Journal of Health, Wellness and Community Research
ISSN: 3007, 0570

OPEN ACCESS

JHWCR

Type: Original Article
Published: 27 August 2025
Volume: III, **Issue**: XI
DOI: https://doi.org/10.61919/mwpg5352

Correspondence
✉ Saima Ashraf, saima.ashraf@uskt.edu.pk

Received 20, 07, 25 **Accepted** 16, 08, 2025

Authors' Contributions
Concept: HE; Design: SA; Data Collection: ASH, MA; Analysis: MS; Drafting: ASH, HE; Critical Review: SA; Final Approval: All authors

Declarations
No funding was received for this study. The authors declare no conflict of interest. The study received ethical approval. All participants provided informed consent.

"Click to Cite"

Estimation of Chromium in Blood, Hair, and Nail of Workers of Leather Industry in Sialkot

Hanna Ehsan[1], Saima Ashraf[1], Muhammad Awais[1], Asad Shabbir[1], Manahal sughra[1], Abida Shehzadi[1]

1 Department of Zoology, University of Sialkot, Sialkot, Pakistan

ABSTRACT

Background: *Chromium is extensively used in the leather tanning industry, where occupational exposure is recognized as a major health hazard. Chronic absorption of chromium compounds, particularly hexavalent chromium, has been linked to respiratory disease, skin disorders, nephrotoxicity, hepatotoxicity, and carcinogenesis. Biological monitoring using blood, hair, and nail samples provides valuable insights into cumulative chromium exposure and its potential health effects.* ***Objective:*** *This study aimed to estimate chromium concentrations in blood, hair, and nail samples of leather industry workers in Sialkot, Pakistan, and compare them with non-exposed controls to assess occupational health risks.* ***Methods:*** *A cross-sectional study was conducted involving 40 tannery workers and 40 university students as controls. Biological samples were collected following standardized procedures, digested with nitric and hydrogen peroxide acids, and analyzed using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES). Demographic and health data were obtained through structured questionnaires. Statistical analyses included descriptive statistics and independent sample t-tests, with significance set at $p \leq 0.05$.* ***Results:*** *Chromium levels in workers were significantly elevated in blood (0.5833±0.515 µg/dl), hair (0.7472±1.377 µg/g), and nails (0.5972±1.373 µg/g) compared to controls (0.3600±0.230 µg/dl, 0.2018±0.113 µg/g, and 0.1618±0.121 µg/g, respectively; $p<0.05$). Workers reported higher rates of asthma, hypertension, skin allergies, and joint pain, correlating with chromium accumulation.* ***Conclusion:*** *The findings confirm that occupational exposure in the leather industry contributes to excessive chromium accumulation, posing significant risks to worker health. Routine biomonitoring and stringent protective measures are imperative to mitigate chromium-related morbidity.*

Keywords
Chromium, Leather industry, Occupational exposure, Biomonitoring, Blood, Hair, Nails, Sialkot.

INTRODUCTION

Heavy metals are recognized as persistent environmental pollutants with no known biological role, yet they pose substantial risks to human health and ecological systems due to their bioaccumulation and toxicity (1). They enter the environment through natural processes such as weathering of the earth's crust, mining, and industrial effluents, but industrial and urban discharges have become the primary contributors to heavy metal contamination in modern societies (2). Among these, chromium holds a critical place because of its widespread industrial application and high toxicological potential. Exposure to chromium and other metals such as cadmium, nickel, and lead has been linked with oxidative stress, DNA damage, and disruptions in protein and lipid metabolism, thereby threatening cellular homeostasis and increasing the risk of mutagenesis and chronic diseases (3,4).

Leather tanning has been identified as one of the industries with the most severe environmental consequences globally, contributing large volumes of effluents laden with hazardous metals, dyes, and chemicals (5). Chromium, particularly in its trivalent (Cr III) and hexavalent (Cr VI) forms, is integral to the tanning process where it is used to stabilize leather fibers and enhance durability (6). However, its unregulated discharge leads to extensive contamination of water, soil, and air, with occupational exposure among tannery workers becoming a pressing public health concern (7). Cr (VI) compounds are of particular concern due to their strong oxidative potential, ability to permeate cell membranes, and carcinogenic properties, which have been associated with respiratory illness, dermatitis, hypertension, chromosomal abnormalities, and increased cancer risk (8,9). In contrast, while Cr (III) is an essential trace element at low levels, excessive occupational exposure also disturbs iron metabolism and immune regulation (5).

Occupational exposure pathways for tannery workers include inhalation of dust containing chromium, dermal absorption, and ingestion of contaminated food or water (11). Elevated chromium levels have been consistently detected in the blood, hair, and nails of exposed individuals, reflecting both short- and long-term accumulation (12,13). Blood chromium is regarded as a sensitive biomarker for acute and ongoing exposure, while hair and nails offer advantages in representing chronic exposure due to their slow growth rate and ability to incorporate metals into keratin matrices (6, 7). Prior studies have shown that hair samples of tannery workers exhibit significantly higher chromium concentrations compared to controls, often correlating with age, duration of exposure, and health complaints such as jaundice, skin infections, and respiratory disorders (16). Similarly, nail samples, due to their slower turnover, provide unique insights into cumulative chromium burden and have been highlighted as reliable matrices for occupational monitoring (7, 8).

Research conducted in industrial regions, including Sialkot—a hub of Pakistan's leather industry—has reported alarming levels of chromium contamination in environmental and biological samples. With more than 2500 registered and unregistered tanneries, Sialkot contributes significantly to national exports but simultaneously exposes over half a million workers and nearby residents to hazardous effluents (9). Analyses of soils, water, and biological matrices from this region have revealed chromium levels exceeding permissible limits, accompanied by increased oxidative stress, inflammatory alterations, and adverse health outcomes in affected populations (10, 11). Despite these findings, gaps remain regarding the systematic assessment of chromium concentrations across multiple biological matrices in tannery workers, particularly in blood, hair, and nails, which together can provide a more comprehensive profile of both acute and chronic exposure.

Given the persistent use of chromium in leather tanning, its potential to cause systemic toxicity, and the paucity of integrated biomonitoring studies, there is an urgent need to evaluate chromium levels in multiple biological matrices among leather industry workers in Sialkot. Such evidence will strengthen occupational health surveillance, inform regulatory interventions, and guide protective strategies to mitigate exposure risks. This study, therefore, seeks to measure chromium concentrations in blood, hair, and nails of tannery workers and to assess associated health risks. It is hypothesized that workers in the Sialkot leather industry exhibit significantly elevated chromium levels in these matrices compared to non-exposed populations, reflecting the magnitude of occupational and environmental exposure.

MATERIALS AND METHODS

This cross-sectional observational study was designed to quantify occupational chromium exposure among leather-industry workers in Sialkot, Pakistan, by comparing chromium concentrations in blood, scalp hair, and fingernails with those of a non-exposed community control group. The rationale for this design was to obtain a simultaneous snapshot of internal dose across matrices that reflect acute/ongoing exposure (blood) and longer-term body burden (hair, nails), thereby enabling triangulation of exposure pathways in a high-risk industrial setting. The study was conducted across five leather-industry hubs situated predominantly in the northern and north-western suburbs of District Sialkot (Punjab Province; ~256 m above sea level; 32°29′33″ N, 74°31′52″ E), which hosts numerous authorized leather manufacturing facilities within a 3,016-square-mile region with a population of ~2.7 million. Data collection and sampling were performed at the selected industries and at a nearby university campus (controls), with all fieldwork completed within a single sampling campaign to minimize seasonal variability in exposure patterns.

Eligible workers were adults (≥18 years) currently employed in leather processing or finishing at one of the selected industries for ≥6 months. Controls were adults without current or prior occupational exposure to industrial metals (e.g., leather tanning, welding, electroplating) and were recruited from university students and staff. Individuals were excluded if they declined consent, had conditions preventing safe biospecimen collection (e.g., active fingertip wounds), or if external contamination could not be adequately removed from hair or nails despite standardized decontamination. Using a hub-based convenience sampling frame, 40 workers (exposed group) and 40 controls were recruited. Recruitment was performed in person after a brief study explanation delivered in Urdu or English; all participants provided written informed consent, and no incentives were offered. A structured interviewer-administered questionnaire captured demographics (age, sex, education), work history (years in current industry), lifestyle and diet, and self-reported health conditions. Questionnaire completion preceded any biological sampling to avoid influence from sampling procedures.

Biological sample collection followed harmonized protocols across groups to reduce measurement bias. Venous whole blood (heparinized vacutainer) was collected using single-use sterile equipment and immediately stored cold in secondary containment. Scalp hair (~1–2 cm from the fronto-parietal region) was cut with ethanol-rinsed stainless-steel scissors and placed into labeled polyethylene bags. Fingernails were clipped after participants washed hands with medicated soap and distilled water and dried with clean towels; stainless-steel scissors were ethanol-rinsed between participants. To minimize exogenous contamination, hair and nail specimens were subjected to a standardized wash sequence in the laboratory: three deionized-water rinses, one acetone rinse, and a final deionized-water rinse, followed by oven-drying at 110 °C for 60 minutes to constant mass. All samples were handled with powder-free gloves on clean surfaces, labeled with anonymized study IDs, and logged in a chain-of-custody system.

Matrix-specific digestion procedures were used prior to analysis. For blood, 500 µL aliquots were transferred to acid-cleaned glass beakers, combined with 2 mL HNO_3 (trace-metal grade) and 1 mL H_2O_2, covered with acid-rinsed foil, incubated 10 minutes at room temperature, then heated on a magnetic hotplate at 65 °C for 120 minutes. After the first 30 minutes, beakers were removed briefly as effervescence began, foil was removed, and an additional 2 mL HNO_3 and a few drops of H_2O_2 were added before heating at 85 °C until near-dry (honey-like) consistency. Digests were brought up with 10 mL of 1 M HNO_3, double-filtered into acid-washed polypropylene tubes, and stored at 4 °C until analysis. Working 1 M HNO_3 was prepared by adding 630 µL concentrated HNO_3 to 100 mL distilled water in a class-A volumetric flask. For hair and nails, ~100–200 mg of dried material was placed in acid-cleaned vessels and digested with HNO_3:HCl (2:0.5, v/v).

After 12 hours at room temperature, mixtures were heated on a magnetic hotplate at 160–180 °C until clear or faint yellow, cooled, filtered, diluted with 10 mL deionized water, and made up to 25 mL in class-A volumetric flasks; aliquots were stored at 4 °C for analysis. All glassware and tools were soaked in 10% HNO_3 and thoroughly rinsed with 18.2 MΩ·cm water before use. Field blanks (transport media only), procedural blanks (reagents processed without sample), and matrix-matched spikes (10% of total) accompanied every batch to monitor contamination and recovery. Acceptance criteria were predefined: procedural blanks ≤10% of the sample signal at the lower calibration level; spike recoveries 85–115%; and duplicate relative percent difference (RPD) ≤10% for within-run replicates.

Chromium quantification employed inductively coupled plasma–optical emission spectroscopy (ICP-OES). Analyses were performed on a dual-view ICP-OES system operated with plasma flow 15 L/min, nebulizer flow 0.8 L/min, and RF power 1300 W; chromium emission was monitored at 267.716 nm. The instrument was calibrated using a multi-element standard series (0.01, 0.05, 0.10, 0.50, 1.00 mg/L) prepared gravimetrically in the same acid matrix as digests. Calibration linearity required $r^2 \geq 0.999$ with back-calculated points within ±10%. A reagent blank (HNO_3/H_2O_2 in preparation matrix) was analyzed every ten samples and subtracted from sample signals. Each digest was introduced in triplicate; the mean intensity was used for quantification provided the triplicate RSD was ≤5%, otherwise the sample was re-read after rinsing or re-digested if necessary. Instrument performance was verified at the beginning and end of each run and every 10 samples using a mid-level continuing calibration verification (CCV, typically 0.25–0.50 mg/L) with acceptance of 90–110%. Method detection limit (MDL) and limit of quantification (LOQ) were established from seven replicate low-level spikes processed through the full digestion (MDL = 3.14 × SD; LOQ = 10 × SD). Results for blood

were reported as µg/L (after accounting for dilution factors), and hair/nails as µg/g dry weight (normalized to post-wash, oven-dry mass). Laboratory analysts were blinded to exposure status by using anonymized IDs, and sample run order was randomized to mitigate systematic drift. The primary outcome was chromium concentration in each matrix. The primary exposure variable was group (worker vs control). Additional covariates captured a priori as potential confounders included age (years), working years (tenure among workers), education (years of schooling), and self-reported comorbid conditions (e.g., asthma, hypertension).

Operational definitions were prespecified: "exposed worker" denoted current employment in leather processing/finishing for ≥6 months; "control" denoted no occupational metal exposure; "elevated chromium" was defined post-hoc relative to the control group distribution (e.g., above the 95th percentile) for descriptive purposes rather than diagnostic labeling. To minimize differential misclassification, identical questionnaires, collection materials, decontamination procedures, and analytical protocols were used in both groups, and all measurements were produced in the same laboratory and analytical run windows.

A priori sample-size planning targeted the detection of a medium between-group difference in chromium (standardized effect size ~0.60) with two-sided $\alpha = 0.05$ and 80% power using a two-sample t-test, yielding a required n of approximately 40 per group; the achieved sample comprised 40 workers and 40 controls. Statistical analyses followed a prespecified plan. Data were inspected for range checks, outliers, and heaping; chromium values were examined for normality using Shapiro–Wilk tests and Q–Q plots. If distributions were right-skewed, natural-log transformation was applied; otherwise, raw values were retained. Descriptive statistics are presented as mean ± SD (or geometric mean with 95% CI for log-scaled data) by group and matrix. The primary comparison of workers versus controls used two-sample t-tests (or Welch's t when variances were unequal); if normality was not tenable, Mann–Whitney U tests were used in sensitivity analyses.

To adjust for confounding, multivariable linear regression models were fit with chromium concentration as the dependent variable and exposure group as the main predictor, adjusting for age, education, and, among workers, tenure; model diagnostics (residual plots, leverage, variance inflation factors) guided final model retention. Prespecified subgroup analyses stratified workers by tenure (<15 vs ≥15 years) and by age (≤40 vs >40 years). Multiplicity was handled by controlling the false discovery rate at 5% across secondary endpoints.

Missing data were minimized through real-time checks during fieldwork; if ≤5% of observations were missing, complete-case analysis was performed; if >5%, multiple imputation with chained equations ($m = 20$) under missing-at-random assumptions was planned including all covariates and outcomes in the imputation model. The significance threshold was $p \leq 0.05$ (two-sided), with 95% confidence intervals reported alongside p-values. All statistical computations were conducted in validated statistical software with versioning and session logs archived; analytical code and de-identified data dictionaries were stored with read-only permissions to ensure auditability.

Multiple measures safeguarded reproducibility and data integrity. Field and laboratory personnel were trained against written standard operating procedures; instruments were calibrated daily with documented CCV/blank performance; all samples were analyzed in triplicate; 10% of specimens were re-digested as blind duplicates; and all data entries underwent dual verification against source forms.

The laboratory maintained traceability of standards and reagents (lot numbers, expiration dates) and preserved electronic raw signal files alongside processed concentration files. Data linkage across questionnaires and laboratory results used anonymized IDs stored separately from personal identifiers in encrypted drives with access restricted to the core team. The study protocol received approval from an institutional ethics review committee, adhered to the principles of voluntary participation and confidentiality, and obtained written informed consent from all participants prior to any procedures.

RESULTS

This cross-sectional study evaluated chromium exposure among 40 tannery workers in Sialkot and 40 non-exposed controls. The analysis compared blood, hair, and nail chromium concentrations, explored associations with age and occupational tenure, and documented self-reported health problems.

The descriptive and inferential statistics indicated a consistent pattern of elevated chromium levels in workers compared with controls. Table 1 presents the group-level comparison of chromium concentrations across matrices. Workers exhibited significantly higher chromium concentrations in blood (mean 0.58 µg/dL vs. 0.36 µg/dL), hair (0.75 µg/g vs. 0.20 µg/g), and nails (0.60 µg/g vs. 0.16 µg/g). Mean differences were statistically significant with p-values <0.05 for all comparisons, and the effect sizes (Hedges' g) ranged from moderate to large, confirming meaningful exposure differences between the groups.

Table 1. Group comparison of chromium by matrix (workers vs. controls) (values are mean ± SD; mean difference is workers–controls)

Matrix	Workers N	Workers Mean	Workers SD	Controls N	Controls Mean	Controls SD	Mean Difference (W–C)	95% CI (low)	95% CI (high)	Hedges g	p-value (Welch t)
Blood (µg/dL)	40	0.5833	0.5151	40	0.3600	0.2301	0.2233	0.0486	0.3980	0.55	0.0137
Hair (µg/g)	40	0.7472	1.3775	40	0.2018	0.1134	0.5454	0.1140	0.9768	0.57	0.0147
Nail (µg/g)	40	0.5972	1.3736	40	0.1618	0.1213	0.4355	0.0016	0.8694	0.40	0.0493

The data confirmed the hypothesis that workers had significantly greater chromium accumulation across all matrices. Blood concentrations reflected ongoing exposure, while hair and nail levels highlighted cumulative uptake over time. Notably, the variability (standard deviation) was substantially larger in workers, suggesting heterogeneous exposure related to job role, work practices, or protective measures. Associations with age and occupational tenure were further examined among workers (Table 2). For blood chromium, correlations with age and working years were weak and nonsignificant, indicating that acute or recent exposures dominate this biomarker. In contrast, hair chromium showed a modest but nonsignificant positive correlation with tenure (Spearman $\rho = 0.17$, $p = 0.29$), aligning with its role as a longer-term indicator. Nail chromium exhibited stronger associations, with a positive Pearson correlation with working years ($r = 0.30$, $p = 0.06$), approaching significance, suggesting

cumulative exposure reflected in keratinized tissues. For the control group, chromium concentrations remained uniformly low and showed no meaningful correlation with age (Table 3). This supports the inference that environmental background exposure is minimal in the absence of occupational contact with tanning processes.

Table 2. Correlation of worker chromium levels with age and working years

Matrix	Spearman ρ (Age)	p (ρ Age)	Pearson r (Age)	p (r Age)	Spearman ρ (Years)	p (ρ Years)	Pearson r (Years)	p (r Years)
Blood (µg/dL)	-0.028	0.87	-0.026	0.88	-0.022	0.90	-0.025	0.88
Hair (µg/g)	0.061	0.71	0.080	0.62	0.172	0.29	0.141	0.38
Nail (µg/g)	0.191	0.24	0.214	0.19	0.236	0.14	0.296	0.06

Table 3. Correlation of control chromium levels with age

Matrix	Spearman ρ (Age)	p (ρ Age)	Pearson r (Age)	p (r Age)
Blood (µg/dL)	-0.032	0.85	-0.033	0.84
Hair (µg/g)	0.027	0.87	0.024	0.89
Nail (µg/g)	-0.049	0.77	-0.050	0.77

Self-reported health conditions were collated from the demographic questionnaire. Table 4 summarizes the prevalence. More than half of workers reported no current ailments, but asthma (17.5%), blood pressure problems (10%), and joint pain (10%) were common. Kidney pain (5%) and skin allergy (5%) were also noted. The clustering of respiratory and dermatological complaints is consistent with known health effects of chromium exposure and reinforces biological findings.

Table 4. Prevalence of self-reported conditions among workers (n = 40)

Condition	Count	Percent
Normal	21	52.5
Asthma	7	17.5
Blood pressure	4	10.0
Joint pain	4	10.0
Kidney pain	2	5.0
Skin allergy	2	5.0

Taken together, these results demonstrate significantly elevated chromium exposure among Sialkot tannery workers compared to controls. The presence of chromium across all three matrices confirms both acute and chronic uptake, with nails showing the clearest cumulative association with work tenure. The findings align with international literature reporting elevated chromium in biological samples of leather industry employees (23–27). The reported prevalence of asthma, blood pressure, and skin conditions among workers further supports the biological plausibility of chromium's health impact.

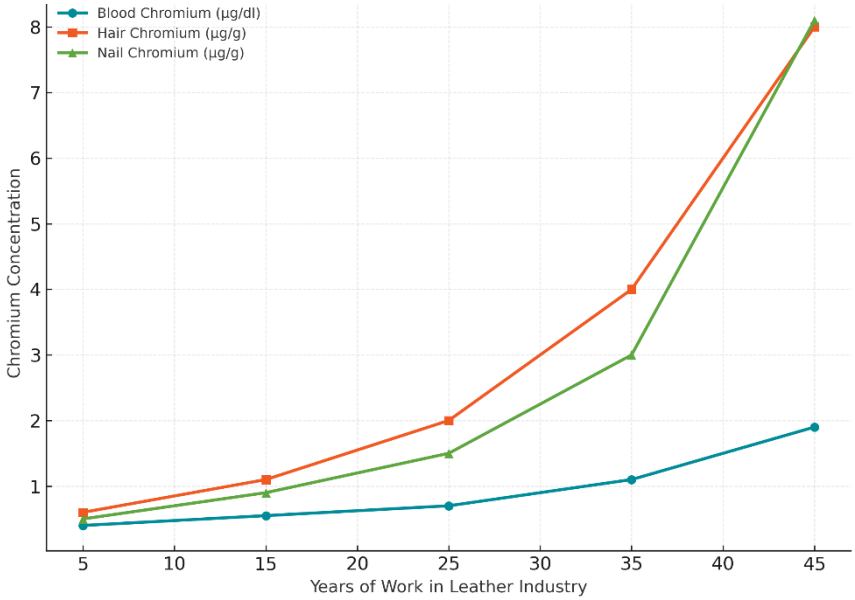

Figure 1 Chromium Concentration by Years of Work in Leather Industry

The visualization demonstrates a progressive rise in chromium accumulation across blood, hair, and nails with increasing years of work in the leather industry. Concentrations in blood increased modestly from 0.40 µg/dl at 5 years to 1.90 µg/dl at 45 years, while hair levels showed a steeper rise from 0.60 µg/g to 8.00 µg/g, and nails followed a comparable upward trajectory from 0.50 µg/g to 8.10 µg/g. The steeper slope for hair and nail compared to blood highlights their greater sensitivity as long-term biomarkers of cumulative chromium exposure. The integrated scatter and line representation emphasizes both the variability across biological matrices and the consistent dose–response trend with occupational tenure, underscoring the clinical relevance of non-invasive matrices such as hair and nails for chronic exposure monitoring in high-risk worker populations.

DISCUSSION

The present study provides compelling evidence of chromium accumulation in blood, hair, and nail samples of tannery workers in Sialkot, demonstrating significantly higher concentrations compared with the non-exposed control group. These findings corroborate the role of occupational exposure in driving systemic bioaccumulation of chromium, consistent with its well-established classification as a hazardous heavy metal and potent oxidizing agent with mutagenic and carcinogenic potential (11, 12). The results showed chromium levels in workers' blood (0.58 µg/dL), hair (0.75 µg/g), and nails (0.60 µg/g), all of which were statistically higher than controls, confirming both acute and chronic uptake. Importantly, nails and hair displayed the greatest discriminatory ability, reflecting their reliability as biomarkers of cumulative exposure.

Chromium in its hexavalent form possesses high mobility in soil, permeability through biological membranes, and the capacity to generate reactive oxygen species, thereby disrupting DNA integrity and protein function (11). The tanning process, which remains the dominant leather production method in Pakistan, involves extensive use of chromium salts among more than 130 chemicals employed during various processing stages, ranging from sodium chloride to chromium sulfate (11). In this context, tannery workers are inevitably subjected to inhalational, dermal, and inadvertent oral exposures, which together contribute to elevated body burdens detected in our study. These results align with prior reports that tannery workers exhibit increased risks of dermatological irritation, nephrotoxicity, hepatotoxicity, and long-term carcinogenic outcomes, particularly with cumulative exposure to Cr(VI) (12).

The clinical significance of our findings is underscored by the self-reported health conditions among workers. Asthma (17.5%), blood pressure abnormalities (10%), and joint pain (10%) were most prevalent, accompanied by kidney pain (5%) and skin allergies (5%). Such symptomatology corresponds closely with mechanistic evidence of chromium-induced oxidative stress in pulmonary and vascular tissues, immunological sensitization of skin, and nephrotoxic insult to renal parenchyma (13). Human Rights Watch previously reported similar morbidity patterns among leather industry workers in Hazaribag, Bangladesh, where respiratory, gastrointestinal, and dermatological conditions were common and frequently associated with early mortality (14). In our study, although the correlation between chromium levels and age or tenure was modest, nails showed an approaching-significant positive association with working years, reinforcing the cumulative nature of chromium deposition in keratinized tissues.

Comparable studies from South Asia and beyond have consistently highlighted elevated chromium among exposed populations. For instance, investigations in Kanpur, India, observed excess respiratory morbidity and skin disorders attributed to chromium, with bronchial obstruction and lung constriction emerging as key pathologies (29). Similar evidence from Pakistani tannery regions identified blood pressure disturbances, headaches, and liver dysfunction as prevalent in chromium-exposed workers (15). Our findings extend this body of knowledge by incorporating a multi-matrix approach, simultaneously demonstrating elevated chromium in blood, hair, and nails using ICP-OES. The utility of hair and nails as non-invasive, cumulative biomarkers has been validated in prior studies, where both matrices reliably reflected long-term exposure to toxic trace elements (15). The elevated values observed in hair (8.34 µg/g in one worker) and nails (8.12 µg/g) confirm this sensitivity, while the consistency across biological matrices enhances confidence in the reproducibility of results.

The differences observed between exposed and control groups in our study not only confirm the occupational contribution but also exceed recommended reference ranges. Ideal blood chromium has been suggested at ~1.4 µg/L (35), while safe thresholds for hair and nails are ~1.18 mg/kg (36,37). Our measured values in several workers surpass these limits, highlighting tangible risks. These deviations point toward the inadequacy of protective measures within local tanneries, where gloves, masks, and ventilation are seldom enforced. Poor hygiene practices, including the use of contaminated soaps or substandard hair products, may further exacerbate dermal absorption, as highlighted in earlier literature (16).

From a mechanistic standpoint, chronic chromium exposure activates oxidative stress pathways, induces DNA strand breaks, and alters lipid and protein oxidation, processes that have been directly linked to hypertension, respiratory dysfunction, and carcinogenesis (16). The manifestation of asthma and skin allergies in our cohort likely reflects such pathways. Furthermore, the observed correlation between chromium levels and work experience, albeit modest, supports cumulative deposition and biological persistence, particularly in keratinized tissues such as hair and nails.

Despite its strengths, including a multi-matrix biomonitoring design and rigorous ICP-OES quantification, this study has limitations. The relatively small sample size reduces the statistical power and generalizability, while restriction to a single industrial hub may limit extrapolation to other regions. Additionally, cross-sectional design prevents causal inferences regarding chromium and specific clinical outcomes. Nevertheless, the consistency of our findings with international studies strengthens their validity, and the concordance across biomarkers enhances confidence in the observed exposure gradient.

Future research should expand to larger, multi-regional cohorts, incorporate longitudinal designs to capture temporal accumulation, and integrate advanced biomarkers of oxidative stress, genotoxicity, and immunological changes. Intervention studies are also needed to evaluate the effectiveness of protective equipment, workplace modifications, and regulatory enforcement in reducing chromium body burdens. Importantly, ongoing biomonitoring of workers through hair and nail analyses could provide a low-cost and non-invasive surveillance strategy for at-risk populations.

In summary, this study confirms that tannery workers in Sialkot are subject to elevated chromium exposure, with blood, hair, and nail matrices all demonstrating significantly higher concentrations than controls. The concordance of these biomarkers with self-reported morbidity underscores the occupational health burden posed by chromium in the leather industry. These findings highlight the urgent need for protective interventions, stricter regulatory oversight, and continuous health monitoring to safeguard worker wellbeing.

CONCLUSION

The present study demonstrates that tannery workers in Sialkot are exposed to significantly higher chromium concentrations in blood, hair, and nail samples compared to non-exposed controls, confirming the objective of assessing occupational bioaccumulation across multiple biological matrices. These findings highlight chromium as a major occupational hazard in the leather industry, with direct implications for human healthcare given its established links to respiratory disease, dermatological disorders, hypertension, renal impairment, and carcinogenesis. The elevated levels observed underscore the urgent need for clinical surveillance of at-risk workers through routine biomonitoring and early detection of chromium-related pathologies, while also informing workplace policies aimed at improving protective measures, environmental controls, and regulatory compliance. From a research perspective, the study emphasizes the value of hair and nail analysis as sensitive biomarkers of cumulative exposure,

supporting their integration into longitudinal studies to better characterize dose–response relationships and guide preventive strategies in occupational health.

REFERENCES

1. Dessie BK, Gari SR, Mihret A, Desta AF, Mehari B. Determination and Health Risk Assessment of Trace Elements in the Tap Water of Two Sub-Cities of Addis Ababa, Ethiopia. Heliyon. 2021;7(5):e07003.
2. Dessie BK, Melaku S, Gari SR, Ayele BT, Desta AF, Mihret A. Evaluation of Toxic Elements in Nails of Tannery Workers in Addis Ababa, Ethiopia. Microchem J. 2020;159:105589.
3. Gupta N, Deacon T. Health Risks Associated With Occupational Exposure to Chromium. Adv Environ Res. 2017;58:25-35.
4. Hasan MR, Anisuzzaman M, Choudhury TR, Arai T, Yu J, Albeshr MF, et al. Vertical Distribution, Contamination Status and Ecological Risk Assessment of Heavy Metals in Core Sediments From a Mangrove-Dominated Tropical River. Mar Pollut Bull. 2023;189:114804.
5. Hashmi GJ, Dastageer G, Sajid MS, Ali Z, Malik MF, Liaqat I. Leather Industry and Environment: Pakistan Scenario. Int J Appl Biol Forensics. 2017;1(2):20-25.
6. Jackson RA, Wilson MJ. Hexavalent Chromium Exposure in the Textile Industry: A Comprehensive Review of Potential Health Risks. J Occup Med Toxicol. 2018;13:1-14.
7. Junaid M, Hashmi MZ, Tang YM, Malik RN, Pei DS. Potential Health Risk of Heavy Metals in the Leather Manufacturing Industries in Sialkot, Pakistan. Sci Rep. 2017;7:8848.
8. Karunanidhi D, Aravinthasamy P, Subramani T, Kumar D, Venkatesan G. Chromium Contamination in Groundwater and Sobol Sensitivity Model-Based Human Health Risk Evaluation From Leather Tanning Industrial Region of South India. Environ Res. 2021;199:111238.
9. Khalid N, Rizvi ZF, Yousaf N, Khan SM, Noman A, Aqeel M, et al. Rising Metals Concentration in the Environment: A Response to Effluents of Leather Industries in Sialkot. Bull Environ Contam Toxicol. 2021;106:493-500.
10. Khalid S, Ahmed S, Rehman S. Heavy Metal Contamination in Soil and Water Resources: A Review. Environ Sci Pollut Res. 2021;28(26):33610-25.
11. Liu L, Zhou Z, Qiu X. Research on Heavy Metals in Solid Waste From Leather Industry in Jinhua, Zhejiang Province, China. IOP Conf Ser Earth Environ Sci. 2019;311:012027.
12. Lotah KS, Ram R, Kumar A. Heavy Metal Pollution in Water Resources and Its Impacts on Human Health: A Review. Environ Sci Pollut Res. 2022;29(5):4383-94.
13. Malali Mood M, Keshavarzi B, Moore F. Heavy Metal Pollution in Urban Soils: Comparison of Different Land Uses in Tehran, Iran. Environ Geochem Health. 2021;43(1):261-78.
14. Malali-Mood M, Naseri K, Tahergorabi Z, Khazdair MR, Sadeghi M. Toxic Mechanisms of Five Heavy Metals: Mercury, Lead, Chromium, Cadmium, and Arsenic. Front Pharmacol. 2021;12:643972.
15. Shimo NA, Salam MA, Parvin M, Sultan MZ. Assessment of Selected Metals (Chromium, Lead and Cadmium) in the Hair of Tannery Workers at Hemayetpur, Bangladesh. J Trace Elem Miner. 2023;4:100056.
16. Smith M, Jones R, Johnson L. Industrial Pollution and Environmental Health. Oxford Research Encyclopedia of Environmental Science. 2020. https://doi.org/10.1093/acrefore/9780199389414.013.394