranaree University of Technology (EC-66-90), and all participants signed informed consent forms prior to participation.

The study population comprised 26 employees working at a lithium battery production facility in Samut Sakhon Province, Thailand. Surface wipe samples were collected following the NIOSH Manual of Analytical Methods (NMAM), Method 9102 [16]. Sampling was conducted at three fixed time points during each working day: BW (08:00), BL (12:00), and AW (17:00) [17]. These samples were collected once per week over a three-week period. The selected sampling days corresponded to the highest production workload of the week, as determined from daily operational logs provided by plant management [18].

To assess unintentional Cu ingestion, the study was based on the assumption that workers may inadvertently transfer surface copper residues into their mouths via behaviors such as eating, drinking, touching the face, or smoking. While inhalation and dermal exposure are plausible pathways in industrial settings, this study focused exclusively on the ingestion route because field observations indicated that hand–mouth contact was the primary mechanism of Cu accumulation, and resource constraints limited the scope of multiroute assessment. The use of gloves was optional for workers, and under actual working conditions, workers did not wear gloves while performing their tasks.

This study investigates surface-level Cu contamination as an indicator of occupational exposure. The production process involved 13 defined job tasks, as outlined in Table 1.

Statistical analysis was performed to compare Cu levels across time points via repeated-measures ANOVA, with significance set at $p < 0.05$. The control group was included to establish a baseline level of Cu contamination unrelated to direct occupational exposure, allowing a clearer comparison with production-area workers.

Table 1 Detailed description of activities, abbreviations, and number of workers

Activity (Full name)	Abbreviation	Work Description	Number of people
Lithium-ion battery cell sorting – Charge and discharge testing	BSBC	Inspect and measure the internal resistance of each lithium-ion cell to screen for quality and prevent risks such as overheating or short circuits.	2
Battery management system (BMS) cable preparation	BMSC	Prepare signal cables for connection to the BMS system, which is responsible for battery control, safety, and performance optimization.	2
Quality control of BMS cable	QC BMSC	Inspect the BMS cables for accuracy, length, connector quality, continuity, resistance, labeling, and overall cleanliness.	3
Spot-welding	SW	Join the positive and negative terminals of cells using nickel strips to form battery modules in parallel and/or series.	3
Battery terminal soldering	BTS	Solder the connections between signal cables or terminals and battery poles using high-quality solder (e.g., Sn63/Pb37).	3
Preparation of fiberglass for battery assembly	PF	Cut and prepare fiberglass sheets used as insulation and structural support in battery packs to prevent short circuits.	2
Battery assembly with fiberglass and circuit integration	AF	Assemble battery units with fiberglass insulation and integrate BMS or protective circuits to ensure safety and durability.	2
Battery pack assembly	BP	Arrange and connect tested cells into structured battery packs, including wiring, BMS, and protective elements.	2
Adhesive bonding	AB	Use industrial adhesives to reinforce the structure of small battery modules, preventing shifting, vibration, or mechanical shock.	2
Quality control in battery assembly	QCBA	Final inspection of battery pack assembly to ensure completeness, safety, and conformity with quality standards.	1
Labeling	LP	Affix labels containing essential battery information to support traceability, maintenance, and safety compliance.	2
2Battery sealing	BS	Seal battery packs to protect against dust, moisture, and mechanical damage, enhancing structural strength.	2
Document management	DM	Organize and maintain production-related documents for traceability, quality assurance, and internal/external audits.	4

2) Sample collection

Hand sampling was conducted using gauze pads moistened with distilled water. Samples were collected from workers' hands (ventral surfaces) of the thumb, index, and middle fingers, as well as the entire palm of the dominant hand [19] via an S-shaped wiping technique as illustrated in Figure 1. A standardized 'S' wiping pattern was employed, which was repeated three times for each hand area. The collected samples were stored in vials and subsequently analyzed according to NIOSH 9102. Heavy metal concentrations were expressed as milligrams of heavy metal per square centimeter (mg cm^{-2}) of skin surface [20]. All the samples were preserved in clean polyethylene containers and stored at ambient room temperature. According to the NMAM, Method 9102, Cu residues on wipe samples are considered stable and do not require refrigeration [16].

Figure 1 Illustration of hand wipe sampling using wash hand wipes for heavy metal analysis.

3) Sample digestion and heavy metal analysis

Analytical-grade reagents, including perchloric acid (70%, Merck, Germany) and nitric acid (65%, Merck, Germany), were used throughout the study. The samples and blanks were digested in a mixture of 20 mL concentrated nitric acid and 1 mL concentrated perchloric acid in 50 mL beakers covered with a watch glass. After a 30-minute equilibration at room temperature, the samples were subjected to an 8-hour heating period at 150 °C. Subsequent heating at 120 °C, with the addition of additional nitric acid as needed, facilitated complete digestion to near dryness (~0.5 mL). The residue was dissolved in 0.5 mL of dilute acid, transferred to a 10 mL volumetric flask, and diluted to volume with deionized water [20].

Heavy metal concentrations were analyzed via inductively coupled plasma–mass spectrometry (Agilent 7500CE Series ICP-MS G3272A). The detection limit of the ICP–MS analysis was 0.001–0.1 ppb. A pneumatic nebulizer introduced approximately 5 mL of sample into the plasma torch, generating temperatures of 6,000–10,000 °C. Within the plasma, sample atoms were ionized and subsequently separated on the basis of their mass–charge ratios via a quadrupole mass spectrometer. Ion detection was accomplished via an electron multiplier or Faraday cup [21–23]. The ion detection data are transmitted to a computer for signal processing and graphical representation of the elemental concentration. The element concentration within the analyzed sample can be accurately quantified by comparing the detected signal to a standard of known concentration. This method enables rapid and precise elemental identification and quantification [24].

4) Health risk assessment of human via ingestion

In this study, the exposure assessment was limited to the ingestion pathway. This decision reflects the specific work practices of the participating employees, whose primary tasks (e.g., BMSC) involve direct manual handling of Cu wires. These tasks do not generate airborne Cu dust or fumes, thereby minimizing inhalation exposure. In contrast, Cu residues on workers' hands can be readily transferred to the mouth while they are eating, drinking, or smoking without proper hand hygiene. Moreover, experimental studies have demonstrated that the dermal uptake of copper through intact human skin is minimal due to its poor permeability, with permeability constants on the order of 10^{-6} cm h^{-1} [25]. Therefore, hand-to-mouth ingestion was considered the most relevant and dominant exposure pathway in this occupational setting, and the risk assessment focused exclusively on ingestion.

The average daily dose (ADD) for noncarcinogenic effects was calculated to estimate the potential daily intake of heavy metals through hand–mouth contact. The ADD (Eq.1) was expressed in milligrams per kilogram of body weight per day (mg·kg·day^{-1}) [26].

$$\mathrm{ADD} = \frac{\mathrm{C_{surface\ residue}} \times \mathrm{CR} \times \mathrm{EV} \times \mathrm{ET} \times \mathrm{EF} \times \mathrm{ED}}{\mathrm{BW} \times \mathrm{AT}} \quad \text{(Eq.1)}$$

$C_{surface\ residue}$ (µg cm^{-2}) refers to the concentration of Cu residues on the workers' hands obtained from surface wipe sampling conducted in this study and is considered our own measurement data. CR (cm^{2} per event) refers to the contact rate, which represents the average hand surface area in contact with Cu residues during a single hand-to-mouth event and is considered our own measurement data. EV (events per hour) refers to the event frequency, which is defined as the number of times the hand contacts the mouth per hour. The default value is 2.9 events per hour [27]. ET (hours per day) refers to the exposure time, representing the average daily working hours, obtained from questionnaire responses of the study participants as their own data. EF (days per year) refers to the exposure frequency, which represents the number of working days per year, obtained from questionnaire responses of the study participants as their own data. ED (years) refers to the exposure duration, representing the number of years workers had been employed in the facility, obtained from questionnaire responses as their own data. BW (kg) refers to the body weight of the workers, obtained from questionnaire responses as their own data. AT (days) refers to the average time, which is calculated as the ED multiplied by 365 days for noncarcinogenic risk assessment, following U.S. EPA guidelines [28]. The reference dose (RfD) value for Cu was determined to be 4.0×10^{-2} mg·kg·day^{-1} [29]. This value was then substituted into Eq.2 to calculate the hazard quotient (HQ), which indicates health risk.

$$\mathrm{HQQ} = \mathrm{ADD_{ingest}} / \mathrm{RfD} \quad \text{(Eq.2)}$$

To assess health risks, HQ was computed for each heavy metal. An HQ value below 1 suggests a negligible noncancer health risk, whereas a value of 1 or above indicates potential adverse health effects [30].

It is not possible to calculate the lifetime cancer risk in this study because Cu is not classified as a carcinogenic substance according to the U.S. Environmental Protection Agency (U.S. EPA). Therefore, cancer risk estimation parameters such as the cancer slope factor (CSF) are not available for Cu, and Cu is not listed in the U.S. EPA's Integrated Risk Information System (IRIS) as a carcinogen [31].

Results and discussion

The study included 30 participants working in lithium-ion battery production, including 10 females and 20 males. The participants' ages ranged from 20-43 years, with a mean age of approximately 28.3 years. Body height ranged from 161 to 181 cm, and body weight ranged from 50 to 89 kg. Work experience varied from 0.08 to 3.52 years, with an average of approximately 1.32 years. Four participants were assigned to document management (DM) tasks. The rest were distributed across various production lines. Both descriptive and inferential statistical methods were applied in this study. Descriptive statistics—including the mean, standard deviation (SD), minimum, and maximum values—were used to summarize and describe the distributions of Cu concentrations and other relevant variables. For inferential analysis, repeated measures analysis of variance (ANOVA) was employed to compare copper concentration levels across three fixed time points: BW, BL, and AW. This method was chosen to evaluate within-subject changes over time. The data were confirmed to follow a normal distribution, which met the assumptions required for the application of repeated-measures ANOVA.

The concentration of Cu in the hands of workers was assessed at three distinct time points throughout the workday: BW, BL, and AW. These measurements aimed to evaluate the extent of copper exposure and potential accumulation on the skin over time. The data are expressed as the mean±SD, along with the corresponding minimum and maximum values, in units of mg·cm^{-2}. A summary of the Cu concentration data is provided in Table 2.

Table 2 Cu concentration data (three time periods)

Time period	Concentration of Cu (mg·cm^{-2}, n=26)
	Mean (Mininum–Maximum)
BW	3.01×10^{-3} (5.56×10^{-4}–1.59×10^{-2})
BL	9.06×10^{-3} (1.90×10^{-3}–4.39×10^{-2})
AW	2.74×10^{-2} (3.25×10^{-3}–1.37×10^{-1})

The skin surfaces of the hands contaminated with Cu across three different time points—BW, BL, and AW—are summarized in Table 2. A progressive increase in the Cu concentration was observed throughout the workday. The mean concentration rose from 3.01×10^{-2} mg·cm^{-2} (BW) to 9.06×10^{-3} mg·cm^{-2} (BL) and peaked at 2.74×10^{-2} mg·cm^{-2} (AW), indicating a cumulative buildup of Cu on workers' hands over time.

The levels of Cu surface contamination in workers' hands were analyzed to compare differences across task areas and sampling time points. These results provide insight into how Cu residues vary depending on work activities and the timing of sample collection, as summarized in Table 3.

The results summarized in Table 3 show a progressive increase in the Cu concentration in workers' hands throughout the day. The concentration of Cu in the BL period was approximately three times greater than that in the BW period, indicating a notable accumulation of Cu during the morning work session. Furthermore, the Cu levels continued to rise during the AW period, reaching values approximately three times greater than those observed in the BL and nearly nine times greater than those in the BW.

All three pairwise comparisons (Table 4)—BW vs. BL, BW vs. AW, and BL vs. AW—show statistically significant differences in copper concentrations on the hand surface ($p < 0.05$). These findings indicate that copper exposure increased progressively throughout the workday.

To rigorously evaluate the variations in the Cu concentration at different time points, pairwise comparisons were conducted via the Bonferroni correction for multiple comparisons. The results, summarized in Table 2, report the mean differences (means±SD), standard errors, 95% confidence intervals, and statistical significance ($p < 0.05$).

BW and BL:

A statistically significant increase in the Cu concentration was observed from BW to BL, with a mean difference of -0.006 mg·cm^{-2} ($p = 0.000$).

The 95% confidence interval (-0.009, -0.002) does not include zero, confirming a meaningful increase in Cu levels before midday.

BW and AW:

The Cu concentration further significantly increased from BW to AW, with a mean difference of -0.022 mg·cm^{-2} ($p = 0.000$).

The confidence interval (-0.034, -0.011) indicates a pronounced accumulation of Cu exposure over the course of the workday.

BL and AW:

The Cu concentration remained significantly greater in the AW period than in the BL period, with a mean difference of -0.017 mg·cm^{-2} ($p = 0.000$). The confidence interval (-0.027, -0.007) suggests a progressive increase in Cu accumulation during the latter half of the day.

Reverse comparisons (AW and BW, AW and BL, and BL and BW): All the reverse comparisons demonstrated positive mean differences, corroborating the increasing trend in the Cu concentration as the workday progressed. The disparity between AW and BW (0.022 mg·cm^{-2}) was the most substantial, followed by the difference between AW and BL (0.017 mg·cm^{-2}).

Table 3 Copper surface contamination levels on workers' hands by task area and time point

Area	Time	Concentration ($mg \cdot cm^{-2}$)			
		Mean	SD	Max	Min
DM	BW	8.505×10^{-4}	3.241×10^{-4}	1.336×10^{-3}	6.744×10^{-4}
	BL	7.298×10^{-4}	1.458×10^{-4}	9.267×10^{-4}	5.933×10^{-4}
	AW	7.351×10^{-4}	1.031×10^{-4}	8.580×10^{-4}	6.057×10^{-4}
BSBC	BW	1.084×10^{-3}	3.005×10^{-4}	1.393×10^{-3}	7.923×10^{-4}
	BL	4.750×10^{-3}	1.131×10^{-3}	5.943×10^{-3}	3.693×10^{-3}
	AW	1.107×10^{-2}	5.171×10^{-3}	1.650×10^{-2}	6.197×10^{-3}
BMSC	BW	5.626×10^{-3}	6.873×10^{-3}	1.579×10^{-2}	1.007×10^{-3}
	BL	2.019×10^{-2}	1.634×10^{-2}	4.375×10^{-2}	6.339×10^{-3}
	AW	7.511×10^{-2}	4.650×10^{-2}	1.369×10^{-1}	2.402×10^{-2}
QC BMSC	BW	3.310×10^{-3}	3.812×10^{-4}	3.686×10^{-3}	2.924×10^{-3}
	BL	4.878×10^{-3}	3.266×10^{-3}	8.602×10^{-3}	2.503×10^{-3}
	AW	7.068×10^{-3}	4.594×10^{-3}	1.212×10^{-2}	3.140×10^{-3}
SW	BW	3.616×10^{-3}	2.791×10^{-3}	7.589×10^{-3}	9.120×10^{-4}
	BL	1.387×10^{-2}	7.798×10^{-3}	2.418×10^{-2}	4.892×10^{-3}
	AW	4.618×10^{-2}	1.667×10^{-2}	6.637×10^{-2}	2.473×10^{-2}
BTS	BW	2.529×10^{-3}	2.053×10^{-3}	6.928×10^{-3}	9.034×10^{-4}
	BL	1.283×10^{-2}	1.361×10^{-2}	4.329×10^{-2}	2.035×10^{-3}
	AW	4.948×10^{-2}	5.442×10^{-2}	1.311×10^{-1}	7.479×10^{-3}
PF	BW	2.265×10^{-3}	1.521×10^{-3}	4.021×10^{-3}	1.343×10^{-3}
	BL	5.977×10^{-3}	6.572×10^{-4}	6.405×10^{-3}	5.220×10^{-3}
	AW	8.498×10^{-3}	4.435×10^{-3}	1.359×10^{-2}	5.471×10^{-3}
AF	BW	2.828×10^{-3}	8.484×10^{-4}	3.585×10^{-3}	1.911×10^{-3}
	BL	6.734×10^{-3}	1.389×10^{-3}	8.266×10^{-3}	5.556×10^{-3}
	AW	1.963×10^{-2}	1.251×10^{-2}	3.046×10^{-2}	5.943×10^{-3}
BP	BW	1.324×10^{-3}	8.201×10^{-4}	2.390×10^{-3}	4.454×10^{-4}
	BL	5.534×10^{-3}	4.389×10^{-3}	1.186×10^{-2}	2.002×10^{-3}
	AW	1.287×10^{-2}	5.414×10^{-3}	1.595×10^{-2}	4.770×10^{-3}
AB	BW	2.431×10^{-3}	9.456×10^{-4}	3.592×10^{-3}	1.360×10^{-3}
	BL	3.379×10^{-3}	1.244×10^{-3}	4.825×10^{-3}	1.786×10^{-3}
	AW	8.917×10^{-3}	4.695×10^{-3}	1.471×10^{-2}	3.762×10^{-3}
QCBA	BW	3.364×10^{-3}	1.326×10^{-3}	4.319×10^{-3}	1.850×10^{-3}
	BL	5.042×10^{-3}	3.967×10^{-3}	9.619×10^{-3}	2.589×10^{-3}
	AW	7.468×10^{-3}	6.738×10^{-3}	1.524×10^{-2}	3.359×10^{-3}
LP	BW	2.536×10^{-3}	4.819×10^{-4}	3.086×10^{-3}	2.189×10^{-3}
	BL	2.759×10^{-3}	4.606×10^{-4}	3.290×0^{-3}	2.457×10^{-3}
	AW	4.549×10^{-3}	5.757×10^{-4}	5.088×10^{-3}	3.943×10^{-3}
BS	BW	3.602×10^{-3}	1.826×10^{-3}	4.919×10^{-3}	1.517×10^{-3}
	BL	7.891×10^{-3}	1.950×10^{-3}	1.008×10^{-2}	6.325×10^{-3}
	AW	7.927×10^{-3}	7.120×10^{-3}	1.612×10^{-2}	3.275×10^{-3}

Table 4 Pairwise comparisons of copper exposure (during three time periods)

Time period	Time period	Mean difference	Std. error	Sig	95% Confidence interval for difference	
					Lower bound	Upper bound
BW	BL	-0.006*	0.001	0.000	-0.009	-0.002
	AW	-0.022*	0.005	0.000	-0.034	-0.011
BL	BW	0.006*	0.001	0.000	0.002	0.009
	AW	-0.017*	0.004	0.000	-0.027	-0.007
AW	BW	0.022*	0.005	0.000	0.011	0.034
	BL	0.017*	0.004	0.000	0.007	0.027

Figure 2 presents the comparative analysis of Cu concentration levels across different tasks at three distinct time periods: BW, BL, and AW. The Cu concentration was measured in mg·cm^{-2}, and the results revealed variations in both task-specific exposure and time-dependent accumulation. The Cu concentration varied significantly among the different tasks, indicating task-dependent exposure. BMSC and BTS exhibited the highest Cu accumulation, particularly in the AW period, suggesting greater exposure levels in these tasks. In contrast, tasks such as BSBC, LP, and AB presented relatively lower Cu concentrations throughout the day, suggesting minimal exposure to these activities. The task-specific differences may be attributed to variations in task duration, material handling, or surface contact frequency.

BW: The lowest Cu concentrations were observed in all the tasks, as expected, due to the absence of prior work-related exposure. BL: The Cu concentration increased significantly compared with that in BW, indicating early-stage accumulation due to work-related exposure. The increase was particularly noticeable in tasks such as the BMSC and BTS. AW: The highest Cu concentrations were recorded across all tasks, with some tasks (e.g., BMSC and BTS) showing markedly higher levels than others. This may be attributed to the nature of the tasks in these production lines, where workers are required to handle copper wires or terminals directly for extended periods without full mechanical separation, leading to increased potential for hand contamination. Additionally, manual processes in these areas likely contribute to increased skin contact with Cu-contaminated surfaces. This pattern suggests progressive accumulation throughout the workday, emphasizing the role of continuous exposure and task-specific Cu deposition.

The DM area, used as a control group, presented extremely low HQ values (10^{-7} range) across all periods, indicating minimal Cu exposure risk. Across all the measured areas, the HQ values remained below 1, indicating that Cu exposure is unlikely to pose significant noncancer health risks under current working conditions. Higher HQ values were recorded for BMSC, SW, BTS, and AF, with the value for BMSC reaching 3.76×10^{-2} in the AW period, suggesting greater Cu exposure in these tasks. Cu exposure increased progressively throughout the day, with AW consistently showing the highest HQ values across all areas. The greatest increase in HQ was observed in BMSC, BTS, and SW, which presented substantial Cu accumulation from BW to AW. Despite the increasing trend, all HQ values remained well below 1, suggesting that short-term exposure remains within safe limits, although long-term effects should still be monitored.

The findings from this study demonstrate a progressive increase in Cu exposure throughout the workday, as evidenced by the increasing Cu concentration levels (Table 3) and hazard quotient (HQ) values (Table 5) from BW to BL and AW. The observed trends suggest that Cu accumulation occurs as workers engage in daily tasks, likely due to repeated contact with Cu-containing materials and workplace surfaces. These results are consistent with previous research highlighting occupational exposure to copper in cable manufacturing environments. A study conducted by Hakim and Moamen [12] investigated health hazards and safety culture among Egyptian cable manufacturing workers. This study revealed significant exposure to chemical hazards, including Cu. Furthermore, the New Jersey Department of Health reported that occupational exposure to Cu can lead to skin irritation, respiratory issues, and other health concerns, reinforcing the need for effective workplace controls to minimize exposure [32].

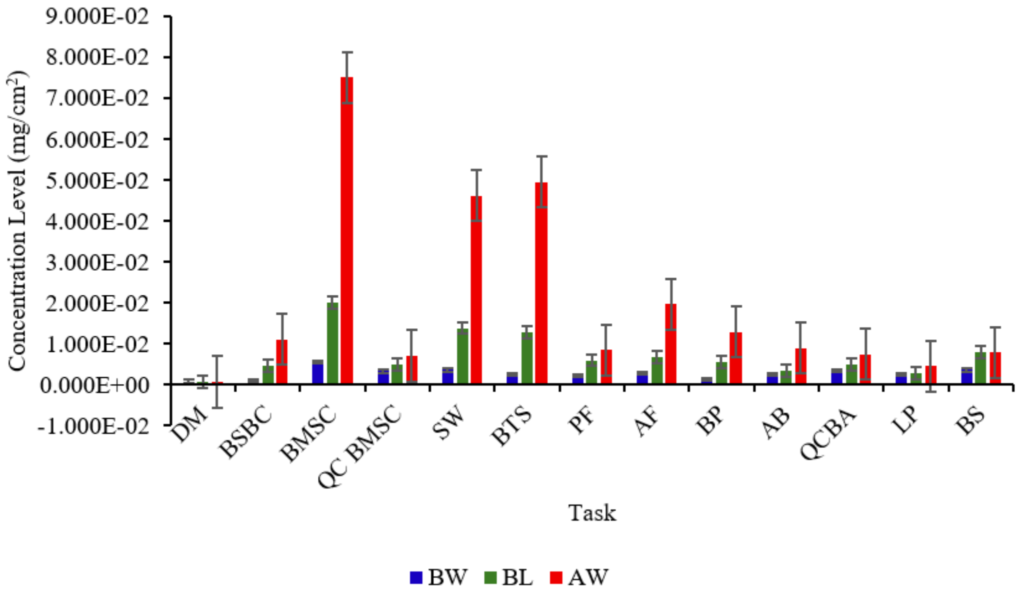

Figure 2 Comparison of concentration levels in different tasks.

Table 5 Health risk assessment of workers exposed to copper from the battery production area

Battery production area	Hazard quotient (HQ)		
	BW	BL	AW
DM*	3.21×10^{-7}	9.32×10^{-7}	7.57×10^{-7}
BSBC	1.13×10^{-4}	4.37×10^{-4}	1.99×10^{-3}
BMSC	2.87×10^{-3}	1.01×10^{-2}	3.76×10^{-2}
QC BMSC	1.97×10^{-3}	2.88×10^{-3}	4.14×10^{-3}
SW	2.12×10^{-3}	7.96×10^{-3}	2.63×10^{-2}
BTS	1.52×10^{-3}	7.46×10^{-3}	2.86×10^{-2}
PF	1.42×10^{-3}	3.63×10^{-3}	5.13×10^{-3}
AF	1.71×10^{-3}	3.98×10^{-3}	1.15×10^{-2}
BP	8.34×10^{-4}	3.27×10^{-3}	7.52×10^{-3}
AB	1.44×10^{-3}	1.97×10^{-3}	5.10×10^{-3}
QCBA	1.67×10^{-3}	2.19×10^{-3}	3.34×10^{-3}
LP	1.42×10^{-3}	1.54×10^{-3}	2.49×10^{-3}
BS	2.07×10^{-3}	4.45×10^{-3}	4.47×10^{-3}

Remark: * Control group

The observed increase in Cu concentrations from BW to AW suggests a cumulative effect of workplace activities throughout the shift. The lowest levels at BW reflect minimal contamination that BW begins, likely representing baseline exposure from environmental residues. The intermediate levels at BL may indicate partial accumulation after morning tasks, despite potential reductions from activities such as eating or limited hand hygiene. The highest concentrations at AW were consistent with prolonged exposure to Cu-containing materials and surfaces during active work. These findings highlight the progressive accumulation of Cu in workers' hands throughout the workday, underscoring the importance of regular handwashing, the use of gloves, and task-specific protective measures.

The findings of this study are in line with previous research indicating occupational exposure to copper. For example, Hakim and Moamen reported that workers in a cable manufacturing factory in Egypt experienced increased Cu exposure due to direct contact with Cu during their work. This finding supports the observations of the present study, where higher Cu concentrations were detected in workers' hands, particularly AW, likely resulting from tasks involving physical contact with Cu-containing materials [12].

BW: The lowest Cu concentrations and HQ values were recorded in all tasks, indicating minimal exposure prior to work activities. BL: A significant increase in the Cu concentration was observed across most tasks, particularly in the BMSC, BTS, and SW, suggesting that Cu exposure intensifies during the morning work session. AW: The highest Cu concentrations and HQ values were recorded in nearly all tasks, with BMSC, SW, and BTS showing the most substantial increases. This suggests prolonged exposure throughout the workday, reinforcing the need for effective workplace safety measures.

The analysis of Cu concentrations and HQ values across different tasks and time periods revealed a progressive increase in Cu exposure throughout the workday. Notably, tasks such as BMSC, BTS, and SW presented the highest Cu concentrations and HQ values, suggesting that workers engaged in these activities are at greater risk of Cu exposure, likely due to the direct handling of Cu materials and prolonged environmental exposure.

Tasks with lower Cu exposure, such as those in the BSBC area, typically involve automated processes and indirect handling of materials. Workers in these areas often operate machines that test or sort batteries, with minimal physical contact with Cu-containing components. The automation reduces direct surface contact and, consequently, lowers the risk of dermal contamination.

In contrast, higher-exposure tasks such as BMSC involve manual operations such as cutting, stripping, or assembling Cu wires and connectors. These processes require frequent direct handling of copper materials and tools, often without continuous glove use, leading to a greater likelihood of Cu residue accumulating on the skin.

These findings align with previous research highlighting the health risks associated with Cu exposure through ingestion and dermal contact. For example, a study documented a case of acute Cu sulfate poisoning resulting from dermal absorption, where a worker developed severe systemic toxicity after skin exposure to a hot Cu sulfate solution. This underscores the potential for significant copper absorption through the skin in occupational settings [29]. Furthermore, chronic exposure to elevated Cu levels, particularly through ingestion, has been linked to liver damage and other systemic effects. While our study indicates that all HQ values remained below 1, suggesting no immediate noncancer health risk, the cumulative increase in Cu exposure observed necessitates ongoing monitoring and implementation of effective workplace safety measures. This finding is consistent with a study by Hakim and Moamen, which reported that workers in a cable manufacturing plant were at increased risk of Cu exposure because of the direct handling of Cu materials. These occupational environments highlight the need for continuous assessment of exposure pathways and appropriate control measures [8,12].

Although no immediate health risks were suggested (HQ < 1 in all cases), it is important to note that an HQ value below 1 indicates exposure within acceptable limits but does not entirely eliminate the possibility of health effects, particularly with repeated or prolonged contact. This interpretation aligns with Kamunda et al. [34], who applied the HQ method to assess heavy metal exposure in industrial environments and emphasized that HQ < 1 may still carry chronic health concerns when exposure is consistent and occurs through ingestion of contaminated dust or dermal contact. Although Cu cancer risk was excluded from this assessment because of a lack of established reference values, evidence from recent studies suggests that chronic occupational exposure to Cu may have serious long-term health consequences. In vivo research has demonstrated that sustained Cu exposure in mice leads to motor dysfunction and dopaminergic neuronal loss, which are hallmark features of Parkinson's disease pathology [35]. Moreover, reviews indicate that both excess copper and Cu deficiency can induce oxidative stress, protein aggregation, and neuroinflammatory processes, which are implicated in neurodegenerative and psychiatric disorders [36]. These findings underscore the necessity for continued surveillance of Cu exposure and implementation of preventive occupational controls, even when acute HQs remain below threshold levels. These findings support the need for continued biological monitoring and the implementation of targeted safety controls in high-risk work areas. According to the hierarchy of controls, preventive strategies should begin with efforts to eliminate or substitute Cu-containing materials where feasible. Engineering controls, such as improved ventilation systems and enclosed workspaces, should be prioritized to reduce airborne Cu exposure. Administrative measures, including hygiene protocols such as regular handwashing, workplace cleaning, and task rotation, can help minimize surface contamination and reduce cumulative exposure. The PPE including nitrile gloves, is recommended for Cu wire handling tasks, as it provides an effective barrier to prevent direct dermal contact with Cu residues. Although the main tasks did not generate airborne Cu dust, the use of N95 respirators may be considered an additional precaution for respiratory protection. This measure helps safeguard workers from incidental particle exposure from surrounding processes and should be considered a last line of defense, particularly in high-exposure areas such as the BMSC, BTS, and SW. However, field observations revealed that workers in actual practice often do not wear PPE, such as gloves, during routine operations, further increasing the likelihood of direct dermal exposure. Further studies should combine biological monitoring of Cu levels in workers with longitudinal exposure assessments and health outcome evaluations to assess potential long-term health risks comprehensively. Investigating seasonal variations, environmental factors, and workplace material composition may provide deeper insights into Cu exposure dynamics. A more detailed risk assessment using real-time exposure monitoring would help refine workplace safety guidelines.

Conclusions

This study provides evidence that Cu exposure increases progressively over workdays, with task-dependent variations influencing exposure levels. While all HQ values were less than 1, indicating that the risk falls within an acceptable range, this does not imply a complete absence of health risks—especially with prolonged or repeated exposure. The findings highlight the importance of implementing workplace safety interventions to mitigate potential long-term risks. However, the study has certain limitations, including its focus solely on ingestion as the exposure route and a relatively small sample size, which may affect the generalizability of the findings. Continued monitoring and a multifaceted approach to prevention are essential to ensure occupational health and safety in Cu-exposed environments. This study enhances the understanding of surface-level Cu exposure patterns in lithium battery manufacturing and offers practical insights that can inform targeted occupational safety measures.

Recommended preventive measures include prioritizing engineering controls (e.g., ventilation systems, enclosed workspaces), enforcing hygiene practices (e.g., regular handwashing, task rotation), and providing PPE (e.g., gloves, respirators) in high-exposure areas such as BMSC, BTS, and SW.

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