Environ Geochem Health (2025) 47:318
https://doi.org/10.1007/s10653-025-02635-1

ORIGINAL PAPER

Evaluation of trace element in the hair and nail samples of conventional and organic farmers in pesticide-treated highland villages

Vivien How · Wei Ven Wong · Jia Yee Leong · Cathrinena Robun · Zurahanim Fasha Anual

Received: 20 March 2025 / Accepted: 28 June 2025 / Published online: 15 July 2025

Abstract This study investigates trace element exposure among conventional and organic farmers in Cameron Highlands, Malaysia, a region known for intensive pesticide use. Despite differences in agricultural practices, both groups may be exposed to environmental contaminants. Inductively Coupled Plasma Mass Spectrometry (ICP-MS) NexION® 350S was used to analyze essential elements (sodium, magnesium, iron, zinc) and toxic elements (chromium, mercury, arsenic, cadmium, lead). A comparative cross-sectional study was conducted among 62 farmers (47 conventional, 15 organic). Data collection involved structured interviews and biological sampling (hair and nails). Findings revealed significant differences in trace element concentrations based on farming practices. Chromium (Cr) levels were significantly higher in conventional farmers, suggesting exposure to synthetic agrochemicals. Mercury (Hg) levels were also elevated, indicating cumulative pesticide and soil contamination exposure. Organic farmers exhibited slightly higher concentrations of essential elements such as iron and sodium, possibly due to variations in soil management and fertilizer use. Correlation analysis revealed potential synergistic and antagonistic interactions among trace elements, with implications for cumulative toxicity and occupational health risks. Despite different agricultural approaches, both groups remain at risk of environmental exposure due to long-term pesticide application in the region. This study underscores the need for sustainable agricultural practices to reduce trace element exposure and protect farmers' health in pesticide-intensive highland villages.

Keywords Environmental exposure · Agricultural health · Biomonitoring · Highland agriculture · Heavy metals

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10653-025-02635-1.

V. How (✉) · W. V. Wong · J. Y. Leong
Department of Environmental and Occupational Health, Faculty of Medicine and Health Sciences, Universiti Putra Malaysia, Seri Kembangan, Malaysia, Selangor 43400
e-mail: vivien@upm.edu.my

W. V. Wong
e-mail: 206351@student.upm.edu.my

J. Y. Leong
e-mail: 205495@student.upm.edu.my

C. Robun · Z. F. Anual
Environmental Health Research Centre (EHRC), Institute for Medical Research (IMR), National Institutes of Health Malaysia, Shah Alam, Malaysia, Selangor 40170
e-mail: cathrinena@moh.gov.my

Z. F. Anual
e-mail: zurahanim@moh.gov.my

Introduction

Cameron Highlands, a vital agricultural hub in Malaysia, is renowned for its intensive farming activities that rely heavily on synthetic agrochemicals to maximise crop yield (PANAP & IPEN, 2015). The widespread use of synthetic pesticides and chemical fertilisers in conventional farming has significantly increased agricultural productivity, but has also raised serious environmental and occupational health concerns. Conventional farmers who frequently handle these agrochemicals are at an increased risk of exposure to hazardous substances, including trace elements such as chromium (Cr), manganese (Mn), mercury (Hg), and lead (Pb), many of which pose well-documented toxicological threats (Mitra et al., 2022).

Conventional farming practices in this region often prioritise the use of synthetic agrochemicals to increase productivity, which has led to environmental concerns and potential health risks among farmers who are directly exposed to these hazardous substances. While these practices have successfully enhanced agricultural output, they have also introduced trace elements such as chromium (Cr), manganese (Mn), mercury (Hg), and lead (Pb) into the environment, some of which have recognised toxicological implications.

In response to growing concerns regarding the adverse health impacts of prolonged pesticide and fertiliser exposure, an increasing number of farmers in Cameron Highlands are transitioning to organic farming. Organic agricultural practices emphasise natural soil enrichment techniques, crop rotation, and biological pest control methods to minimise chemical inputs. However, despite these efforts to reduce synthetic agrochemical exposure, organic farmers remain susceptible to environmental contamination from neighbouring conventional farms (Ramakrishnan et al., 2021). For instance, past studies suggested that pesticide drift, contaminated irrigation systems, and soil leaching facilitate the unintended transfer of synthetic agrochemicals and trace elements, undermining the benefits of organic farming (Smith et al., 2019). This raises questions about the actual reduction in exposure risks, even with organic methods.

The issue of pesticide exposure among smallholder farmers is not unique to Malaysia but is widely reported across other Southeast Asian nations and the Global South. In Thailand, for instance, studies have documented elevated levels of pesticide residues and associated health risks among vegetable farmers using conventional practices (Panuwet et al., 2012). Similarly, Vietnamese farmers frequently report inadequate protective behaviors and a high prevalence of acute pesticide-related symptoms (Nguyuen et al., 2018). In Indonesia, studies show significant environmental contamination in rural agricultural areas, further complicating the exposure scenario even for farmers claiming to adopt safer practices (Dewi et al., 2022). These findings underscore a shared regional challenge of balancing agricultural productivity with occupational and environmental health, thereby situating the current study within a broader context of systemic pesticide exposure issues in tropical, small-scale farming environments.

Occupational exposure to trace elements in agricultural settings is particularly concerning due to their bioaccumulative nature and potential for both acute and chronic health effects (Srivastav, 2020). Essential metals such as sodium (Na), magnesium (Mg), iron (Fe), zinc (Zn) are crucial for various physiological functions, including enzymatic reactions, cellular metabolism, and immune regulation, but must remain within optimal ranges to prevent deficiencies or toxicity (Witkowska et al., 2021). Conversely, toxic metals such as chromium (Cr), arsenic (As), cadmium (Cd), mercury (Hg), lead (Pb) pose significant health risks due to their ability to bioaccumulate and cause neurotoxicity, carcinogenicity, and metabolic disturbances (Mitra et al., 2022). These elements exhibit distinct toxicokinetic properties; some disrupt essential biochemical pathways, while others contribute to cumulative toxicity with prolonged exposure (Ledoigt et al., 2015).

To evaluate exposure comprehensively, this study utilizes hair and nails as biological matrices. Unlike blood or urine, which reflect recent or acute exposures, hair and nails provide a longer-term record of cumulative exposure. Hair sequesters trace elements over weeks, while nails, due to their slower growth rate, reflect exposure over several months (Chojnacka & Mikulewicz, 2018). This makes them suitable biomarkers for assessing chronic environmental and occupational exposure in agricultural settings.

Therefore, this study aims to assess and compare the chronic exposure to trace elements among conventional and organic farmers in pesticide-treated highland villages of Cameron Highlands. Using hair and nail samples, it investigates differences in exposure profiles and explores potential synergistic or antagonistic interactions between essential and toxic elements, contributing to a more holistic understanding of occupational and environmental health risks in agricultural communities.

Methods

Research design

This research was quantitative research that was conducted on 62 farmers who had worked for at least 1 year, including males and females from Cameron Highland. The 62 farmers comprised 47 conventional farmers and 15 organic farmers. This study employed a comparative cross-sectional study design to investigate various trace elements contained in nails among vegetable farmers from Cameron Highland.

Study location and population

This study was conducted in Cameron Highlands, Pahang, Malaysia, an intensive agricultural zone known for vegetable and flower farming. Sampling was performed in four key farming locations: Brinchang, Tanah Rata, Bertam Valley, and Tringkap. These areas host both conventional and organic farming activities. The map in Fig. 1 illustrates the geographical distribution of these study sites and provides spatial context for understanding potential exposure pathways. There is no known industrial or mining activity was identified within the immediate vicinity of these sampling areas. Thus, the likelihood of non-agricultural toxic metals sources influencing the results is minimal. Nonetheless, the map helps visualize environmental settings and supports the interpretation of trace element distributions.

The study's inclusive criteria consisted of vegetable farmers living and working in the study area for at least 12 months, aged between 18 and 60 years old, and residing in Cameron Highland for a minimum of

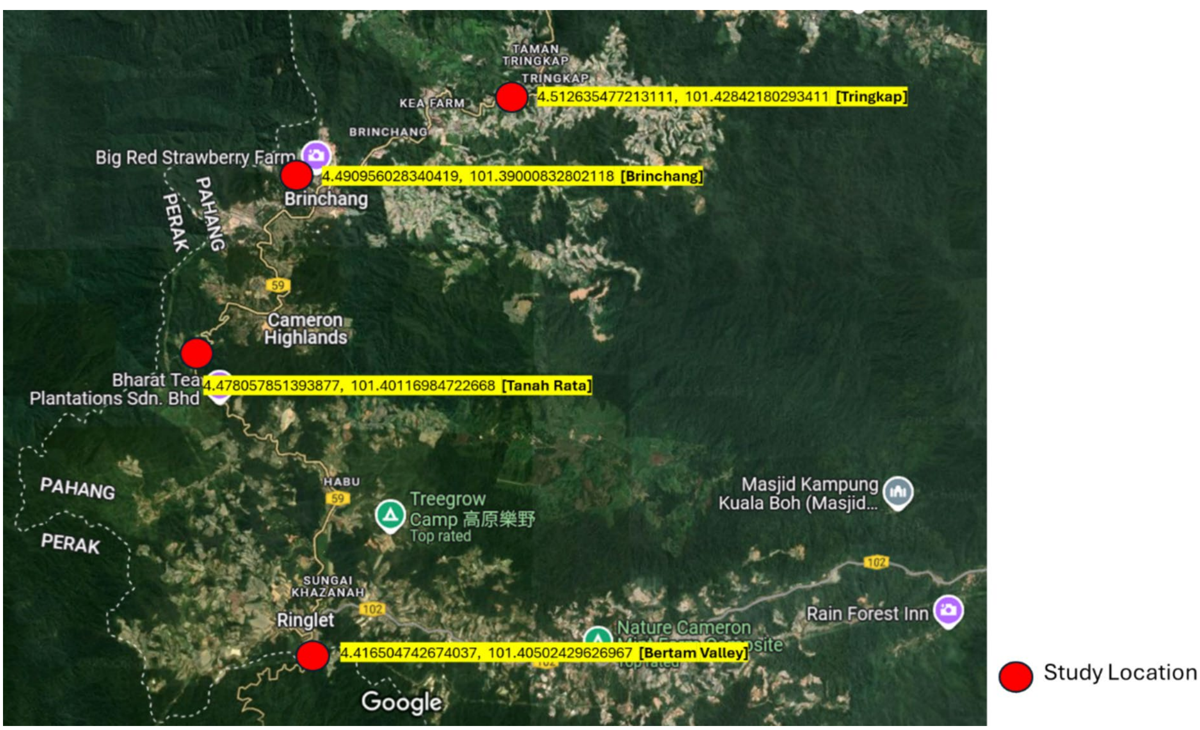

Fig. 1 Map of Cameron Highlands showing the four selected study locations (Bertam Valley, Tanah Rata, Brinchang, and Tringkap), where both conventional and organic farmers were recruited. This satellite image reflects the intensive agricultural use of land across the highlands, and supports spatial analysis of potential trace element exposure

12 months in a farming occupation. Organic farmers needed to have experience in organic farming without using synthetic agrochemicals for the past year, while conventional farmers engaged in routine farming with synthetic pesticides and fertilizers. On the other hand, the exclusive criteria excluded farmers with chronic liver and kidney diseases under medication or post-operation from the study.

Data collection

I) Face-to-face interview.

A validated questionnaire adapted from Tsagué Manfo et al., (2020) was used to gather demographic and occupational information from the study participants. A face-to-face interview was conducted to ensure data collection and clarification of responses, providing a comprehensive understanding of each participant's exposure to potential environmental contaminants.

II) Hair Sampling and Storage.

The hair sample collection protocol is based on the standard protocol recommended by Elekdag-Turk et al. (2019). Participants were instructed to allow their hair to grow for four weeks before the collection date. Each respondent was provided with a new set of stainless-steel scissors for hygiene purposes on the hair collection day. Approximately 20–30 strands of hairs were collected from the occipital region, 2 mm from the scalp and trimmed to a length of about 3 cm. The required hair sample weight was 0.01 – 0.05 g. The hair samples were placed in sterile, zip-locked plastic bags and stored at room temperature until shipment to the laboratory for subsequent trace element analysis.

III) Nail Sampling and Storage.

The nail sample collection protocol is based on the standard protocol recommended by Elekdag-Turk et al. (2019). Participants were instructed to grow both their fingernails and toenails for a period of four to six weeks before sample collection to ensure sufficient sample material. On the day of collection, each participant was provided with a new set of sterile stainless steel nail clippers to minimize contamination. Participants trimmed the free edge of their fingernails and toenails, with approximately 5 g of nail clippings collected per individual. The samples were then placed in sterile, labeled, zip-locked plastic bags. Nail samples were stored at room temperature until they were transported to the laboratory for trace element analysis.

IV) Laboratory Analysis.

The Analytical Methodology to Evaluate Trace Elements in Hair and Nail was based on a Paper by Przybylowicz et al., (2012) which examined the distribution of trace elements in alternative biological matrices. The trace element analysis from the hair and nail sample was carried out using a NexION 350S Inductively Coupled Plasma Mass Spectrometer (ICP-MS; Perkin-Elmer, USA) in the Environmental Health Laboratory, Institute of Medical Research (IMR), Malaysia.

To minimize external contamination and ensure that the detected trace elements reflect internal accumulation, all hair and nail samples underwent a standardized washing procedure prior to digestion and analysis. Samples were first rinsed with ultrapure deionized water to remove dust and debris, followed by a gentle wash with acetone to eliminate surface oils and potential pesticide residues. This process was repeated once and followed by another rinse with deionized water. The cleaned samples were then dried in a laminar flow cabinet and stored in clean containers until digestion and analysis.

Quality assurance

Validation procedures were conducted to ensure that the test batches met the specified internal quality controls. Each analysis included a blank, internal standard as well as quality control to remove the batch-specific error. The calibration curves established for trace elements (Na, Mg, NH_3, Cr, Mn, Fe, Ni, CO, Cu, As, Cd, Hg and Pb) determination exhibited high linearity ($r^2 > 0.999$). The quantitative measurements were based on external calibration standards, which were prepared from a 10 µg/mL Multi-Element Standard 3 in 1% (v/v) HNO_3 acid with concentrations in 1.25, 2.5, 5.0, and 20.0 µg/L for all trace elements. Matrix spiking was conducted to assess the method's precision. Additionally, certified reference material (CRM) human hair and nail (European Reference Materials

ERM-DB001) was used to ensure the quality of analyses. The recovery values for these elements were within the acceptable range of 85% to 115%.

Ethical considerations

Before commencing data collection, ethical approval clearance was diligently secured from the Ethics Committee at the University Putra Malaysia (Approval Code: JKEUPM-2023-187). Respondents' identities were treated with the utmost confidentiality, and all collected data remained strictly confidential, and not disclosed to any external parties. Furthermore, each respondent willingly and voluntarily participated in the study, with informed consent being an essential prerequisite. A consent form was provided, and respondents were required to sign it, demonstrating their full understanding and voluntary participation in the research, ensuring full compliance with ethical guidelines and standards.

Statistical analysis

All statistical analyses were conducted using IBM SPSS Statistics Version 26. Categorical variables in Table 1 (socio-demographic characteristics) and Table 2 (occupational background) were analyzed using the Chi-square test or Fisher's Exact Test, depending on the expected cell counts. For continuous or ordinal data such as the duration of farming (Table 2), the Mann–Whitney U test was applied due to non-normal distribution and unequal group sizes. For the comparison of trace element concentrations in hair (Table 3) and nail (Table 4) samples between conventional and organic farmers, the Mann–Whitney U test was used, as the data were not normally distributed. To examine relationships between trace elements in hair and nail

Table 1 Socio-demographic distribution among Farmers (N = 62), Cameron Highland

Sociodemographic Characteristics	Frequency (n)	Percentage (%)	p-value	
[a]Gender	Male	49	79	1.000
	Female	13	21	
[b]Age	20–30	6	9.7	0.996
	31–40	17	27.4	
	41–50	22	35.5	
	51–60	17	27.4	
[b]BMI	Underweight	3	4.8	0.694
	Normal	31	50	
	Overweight	24	38.7	
	Obese	4	6.5	
[a]Education Level	Primary	7	11.3	0.933
	Secondary	33	53.2	
	Tertiary	22	35.5	
[a]Type of Farm	Conventional	47	75.8	1.000
	Organic	15	24.2	
[a]Smoking Habit	Yes	12	19.4	1.000
	No	50	80.6	
[b]Alcohol Consumption	No alcohol	24	38.7	0.999
	Once a week	5	8.12	
	3 to 4 times a week	2	3.2	
	3 times a month	30	48.4	
	1 to 2 times a year	1	1.6	
[b]Duration of year working in the farmland	1 to 5 years	12	19.4	
	6 to 10 years	14	22.6	0.973
	More than 10 years	36	58.1	

[a]Fisher's Exact Test;[b]Chi-square test

Table 2 Occupational background among farmers at Cameron Highland (N = 62)

	Conventional (n = 47)		Organic (n = 15)		*p*-value
	Median (IQR)	n (%)	Median (IQR)	n (%)	
[a]Duration of Year Working in The Farmland	17 (11–23)		14 (12—16)		0.0335*
[b]Type of PPE					
Disposable Face mask		4 (8.5)		-	0.1510
Half face mask		1 (2.1)		-	
No PPE		35 (74.5)		9 (60.0)	
Raincoat		-		1 (6.7)	
High-cut safety shoes		6 (12.8)		5 (33.3)	
Short-cut safety shoes		1 (2.1)		-	
[c]Symptoms During Handling Pesticide					
No symptoms		47 (100.0)		15(100.0)	1.000
Have symptoms		-		–	
[c]Symptoms After Handling Pesticide					
No symptoms		35 (74.5)		14 (93.3)	0.1587
Have symptoms		12 (25.5)		1 (6.7)	
[b]Pesticide Purchase					
Not Using		–		15 (100.0)	0.0032*
Physical Store		47 (10.0)		–	
Online		–		–	
[b]Wash Pesticide Container					
No washing is practised		34 (72.3)		–	0.0040*
Rinse with water on the farm		12 (25.5)		–	
Not Using		1 (2.1)		15 (100.0)	
[c]Pesticide Storage					
Not Using		–		15 (100.0)	0.0013*
In the farm		15 (31.9)		–	
[b]Pesticide Container Disposal					
No disposal is practised		–		15 (100.0)	< 0.001**
Throw as general waste		29 (61.7)		–	
Gather to recycle centre		18 (38.3)		–	
Burn		–		–	

[a]Mann-Whitney U-test Test; [b]Chi-square test; [c]Fisher's Exact Test

samples (Tables 5 and 6), Spearman's rank correlation was performed, given the non-parametric nature of the data. All tests were two-tailed, and a p-value of less than 0.05 was considered statistically significant.

Results

Socio-demographic characteristics of farmers in Cameron highland

Table 3 Comparison of the Level of Trace Elements in Hair Sample among Farmers (N = 62), Cameron Highland

Trace elements (mg/kg)	Median (IQR)		#MDL	##MQL	a *p*-value
	Conventional Farmer (n = 48)	Organic Farmer (n = 14)			
Sodium (Na)	11.97 (3.14–27.08)	17.44 (3.39–31.49)	0.8217	2.6168	0.422
Magnesium (Mg)	33.18 (5.71–37.05)	19.18 (2.41–17.55)	0.5613	1.7875	0.188
Ammonia (NH_3)	0.03 (0.01–0.04)	0.03 (0.01–0.03)	0.0114	0.0363	0.099
Chromium (Cr)	0.71 (0.21–0.57)	0.17 (0.054–0.198)	0.0159	0.0506	0.008*
Manganese (Mn)	0.33 (0.09–0.39)	0.24 (0.0013–0.236)	0.0098	0.0313	0.784
Iron (Fe)	6.41 (1.68 –7.55)	13.28 (2.16–11.82)	1.2656	4.0305	0.325
Nickel (Ni)	0.52 (0.00–0.52)	0.08 (0.04–0.38)	0.0268	0.0852	0.698
Cobalt (Co)	0.008 (0.004–0.009)	0.0071 (0.00–0.068)	0.0055	0.0176	0.257
Copper (Cu)	6.33 (3.99 –9.02)	5.80 (3.74–8.31)	0.0138	0.0438	0.585
Zinc (Zn)	119.39 (102.47–188.56)	132.83 (114.32–209.99)	0.2775	0.8838	0.146
Arsenic (As)	0.04 (0.03–0.05)	0.03 (0.01–0.04)	0.0187	0.0597	0.314
Cadmium (Cd)	0.02 (0.02–0.06)	0.01 (0.02–0.09)	0.0070	0.0222	0.399
Mercury (Hg)	0.66 (0.29–0.86)	0.39 (0.12–0.47)	0.0027	0.0087	0.054
Lead (Pb)	0.42 (0.02–0.44)	0.30 (0.07–0.25)	0.0040	0.0129	0.513

[a] Mann Whitney U-test

#MDL (Method Detection Limit) = the lowest concentration of a substance that can be reliably detected by analytical method

#MQL (Method Quantification Limit) = the lowest concentration of a substance that can be reliably quantified using analytical method

*p-value is significant at 0.05 level;

**p-value is significant at 0.001 level

Table 1 outlines the socio-demographic characteristics and health risk factors of farmers in Cameron Highlands, Pahang. The sample was predominantly male (79%), with most participants aged 41–50 (35.5%), followed by those in the 31–40 and 51–60 age groups (27.4% each). Half of the farmers had a normal BMI, while 38.7% were overweight. Educationally, 53.2% completed secondary school, and 80.6% did not smoke. The majority were low alcohol consumers, with 48.4% drinking monthly and 38.7% abstaining. Most farmers (75.8%) worked on conventional farms, with over half (58.1%) having more than 10 years of agricultural experience. No statistically significant differences were observed between conventional and organic farmers across all socio-demographic characteristics, indicating comparable backgrounds between the two groups.

Occupational characteristics of farmers in Cameron highland

Table 2 compares the occupational background between conventional and organic farmers in Cameron Highlands. The median duration of farming was significantly longer among conventional farmers (17 [11–23] years) than organic farmers (14 [12–16] years) ($p = 0.0335$, Mann–Whitney U test). No significant differences were observed in PPE usage or symptoms after pesticide handling.

In contrast, pesticide-related practices showed clear and significant differences. All organic farmers reported no involvement in pesticide purchase, washing, storage, or disposal, while conventional farmers commonly engaged in these activities. These differences were statistically significant ($p < 0.05$), indicating substantially higher potential for occupational pesticide exposure among conventional farmers.

Comparison of trace elements in hair sample of farmers in Cameron highland

Table 3 presents the comparison of trace element concentrations in hair samples between conventional and organic farmers using the Mann–Whitney U test. Overall, conventional farmers exhibited higher median concentrations of most toxic elements

Table 4 Comparison of the Level of Trace Elements in Nail Sample among Farmers (N = 62), Cameron Highland

Trace elements (mg/kg)	Mean (SD)		#MDL	##MQL	[a] p-value
	Conventional Farmer (n = 48)	**Organic Farmer (n = 14)**			
Sodium (Na)	107.1 (38.11–132.82)	87.38 (44.67–117.53)	0.8217	2.6168	0.498
Magnesium (Mg)	85.78 (53.81–122.09)	90.33 (73.02–139.62)	0.5613	1.7875	0.732
Ammonia (NH_3)	0.06 (0.01–0.06)	0.04 (0.02–0.06)	0.0114	0.0363	0.479
Chromium (Cr)	0.865 (0.33–0.65)	0.70 (0.05–0.67)	0.0159	0.0506	0.737
Manganese (Mn)	2.45 (0.19–2.58)	1.56 (0.13–0.73)	0.0098	0.0313	0.353
Iron (Fe)	96.86 (10.31–103.82)	146.88 (35.54–133.89)	1.2656	4.0305	0.335
Nickel (Ni)	2.00 (0.33–1.77)	2.21 (0.03–2.23)	0.0268	0.0852	0.836
Cobalt (Co)	0.06 (0.03–0.04)	0.03 (0.01–0.02)	0.0055	0.0176	0.250
Copper (Cu)	4.57 (3.16–6.69)	4.21 (3.59–6.63)	0.0138	0.0438	0.536
Zinc (Zn)	121.74 (76.29–173.24)	81.10 (72.96–130.36)	0.2775	0.8838	< 0.001**
Arsenic (As)	0.10 (0.04–0.12)	0.09 (0.07–0.14)	0.0187	0.0597	0.728
Cadmium (Cd)	0.02 (0.00–0.01)	0.002 (0.00–0.001)	0.0070	0.0222	0.396
Mercury (Hg)	0.37 (0.18–0.49)	0.29 (0.13–0.38)	0.0027	0.0087	0.336
Lead (Pb)	1.02 (0.04–1.05)	0.64 (0.42–0.92)	0.0040	0.0129	0.337

[a] Mann Whitney U-test

#MDL (Method Detection Limit) = the lowest concentration of a substance that can be reliably detected by analytical method

#MQL (Method Quantification Limit) = the lowest concentration of a substance that can be reliably quantified using analytical method

*p-value is significant at 0.05 level;

**p-value is significant at 0.001 level

compared to organic farmers. Notably, the concentration of chromium (Cr) was significantly elevated in the conventional group (0.11 [0.71–0.57] mg/kg) compared to the organic group (0.07 [0.054–0.198] mg/kg, $p = 0.008$), suggesting greater exposure likely linked to the use of synthetic pesticides and fertilizers. Mercury (Hg) levels were also higher in conventional farmers (0.66 [0.29–0.86] mg/kg) than in organic farmers (0.39 [0.12–0.47] mg/kg), with a p-value of 0.054, approaching statistical significance.

Other toxic elements such as arsenic (As), cadmium (Cd), and lead (Pb) did not differ significantly between the two groups, although median levels were slightly higher among conventional farmers. For essential elements, the patterns were more varied. Magnesium (Mg) and copper (Cu) showed higher concentrations among conventional farmers, while iron (Fe) and sodium (Na) levels were higher in organic farmers, though none reached statistical significance. Zinc (Zn) also appeared slightly elevated in organic farmers, whereas ammonia (NH_3), often associated with organic fertilizer use, was modestly higher in the organic group ($p = 0.099$).

These findings highlight a distinct difference in chromium exposure between farming practices, reinforcing the role of agrochemical use in trace element accumulation. However, for most other elements, both groups showed overlapping exposure profiles, potentially due to shared environmental background contamination in this pesticide-intensive highland region.

Comparison of trace elements in nail sample of farmers in Cameron highland

Table 4 compares the concentrations of trace elements in nail samples between conventional and organic farmers using the Mann–Whitney U test. Among essential elements, zinc (Zn) levels were found to be significantly higher in conventional farmers (121.74 [96.72–173.84] mg/kg) compared to organic farmers (81.10 [73.22–90.99] mg/kg), with a p-value of < 0.001. This finding suggests a potential link between conventional farming practices and zinc exposure, possibly due to the use of zinc-enriched fertilizers or agrochemicals.

Table 5 The Association of trace elements in hair sample among farmers (N = 62), Cameron Highland

	Na	Mg	NH_3	Cr	Mn	Fe	Ni	Co	Cu	Zn	As	Cd	Hg	Pb
Sodium	1													
Magnesium	-0.201 (0.118)	1												
Ammonia	0.378 (0.002)**	-0.385 (0.002)**	1											
Chromium	-0.135 (0.295)	-0.015 (0.911)	0.004 (0.972)	1										
Manganese	0.165 (0.200)	0.197 (0.125)	-0.006 (0.964)	-0.109 (0.398)	1									
Iron	0.001 (0.993)	0.035 (0.785)	0.206 (0.107)	0.101 (0.433)	0.330 (0.009)**	1								
Nickel	-0.094 (0.467)	0.148 (0.251)	0.022 (0.866)	0.013 (0.921)	0.166 (0.191)	0.168 (0.191)	1							
Cobalt	-0.103 (0.424)	0.598 (**)	0.001 (0.993)	0.173 (0.179)	0.434 (**)	0.434 (**)	0.367 (0.003)**	1						
Copper	0.157 (0.224)	-0.226 (0.077)	0.160 (0.213)	-0.085 (0.510)	-0.018 (0.889)	-0.018 (0.889)	-0.345 (0.006)**	-0.230 (0.072)	1					
Zinc	-0.046 (0.721)	0.297 (0.019)*	-0.103 (0.424)	0.075 (0.565)	0.105 (0.415)	0.184 (0.152)	0.036 (0.780)	0.395 (0.001)**	-0.206 (0.109)	1				
Arsenic	0.082 (0.529)	-0.456 (**)	0.146 (0.257)	0.022 (0.866)	-0.083 (0.523)	-0.019 (0.881)	-0.057 (0.661)	-0.338 (0.007)**	0.044 (0.733)	-0.187 (0.145)	1			
Cadmium	0.163 (0.206)	-0.246 (0.054)	0.234 (0.068)	-0.009 (0.946)	0.343 (0.006)**	0.024 (0.850)	0.102 (0.430)	0.059 (0.650)	0.057 (0.659)	0.088 (0.495)	0.352 (0.005)**	1		
Mercury	0.317 (0.012)*	-0.285 (0.025)*	0.281 (0.027)*	-0.044 (0.736)	0.200 (0.120)	-0.121 (0.350)	-0.303 (0.017)*	-0.148 (0.251)	0.350 (0.005)	-0.100 (0.439)	0.240 (0.061)	0.388 (0.002)**	1	
Lead	0.150 (0.245)	0.104 (0.423)	-0.034 (0.791)	0.089 (0.490)	0.328 (0.009)**	0.073 (0.572)	0.421 (0.001)**	0.109 (0.398)	-0.128 (0.320)	0.168 (0.193)	-0.002 (0.987)	0.047 (0.716)	-0.026 (0.840)	1

Spearman Correlation test: **p*-value is significant at 0.05 level; ***p*-value is significant at 0.001 level

Sodium (Na), Magnesium (Mg), Ammonia (NH3), Chromium (Cr), Manganese (Mn), Iron (Fe), Nickel (Ni), Cobalt (Co), Copper (Cu), Zinc (Zn), Arsenic (As), Cadmium (Cd), Mercury (Hg), Lead (Pb)

Table 6 The Association of Trace Elements in Nail Sample among Farmers (N = 62), Cameron Highland

	Na	Mg	NH_3	Cr	Mn	Fe	Ni	Co	Cu	Zn	As	Cd	Hg	Pb
Sodium	1													
Magnesium	-0.066 (0.610)	1												
Ammonia	-0.046 (0.724)	0.458 **	1											
Chromium	0.190 (0.139)	-0.162 (0.208)	-0.008 (0.951)	1										
Manganese	0.209 (0.104)	0.288 (0.023)*	0.304 (0.016)*	0.306 (0.016)*	1									
Iron	0.005 (0.967)	0.052 (0.687)	0.229 (0.074)	0.552 **	0.412 (0.001)**	1								
Nickel	0.089 (0.489)	-0.067 (0.608)	-0.800 (0.537)	0.728 **	0.169 (0.189)	0.522 **	1							
Cobalt	0.150 (0.246)	0.280 (0.028)*	0.408 (0.001)**	0.381 (0.002)**	0.232 (0.069)	0.318 (0.012)*	0.318 (0.012)*	1						
Copper	0.003 (0.979)	0.071 (0.582)	0.152 (0.239)	-0.076 (0.556)	0.341 (0.007)**	0.007 (0.957)	-0.151 (0.240)	0.02 (0.868)	1					
Zinc	-0.084 (0.518)	-0.144 (0.263)	-0.271 (0.033)	0.125 (0.332)	0.133 (0.304)	-0.021 (0.874)	0.031 (0.809)	0.169 (0.190)	0.380 (0.002)**	1				
Arsenic	0.084 (0.515)	-0.081 (0.531)	0.125 (0.334)	0.494 **	0.368 (0.003)**	0.247 (0.053)	0.241 (0.059)	0.284 (0.025)*	0.614 **	0.372 (0.003)**	1			
Cadmium	0.092 (0.475)	0.386 (0.002)**	0.374 (0.003)**	0.010 (0.936)	0.262 (0.040)*	0.161 (0.211)	0.105 (0.417)	0.222 (0.083)	0.052 (0.686)	-0.094 (0.467)	0.044 (0.736)	1		
Mercury	0.054 (0.674)	-0.117 (0.365)	-0.082 (0.527)	-0.089 (0.492)	-0.161 (0.211)	-0.187 (0.145)	0.024 (0.855)	-0.043 (0.742)	0.136 (0.293)	0.172 (0.181)	0.077 (0.554)	-0.060 (0.644)	1	
Lead	-0.046 (0.725)	0.039 (0.765)	-0.179 (0.165)	-0.054 (0.677)	-0.045 (0.727)	-0.043 (0.741)	0.037 (0.775)	0.055 (0.674)	0.015 (0.908)	-0.024 (0.854)	-0.039 (0.761)	-0.055 (0.670)	-0.081 (0.531)	1

Sodium (Na), Magnesium (Mg), Ammonia (NH3), Chromium (Cr), Manganese (Mn), Iron (Fe), Nickel (Ni), Cobalt (Co), Copper (Cu), Zinc (Zn), Arsenic (As), Cadmium (Cd), Mercury (Hg), Lead (Pb)

Spearman Correlation test

*p-value is significant at 0.05 level; **p-value is significant at 0.001 level

Other essential elements, including sodium (Na), magnesium (Mg), and iron (Fe), showed modest differences between the groups. Sodium and magnesium levels were slightly higher among organic farmers, whereas iron concentrations were greater in organic farmers, though none of these differences were statistically significant. Copper (Cu) and cobalt (Co) also demonstrated minor variations between groups, but without significance.

For toxic elements, conventional farmers generally exhibited higher median concentrations of chromium (Cr), manganese (Mn), lead (Pb), and mercury (Hg) compared to organic farmers. However, these differences were not statistically significant. Nickel (Ni), on the other hand, showed a slightly higher median level in organic farmers, although this difference was also non-significant. The levels of arsenic (As) and cadmium (Cd) were low in both groups and did not show meaningful variation.

Overall, the key finding in nail samples was the significantly elevated zinc concentration in conventional farmers. Other trace elements showed similar exposure profiles between the two groups, indicating a potentially shared environmental source or background exposure across the highland farming communities.

The association of trace elements in hair sample of farmers in Cameron highland

Table 5 presents the associations between trace elements in the hair samples of farmers, revealing patterns that may reflect co-exposure or shared pathways of accumulation. Ammonia (NH_3) was positively correlated with sodium (Na) and negatively correlated with magnesium (Mg), suggesting possible relationships in their uptake or metabolic regulation. Sodium also showed a significant positive correlation with mercury (Hg), while magnesium was positively correlated with cobalt (Co) and zinc (Zn), and negatively with arsenic (As). These correlations indicate potential interactions among elements, but the underlying causes remain unclear and could stem from a combination of environmental, dietary, or occupational sources.

Cobalt was also positively associated with manganese (Mn), iron (Fe), and nickel (Ni), while iron showed a strong correlation with manganese and cobalt. These patterns may reflect similar geochemical behavior or concurrent environmental exposure. Toxic elements such as cadmium (Cd) were positively correlated with arsenic, manganese, and mercury, suggesting the possibility of multi-element exposure. Lead (Pb) exhibited positive associations with manganese and nickel. While these correlations may be suggestive of shared exposure pathways, the specific sources—whether agricultural, environmental, or otherwise—were not directly assessed in this study and should be interpreted with caution. The significant associations between these elements, however, underscore the complex interactions and exposure scenarios faced by farmers in pesticide-treated highlands, with implications for occupational health and safety.

The association of trace elements in nail sample of farmers in Cameron highland

Table 6 presents the associations between trace elements in nail samples among farmers, highlighting potential interactions and exposure patterns. Magnesium (Mg) shows significant associations with several trace elements, including ammonia (NH_3), manganese (Mn), cobalt (Co), and cadmium (Cd), indicating a possible shared exposure source or co-exposure pathways, possibly linked to agricultural practices or environmental factors. Chromium (Cr) displays a strong association with iron (Fe) and manganese (Mn), suggesting that exposure to chromium might be linked to increased levels of these elements in the body. Nickel (Ni) is strongly correlated with Cr, Fe, and cobalt, indicating that nickel exposure could occur alongside exposure to other trace elements, likely from occupational sources.

Toxic elements such as arsenic (As) demonstrate significant positive correlations with Cr, Mn, copper (Cu), and zinc (Zn), suggesting possible co-contamination or shared environmental sources. Cadmium (Cd) correlates positively with Mg, NH_3, and Mn, indicating a potential combined exposure risk from both essential and toxic elements. Overall, the table reveals a complex interplay between trace elements, with certain elements like Mg and Cr serving as central components in multiple associations. These findings point to potential sources of co-exposure and emphasize the need to understand how different agricultural practices and environmental factors may influence trace element levels in farmers.

Discussion

The shared environmental background in Cameron Highland, characterised by the long-standing use of pesticides and fertilizers, plays a critical role in trace element exposure. Despite having different farming methods, agrochemicals' historical and ongoing use has contaminated soils and caused environmental interactions that have an impact on both conventional and organic farmers. The potential cross-contamination raises concerns about the exposure risk for all farmers in the region and emphasizes the need for improved safety measures, environmental monitoring, and sustainable farming practices.

Comparison of trace elements in hair sample of farmers in Cameron highland

Essential/beneficial trace elements and occupational exposure

Farming practices and environmental factors can have an impact on essential elements like sodium (Na), magnesium (Mg), iron (Fe), copper (Cu), and zinc (Zn), which are crucial for biological functions. Magnesium (Mg) levels are higher among conventional farmers than organic farmers, suggesting a possible association with using magnesium-enriched fertilisers commonly found in conventional agriculture (Beeby et al., 2020). However, this difference is not statistically significant, implying that while farming practices may play a role, the environmental background of pesticide-treated soils could contribute to Mg levels across both farmer groups.

Zinc (Zn), another essential trace element, is slightly higher in organic farmers than in conventional farmers, although this difference is not statistically significant. The elevated Zn in organic farmers could be attributed to the uptake from natural soil sources or organic soil amendments (Reeve et al., 2016). Additionally, compost and animal manure play a significant role as organic sources of zinc. As these organic matters decompose, they not only improve soil structure and fertility but also enhance zinc availability to plants. The nutrient-release process from compost and manure is gradual, providing a sustained source of zinc that aligns well with the nutrient uptake needs of crops (Gordillo et al., 2016).

Iron (Fe), necessary for enzymatic functions and oxygen transport (Vigani & Murgia, 2018), shows a higher mean concentration in organic farmers than in conventional farmers. This trend, although not statistically significant, could be influenced by differences in soil health and nutrient uptake in organic farming, which relies on natural fertilizers that might contain bioavailable iron (Reeve et al., 2016). Another significant source of iron in organic farming is the use of organic matter, including compost, green manure, and animal manure (Birkhofer et al., 2016). These organic materials, when added to the soil, undergo decomposition and mineralization processes that release iron in a bioavailable form. Compost and manure not only improve the soil's iron content but also enhance the soil's cation exchange capacity and microbial activity, thereby improving the uptake of iron and other micronutrients by plants (Aditi et al., 2019).

Toxic elements and occupational exposure

Toxic elements including chromium (Cr), mercury (Hg), arsenic (As), cadmium (Cd), and lead (Pb) were also examined, given their potential health risks and presence in agricultural settings. A significant difference in chromium (Cr) levels is observed between conventional and organic farmers. Chromium exposure is likely linked to conventional pesticide use, as Cr compounds are common contaminants in synthetic agrochemicals (Liu et al., 2017). Some phosphate fertilizers, particularly those derived from mineral rock phosphates, can contain trace amounts of chromium as an impurity (Ding et al., 2014). When these fertilizers are applied to agricultural soils over time, they can lead to an accumulation of chromium, particularly in areas with intensive fertilizer use. In addition to fertilizers, industrial farming systems often use pesticides and herbicides that may contain trace metals, including chromium, as part of their formulation (Nguyen et al., 2017). These agrochemicals, although not specifically designed to supply chromium, can contribute to its presence in soils. The repeated application of these chemicals can influence soil chromium concentrations, and depending on the form (trivalent chromium [Cr(III)] or hexavalent chromium [Cr(VI)]), this can have varying implications for soil health and potential plant uptake (Liu et al., 2022).

Mercury (Hg) levels are higher in conventional farmers compared to organic farmers, approaching statistical significance. Given that mercury is not typically used in modern pesticides but can be a contaminant, the elevated Hg in conventional farmers suggests potential occupational exposure through pesticide handling or soil contamination from legacy pesticide use in the Cameron Highlands. Historically, organomercury compounds were commonly used as seed treatments and fungicides; although their use has significantly decreased or been banned in many countries (Kroeksakul et al., 2023), some older agricultural practices or residual contamination in soils may still contribute mercury to agricultural fields. Additionally, certain formulations of current pesticides may still carry trace amounts of mercury as contaminants, which can accumulate in soils over time (Rice et al., 2014).

When considering that both organic and conventional farms are located in a pesticide-treated region, the possibility of finding no significant differences in the levels of toxic elements such as arsenic (As), cadmium (Cd), and lead (Pb) in hair samples of farmers from both groups becomes more plausible. The shared environmental setting likely plays a dominant role in exposure to these toxic elements, regardless of the farming practices employed. One of the primary reasons for similar levels of toxic elements in both groups is the contamination of farmland soil. Since both organic and conventional farms are situated in an area historically or currently treated with pesticides, the soil may contain residual concentrations of As, Cd, and Pb (Wahyuningsih et al., 2023). Many pesticides, particularly older formulations, have been known to contain heavy metals as active ingredients or impurities (Widowati et al., 2020). As these toxicants do not degrade easily and can remain in the environment for long periods, both organic and conventional farmers may experience similar levels of exposure due to the shared contaminated land (Defarge et al., 2017).

Atmospheric dispersion of toxic elements also contributes to uniform exposure across both organic and conventional farmers. Pesticides and other agricultural chemicals, when sprayed, can become airborne and travel beyond their initial point of application (Damalas & Koutroubas, 2016). This airborne contamination can settle on both organic and conventional farms, resulting in similar levels of toxic elements in the environment surrounding all farmers. Hence, regardless of individual farm practices, both groups of farmers might inhale contaminated air or encounter dust particles containing As, Cd, and Pb, leading to comparable exposure levels. Water sources used for irrigation or direct consumption can be another equalizing factor (Sharma et al., 2016). If the water used on both organic and conventional farms is contaminated with toxic elements due to pesticide runoff, industrial pollution, or naturally occurring heavy metals, this water can serve as a vector for As, Cd, and Pb exposure. Since both groups of farmers utilize the same regional water sources for agricultural or personal use, the levels of these toxicants in their hair samples could be similar, reflecting the shared exposure to water.

Furthermore, the use of soil amendments like compost, manure, or lime in organic farming does not necessarily eliminate exposure to toxic elements (Zhang et al., 2018). If these amendments are derived from local sources, they might also be contaminated due to the overarching presence of pesticide residues in the region. Hence, while organic farms typically avoid synthetic inputs, the use of contaminated organic amendments can result in similar levels of soil and plant contamination as in conventional farming, contributing to similar exposure risks for both farmer groups. On another note, since hair is a cumulative biomarker for exposure to toxic elements from all sources, the similarities in environmental contamination and exposure pathways in a pesticide-treated region can mask any potential differences that may arise from farming practices alone (Lehmann et al., 2017). The common environmental background exposure to As, Cd, and Pb across both organic and conventional farms would result in similar bioaccumulation of these toxicants in the hair of farmers.

Comparison of trace elements in nail sample of farmers in Cameron highland

Essential/beneficial trace elements and occupational exposure

The analysis of essential trace elements, including sodium (Na), magnesium (Mg), and zinc (Zn), highlights the potential influences of farming practices on exposure levels. Although the levels of Na and Mg are slightly higher in organic farmers compared to conventional farmers, these differences are not statistically significant. This suggests that, despite varying farming practices, shared environmental factors such as soil content and water sources might contribute to similar levels of these elements in both farmer groups.

Zinc (Zn) is the only essential element showing a statistically significant difference, with levels being markedly higher in conventional farmers compared to organic farmers. The differences in zinc levels between hair and nail samples of organic versus conventional farmers might reflect the variability in exposure routes, nutritional status, and the biological mechanisms of zinc incorporation into these tissues (Sheoran et al., 2018). Hair is a protein-rich tissue that incorporates minerals from both external exposure (such as dust and soil particles) and internal metabolism (Yang et al., 2014). In organic farmers, close physical contact with soil and plant materials, which may be enriched with bioavailable zinc due to organic farming practices, could lead to higher deposition of zinc in the hair. Furthermore, the nutritional status of organic farmers may play a role; if their diet is more plant-based and rich in whole grains, nuts, and legumes—which are high in zinc—this dietary intake could further contribute to elevated zinc levels in hair (Johansson et al., 2014).

Conversely, higher zinc levels in the nails of conventional or industrial farmers may be linked to different exposure mechanisms. Unlike hair, which can be more readily influenced by short-term environmental exposure, nails grow more slowly and reflect longer-term internal zinc levels (Parizanganeh et al., 2014). In conventional farming, the use of synthetic fertilizers, which can contain zinc as a nutrient or contaminant, may contribute to the farmers' zinc exposure over time. Additionally, some conventional pesticides and herbicides include zinc compounds as part of their formulation, leading to increased occupational exposure for these farmers (Schweizer et al., 2018). The pathway of zinc incorporation into nails is influenced more by systemic metabolism than by external contamination, and since nails grow at a slower rate than hair, they provide a more stable indicator of long-term zinc status (Parizanganeh et al., 2014). For conventional farmers, continuous exposure to zinc through fertilizers, pesticides, and soil contact over time may lead to its accumulation in the body, which is reflected in higher zinc concentrations in nail samples. The zinc in these inputs may be more bioavailable or present in a form that is more readily absorbed into the body and subsequently incorporated into the nail matrix.

Besides, the occupational environment between organic and conventional farmers differs in terms of exposure duration and the type of agricultural inputs used. Organic farmers may experience episodic and direct contact with soil and organic amendments that increase zinc in their hair. In contrast, conventional farmers often use more mechanized practices and may have prolonged exposure to zinc-containing agrochemicals, leading to systemic accumulation of zinc that becomes more evident in the nail.

Toxic elements and occupational exposure

Conventional farmers generally show higher levels of these elements, which is consistent with their use of synthetic pesticides and fertilizers known to contain or be contaminated with toxic trace metals. However, none of these differences reach statistical significance, suggesting that the environmental context, including residual contamination from historically treated pesticide soils, contributes similarly to exposure across both farming practices.

Chromium (Cr) and manganese (Mn) are often present as byproducts or contaminants in agrochemicals, such as fertilizers, pesticides, and soil amendments. Conventional farmers typically use synthetic inputs more frequently than organic farmers, which could account for the slightly elevated levels observed in their samples. However, organic farming is not completely free from exposure to these elements since natural or organic inputs can also contain trace amounts of Cr and Mn (Gong et al., 2019). Additionally, soil amendments like compost and manure, which are frequently used in organic farming, may still introduce these trace metals, especially if they are sourced from contaminated materials (Khan et al., 2017). Therefore, the difference in exposure between the two groups may not be large enough to reach statistical significance.

As for arsenic (As), cadmium (Cd), mercury (Hg), and lead (Pb), our finding reinforces the notion that both groups are exposed to these toxic metals through shared environmental sources, such as contaminated soils, water, or historical use of pesticides containing these metals. Although conventional farming practices might contribute additional inputs of these elements, the fact that no significant difference is found suggests that the baseline contamination is sufficiently high in the agricultural environment to affect both organic and conventional farmers similarly (Smith et al., 2019). This shared environmental exposure can mask the potential impact of farming practices, leading to similar levels of these toxic elements in both groups.

The finding that mercury (Hg) levels are higher in the hair and nails of conventional farmers compared to organic farmers can be attributed to differences in exposure sources and farming practices. Soil contamination plays a significant role in mercury exposure, and this is often more pronounced in conventional farming systems. The repeated use of fertilizers and pesticides in conventional farming can lead to increased soil contamination with mercury over time (Rice et al., 2014). As a result, conventional farmers working in contaminated soils may be exposed to mercury through direct contact with soil, inhalation of mercury-laden dust, or through the food chain if crops grown on these soils accumulate mercury (Zakir et al., 2011). Since both hair and nails are biological tissues that incorporate mercury from both external environmental exposure and internal body burden, the increased soil contamination in conventional farming can contribute to the higher levels found in these samples.

Besides, the difference in mercury levels between hair and nail samples in conventional farmers compared to organic farmers may reflect the bioaccumulation and exposure routes. Hair is a strong indicator of recent and chronic mercury exposure, reflecting both external contamination and internal metabolism of mercury (Skröder et al., 2017). Since conventional farmers are more likely to use chemical inputs or be in environments with higher mercury contamination, the elevated mercury levels in hair samples are consistent with greater recent exposure to mercury.

Nails, on the other hand, grow more slowly than hair and are indicators of longer-term and cumulative exposure (Hopps, 1977). Since mercury binds to keratin proteins (Zhang, 2011), which are found in both hair and nails, the consistent exposure of conventional farmers to mercury over time is more likely to result in detectable differences in nail mercury levels. The higher concentrations in both hair and nails suggest that conventional farmers are subject to continuous or repeated exposure to mercury, which is consistent with their farming practices. Conversely, organic farmers are less likely to encounter high levels of mercury due to restricted use of synthetic chemicals, potentially lower environmental contamination, and more conservative farming practices that reduce direct contact with mercury sources.

The Association of trace elements in hair sample of farmers in Cameron highland

Co-occurrence and shared sources of exposure

The positive correlations between ammonia (NH_3), sodium (Na), and magnesium (Mg) in hair samples imply a shared source of exposure, likely related to agricultural inputs. Ammonia is often present in fertilizers, and its association with Na and Mg could indicate that these elements co-occur in fertilizers or soil amendments applied in the farming environment (Bansal, 2023). For instance, ammonium-based fertilizers often contain sodium as a secondary component or contaminant, while magnesium may be added to correct soil deficiencies or improve plant health (Şenbayram et al., 2015). On the other hand, the significant positive correlation between iron (Fe) and manganese (Mn) in the hair samples suggests concurrent exposure, possibly due to their combined presence in common agricultural inputs. Iron and manganese are frequently found together in both soil enhancers and pesticides (Munir et al., 2021). For example, micronutrient fertilizers often contain Fe and Mn as essential elements to promote plant growth and correct deficiencies. Additionally, both elements may exist as contaminants or additives in some agricultural chemicals (He et al., 2005). As such, their association with hair samples supports the idea that farmers are exposed to these elements simultaneously, potentially through direct contact with treated soils, the application of micronutrient fertilizers, or the inhalation of dust that contains these trace metals.

Cobalt (Co) shows significant correlations with several elements, including magnesium (Mg), manganese (Mn), iron (Fe), and nickel (Ni). This pattern suggests a possible shared exposure pathway or co-contamination within the agricultural environment. Cobalt naturally occurs in mineral-rich soils and can be introduced into the farming environment through certain fertilizers, particularly those that include micronutrient mixtures or are sourced from mineral deposits (Stubblefield et al., 2020). Additionally, cobalt may be present in some pesticides or fungicides as a trace contaminant. The fact that cobalt is associated with multiple elements indicates that farmers may be exposed to these elements simultaneously, either through direct contact with cobalt-containing products or through environmental pathways such as contaminated dust, water, or crops (Tóth et al., 2009).

Potential antagonistic and synergistic interactions

The correlations identified between trace elements in hair samples point to potential antagonistic and synergistic interactions that could significantly influence the bioavailability, absorption, and toxicity of these elements. Understanding these interactions is essential in evaluating the cumulative exposure risk among farmers, as the combined presence of elements can alter their biological impact.

Synergy between elements occurs when the combined exposure to multiple elements enhances their absorption, bioavailability, or toxicity, often resulting in more severe health effects than exposure to individual elements alone. For instance, the observed positive correlations of mercury (Hg) with sodium (Na), ammonia (NH_3), and cadmium (Cd) suggest a synergistic interaction. When mercury co-occurs with these elements, their interaction could increase the absorption of mercury or exacerbate its toxic effects (Machado & Dinis-Oliveira, 2023). For instance, sodium may enhance the solubility and mobility of mercury within the body, facilitating its transport to different organs and tissues (Bridges & Zalups, 2017). Similarly, ammonia, commonly found in fertilizers, can alter pH levels or cellular transport mechanisms, potentially increasing mercury's uptake or toxicity (Edwards et al., 2024).

The positive association between mercury and cadmium is particularly concerning because both are highly toxic heavy metals that can cause neurotoxic, renal, and cardiovascular damage. A synergistic effect between these two elements could elevate the health risks to farmers, as co-exposure may amplify the adverse effects on the nervous system, kidneys, and other organs. This combined toxicity could occur through mechanisms like increased oxidative stress, inflammation, or competition for binding to detoxifying proteins and enzymes.

On the other hand, magnesium (Mg) shows negative correlations with ammonia (NH_3), arsenic (As), and mercury (Hg), suggesting potential antagonistic interactions. Antagonism between elements occurs when one element reduces the absorption, bioavailability, or toxicity of another, potentially offering a protective effect. Our findings suggested that magnesium could play a protective role by mitigating the toxicity or absorption of harmful elements like arsenic and mercury. For example, magnesium is known to compete with certain toxic metals for binding sites or transport pathways within the body, effectively reducing their uptake into cells and tissues (Witkowska et al., 2021). This mechanism may involve the blocking of specific ion channels or transport proteins that facilitate the entry of toxic elements. Magnesium's antagonistic relationship with arsenic and mercury could reduce the bioavailability of these toxicants, thereby lowering their potential for causing harm (Alengebawy et al., 2021). Since both arsenic and mercury are known to induce oxidative stress, disrupt cellular metabolism, and damage DNA, the presence of magnesium may help protect against these toxic effects by lowering the accumulation of these elements in key organs (Balali-Mood et al., 2021). This antagonism could be particularly relevant for farmers who may have access to magnesium through their diet or soil exposure, potentially providing a natural buffer against arsenic and mercury toxicity.

The association of trace elements in nail sample of farmers in Cameron highland

Co-occurrence and shared sources of exposure

The positive associations between elements in nail samples such as manganese (Mn), magnesium (Mg), ammonia (NH_3), and chromium (Cr) suggest that these elements may co-occur due to shared sources, pathways, and activities in agricultural settings. Given that fertilizers, pesticides, and other soil amendments are routinely used across different types of farming, these inputs are likely to contain mixtures of trace elements. For instance, fertilizers derived from mineral deposits can contain Mn, Mg, and Cr as naturally occurring components, while pesticides may contain these elements as either active ingredients or contaminants. Additionally, ammonia-based fertilizers are commonly used in both conventional and organic agriculture, contributing not only nitrogen to the soil but also potentially altering the bioavailability and mobility of other elements, such as Mn and Cr (Barłóg et al., 2022). The correlations among these elements, therefore, likely arise from farmers' direct contact with treated soils, agrochemical applications, and exposure to dust and residues that carry these elements.

The strong positive correlation between iron (Fe) and chromium (Cr) in the nail samples indicates a potential shared source or exposure pathway. Both Fe and Cr are common in soils and may be enriched through the use of soil amendments, such as lime, compost, or mineral-based fertilizers (Palansooriya et al., 2019). Iron, an essential nutrient for plant growth, is a frequent component of soil fertilizers, while chromium may be present as a contaminant or a secondary component in certain agrochemicals. The co-occurrence of these elements in nails suggests that their exposure is related to farming activities that involve contact with the soil or the use of products that contain these metals. Additionally, nails are indicators of longer-term exposure, reflecting cumulative absorption of trace elements through prolonged occupational activities. Hence, the Fe–Cr correlation points to persistent exposure from shared environmental sources, particularly in soils and agrochemical applications.

The significant correlations of nickel (Ni) with both chromium (Cr) and iron (Fe) further support the idea of shared sources of exposure in the farming environment. Nickel is often found in association with Fe and Cr in mineral deposits, fertilizers, and pesticides, making their co-presence in the agricultural setting plausible. The simultaneous exposure to Ni, Cr, and Fe can occur through multiple pathways, such as handling of agrochemicals, inhalation of dust particles, and contact with contaminated soils. The presence of these elements together in nail samples highlights that the farming practices and environmental conditions in Cameron Highlands contribute to occupational exposure to multiple trace elements. Nickel's role as a contaminant in fertilizers or as a minor component in soil amendments used for crop cultivation may further enhance its correlation with iron and chromium, reflecting a complex interplay of co-contaminants within the farming environment (Alengebawy et al., 2021).

The widespread use of synthetic pesticides and fertilizers in agricultural activities is a plausible explanation for the observed correlations between these trace elements. Modern agrochemicals often contain multiple trace elements, either as active components to enhance efficacy or as impurities from the manufacturing process. The long-term application of these agrochemicals in farming can result in the accumulation of trace elements in soils, which then become sources of exposure to farmers. Such shared exposure pathways are likely responsible for the co-occurrence of elements like Mn, Mg, NH_3, Cr, Fe, and Ni in farmers' nail samples. Additionally, the mixing of organic and conventional farming practices in pesticide-treated regions like Cameron Highlands means that both groups of farmers are exposed to similar environmental contaminants, contributing to the correlations observed in the nail samples.

Potential antagonistic and synergistic interactions

The findings reveal the potential for both synergistic and antagonistic interactions among trace elements in the nail samples of farmers, highlighting how these relationships could influence bioavailability, absorption, and toxicity. These interactions are particularly relevant in an agricultural context where farmers are exposed to a mixture of elements through occupational activities, fertilizers, pesticides, and environmental contaminants.

The positive correlation between ammonia (NH_3) and magnesium (Mg) suggests a potential synergistic relationship. Ammonia is commonly found in fertilizers, and its co-occurrence with magnesium in the farming environment could influence how both elements are taken up by the body. Magnesium plays an important role in biological processes, and its synergistic interaction with ammonia could facilitate the transport of both elements through similar pathways and influence cellular uptake mechanisms (Ahmed et al., 2023). This enhanced co-exposure might increase the bioaccumulation of ammonia and magnesium in tissues, including nails, thereby potentially affecting the metabolic functions of farmers and altering the toxicity of these elements when they are present together.

Cobalt (Co) demonstrates strong positive correlations with several elements, including magnesium (Mg), ammonia (NH_3), chromium (Cr), and iron (Fe), indicating possible synergistic relationships that could lead to increased co-bioavailability and toxicity. Cobalt is known to share absorption and transport mechanisms with other metals, and its synergistic interactions with these elements suggest that their combined exposure in agricultural settings could lead to greater uptake and accumulation in farmers (Genchi et al., 2023). For example, cobalt and iron share similar binding sites for transport proteins, which could enhance their uptake when present together. Furthermore, cobalt's correlation with chromium, an element often found in fertilizers and pesticides, could imply enhanced exposure from agricultural activities, thereby raising concerns about combined toxic effects. These potential synergistic interactions could result in more pronounced adverse health effects, such as oxidative stress, disruption of metabolic pathways, and potential organ damage.

Interestingly, zinc (Zn) shows no significant correlations with most elements except copper (Cu), where a strong positive association is observed. Zinc and copper have complex interactions in biological systems, often exhibiting both synergistic and antagonistic effects based on their relative concentrations and environmental exposure (Wang et al., 2020). In agricultural settings, zinc is frequently used as a nutrient in fertilizers and as a component in pesticides, which can lead to increased exposure among farmers. Copper is also commonly present in agricultural environments, and both elements may share similar pathways for absorption and metabolism. The strong correlation between zinc and copper may suggest that these elements are co-occurring in farming environments, potentially due to their use in similar agricultural products or shared environmental pathways, such as soil or dust exposure. In biological systems, zinc and copper are known to compete for the same transport proteins, such as metallothioneins, which play a crucial role in metal homeostasis and detoxification (Ruttkay-Nedecky et al., 2013). This competition can lead to antagonistic effects, where an excess of one element may inhibit the uptake and bioavailability of the other. For instance, high zinc levels can impede copper absorption, potentially reducing its bioavailability and mitigating its toxicity. Conversely, if copper concentrations are higher, zinc uptake could be similarly inhibited. These competitive dynamics may provide a buffering effect against toxicity, but they could also lead to deficiencies or imbalances in essential trace elements, depending on their relative exposure levels in the farming environment.

Study limitation

This study has several limitations that should be acknowledged. First, the use of self-reported symptom data introduces the possibility of recall bias and over-reporting, especially for non-specific symptoms such as headaches, skin irritation, or fatigue. While structured interviews were used to minimize inconsistency, subjective responses may not fully reflect actual health outcomes. Second, the cross-sectional design of this study limits causal inference; associations between trace element exposure and farming practices should be interpreted with caution. Third, environmental sampling (e.g., soil, water, or air) was not conducted alongside biomonitoring, which restricts the ability to pinpoint exact sources of exposure. Lastly, the relatively small sample size, particularly in the organic farmer group, may limit the generalizability of the findings.

Despite these limitations, the study provides valuable insights into occupational and environmental exposure to trace elements in pesticide-intensive highland agriculture. Future research should consider longitudinal designs, clinical symptom validation, and integrated environmental sampling to strengthen exposure assessment and health outcome analysis.

Conclusion

This study provides critical insights into the occupational exposure to trace elements among conventional and organic farmers in Cameron Highlands, highlighting the influence of farming practices and shared environmental conditions. The socio-demographic profile and occupational behaviours—particularly low PPE usage and suboptimal pesticide handling practices among conventional farmers—contribute to differing levels of trace element exposure risk. Analysis of hair and nail samples reveals that essential elements such as zinc and magnesium, and toxic elements like chromium and mercury, are more prevalent in conventional farmers, suggesting a strong link between agrochemical use and internal exposure. However, the detection of certain trace elements in both groups highlights the impact of shared environmental contamination, driven by historical and ongoing pesticide and fertilizer use in the highlands.

The observed correlations between trace elements point to complex co-exposure dynamics, suggesting potential synergistic and antagonistic effects that may influence toxicity, absorption, and health outcomes. While organic farming practices may reduce direct exposure to synthetic agrochemicals, the risk of cross-contamination from surrounding conventional farms remains a concern due to environmental dispersion through soil, water, and air.

To mitigate these risks, targeted interventions are needed at both the occupational and policy levels. Training programs on chemical safety and personal protection should be made widely accessible to farmers, alongside government-subsidized access to certified PPE. Strengthening the enforcement of pesticide regulations, including proper storage, usage, and disposal, is crucial to reduce long-term exposure. Environmental monitoring programs should be institutionalized to track contamination trends, and remediation initiatives should be launched to rehabilitate polluted soils. Promoting integrated pest management (IPM) and expanding support for organic transition can further contribute to sustainable agricultural development.

These findings reinforce the urgent need for a dual approach—enhancing occupational safety and addressing environmental contamination—to protect the health of all farmers. Future research should focus on evaluating the long-term health outcomes of trace element exposure and developing comprehensive, multi-level strategies to safeguard occupational and environmental health in agricultural settings.

Acknowledgements A special thanks to the Director General of Health Malaysia for permitting to publish of this article. This study was conducted under the Researcher Industry Scientific Exchange (RISE) platform governed by the Ministry of Science, Technology and Innovation (MOSTI). It involved technology transfer, consultation, utilization of state-of-the art technology as well as sharing of research expertise by the experts to the industry. The authors acknowledge support and assistance provided by staff of the Environmental Health Research Centre, Institute for Medical Research for aid in laboratory analysis throughout the commencement of the project. This study is financially supported by the Baba Eco Group Berhad.

Author contributions V.H. conceptualized the study, secured the research grant, and supervised the overall research framework, including study design, data interpretation, and manuscript preparation. As the corresponding author, V.H. coordinated the research activities and ensured the manuscript's integrity and coherence. W.W.V. and J.Y. were responsible for data collection, laboratory testing, and drafting the manuscript. C.R. and Z.F.A. provided laboratory guidance, developed the laboratory testing protocol, and validated the analytical procedures. Z.F.A. was instrumental in facilitating access to the laboratory and ensuring the quality control of trace element analyses. V.H., C.R., and Z.F.A. contributed to data acquisition, reviewed the results, and critically revised the manuscript for intellectual content. All authors reviewed and approved the final version of the manuscript.

Funding Open access funding provided by The Ministry of Higher Education Malaysia and Universiti Putra Malaysia.

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

References

Aditi, C., Tripathi, S., Ind, G., Dev, S., & Singh, N. (2019). Effect of fertilizer levels, biocompost and biofertilizer on content and uptake of nutrients of fodder sorghum (*Sorghum bicolor* (L.) Moench). *Excellent Publishers, 8*(10), 1130–1136. https://doi.org/10.20546/ijcmas.2019.810.132

Ahmed, N., Zhang, B., Bozdar, B., Chachar, S., Rai, M., Li, J., et al. (2023). The power of magnesium: Unlocking the potential for increased yield, quality, and stress tolerance of horticultural crops. *Frontiers in Plant Science*. https://doi.org/10.3389/fpls.2023.1285512

Alengebawy, A., Abdelkhalek, S. T., Qureshi, S. R., & Wang, Q. (2021). Heavy metals and pesticides toxicity in agricultural soil and plants: Ecological risks and human health implications. *Toxics*. https://doi.org/10.3390/toxics9030042

Balali-Mood, M., Naseri, K., Tahergorabi, Z., Khazdair, M. R., & Sadeghi, M. (2021). Toxic mechanisms of five heavy metals: mercury, lead, chromium, cadmium, and arsenic. *Frontiers in Pharmacology*. https://doi.org/10.3389/fphar.2021.643972

Bansal, O. P. (2023). The concentration of potentially toxic metals in human hair, nails, urine, blood, and air, and their impact on human health: A review. *European Journal of Theoretical and Applied Sciences, 1*(2), 185–216. https://doi.org/10.59324/ejtas.2023.1(2).18

Barłóg, P., Grzebisz, W., & Łukowiak, R. (2022). Fertilizers and fertilization strategies mitigating soil factors constraining efficiency of nitrogen in plant production. *Plants*. https://doi.org/10.3390/plants11141855

Beeby, J., Moore, S., Taylor, L., & Nderitu, S. (2020). Effects of a one-time organic fertilizer application on long-term crop and residue yields, and soil quality measurements using biointensive agriculture. *Frontiers in Sustainable Food System, 19*, 4. https://doi.org/10.3389/fsufs.2020.00067

Birkhofer, K., Smith, H. G., & Rundlöf, M. (2016). Environmental impacts of organic farming.. Available from: https://doi.org/10.1002/9780470015902.a0026341

Bridges, C. C., & Zalups, R. K. (2017). Mechanisms involved in the transport of mercuric ions in target tissues. *Archives of Toxicology, 91*(1), 63–81. https://doi.org/10.1007/s00204-016-1803-y

Chojnacka, K., & Mikulewicz, M. (2018). Biomarkers of trace element status. *Recent Advances in Trace Elements, 23*, 457–467. https://doi.org/10.1002/9781119133780.ch22

Damalas, C. A., & Koutroubas, S. D. (2016). Farmers' exposure to pesticides: Toxicity types and ways of prevention. *Multidisciplinary Digital Publishing Institute, 4*(1), 1–1. https://doi.org/10.3390/toxics4010001

Defarge, N., Vendômois, J. S. D., & Séralini, G. (2017). Toxicity of formulants and heavy metals in glyphosate-based herbicides and other pesticides. *Toxicology Reports, 30*(5), 156–163. https://doi.org/10.1016/j.toxrep.2017.12.025

Dewi, Y. A., Yulianti, A., Hanifah, V. W., Jamal, E., Sarwani, M., Mardiharini, M., Anugrah, I. S., Darwis, V., Suib, E., Herteddy, D., Sutriadi, M. T., Kurnia, A., & Harsanti, E. S. (2022). Farmers' knowledge and practice regarding good agricultural practices (GAP) on safe pesticide usage in Indonesia. *Heliyon, 8*(1), e08708. https://doi.org/10.1016/j.heliyon.2021.e08708

Ding, C., Li, X. G., Zhang, T., Ma, Y., & Wang, X. (2014). Phytotoxicity and accumulation of chromium in carrot plants and the derivation of soil thresholds for Chinese soils. *Ecotoxicology and Environmental Safety, 25*(108), 179–186. https://doi.org/10.1016/j.ecoenv.2014.07.006

Edwards, T. M., Puglis, H. J., Kent, D. B., Durán, J. L., Bradshaw, L. M., & Farag, A. M. (2024). Ammonia and aquatic ecosystems—A review of global sources, biogeochemical cycling, and effects on fish. *Science of the Total Environment, 907*, 167911. https://doi.org/10.1016/j.scitotenv.2023.167911

Elekdag-Turk, S., Almuzian, M., Turk, T. et al. (2019). Big toenail and hair samples as biomarkers for fluoride exposure – a pilot study. *BMC Oral Health, 19*, 82. https://doi.org/10.1186/s12903-019-0776-7

Genchi, G., Lauria, G., Catalano, A., Carocci, A., & Sinicropi, M. S. (2023). Prevalence of cobalt in the environment and its role in biological processes. *Biology*. https://doi.org/10.3390/biology12101335

Gong, Q., Chen, P., Shi, R., Gao, Y., Zheng, S. A., Xu, Y et a;. (2019). Health assessment of trace metal concentrations in organic fertilizer in Northern China. Multidiscip Digit Publ Inst. 2019 Mar 21;16(6):1031–1031. https://doi.org/10.3390/ijerph16061031

Gordillo, F. A., Guzmán, J. M., & Chávez, E. F. (2016). Zinc in controlled composting process based on organic waste. https://doi.org/10.13031/wtcw.2016007

He, Z., Yang, X., & Stoffella, P. J. (2005). Trace elements in agroecosystems and impacts on the environment. *Journal of Trace Elements in Medicine and Biology, 19*(2–3), 125–140. https://doi.org/10.1016/j.jtemb.2005.02.010

Hopps, H. C. (1977). The biologic bases for using hair and nail for analyses of trace elements. *Science of the Total Environment, 7*(1), 71–89. https://doi.org/10.1016/0048-9697(77)90018-3

Johansson, E., Hussain, A., Kuktaite, R., Andersson, S., & Olsson, M. (2014). Contribution of organically grown crops to human health. *International Journal of Environmental Research and Public Health, 11*(4), 3870–3893. https://doi.org/10.3390/ijerph110403870

Khan, M. N., Mobin, M., Abbas, Z. K., & Alamri, S. A. (2017). Fertilizers and their contaminants in soils, surface and groundwater. Elsevier BV. pp. 225–40. https://doi.org/10.1016/b978-0-12-809665-9.09888-8

Kroeksakul, P., Ngamniyom, A., Silprasit, K., Sutthisaksopon, P., Sriyapai, T., Phowan, N., et al. (2023). Evaluation of pesticide and heavy metal contamination on soil properties and microbiota in Thailand's mountainous region. *Pol Soc Ecol Eng., 24*(7), 331–344. https://doi.org/10.12911/22998993/165957

Ledoigt, G., Sta, C., Goujon, E., Souguir, D., & Ferjani, E. E. (2015). Synergistic health effects between chemical pollutants and electromagnetic fields. *De Gruyter*. https://doi.org/10.1515/reveh-2015-0028

Lehmann, E., Oltramare, C., Dibié, J. N., Konaté, Y., & Alencastro, L. F. D. (2017). Assessment of human exposure to pesticides by hair analysis: The case of vegetable-producing areas in Burkina Faso. *Environment International, 8*(111), 317–331. https://doi.org/10.1016/j.envint.2017.10.025

Liu, B., Huang, Q., Cai, H., Guo, X., Wang, T., & Gui, M. (2017). Distribution and speciation of chromium and cadmium in an organic and inorganic fertilized chernozem. *Elsevier BV., 27*(6), 1125–1134. https://doi.org/10.1016/s1002-0160(17)60361-8

Liu, S., Yu, F., & Zhang, J. (2022). Heavy-metal speciation distribution and adsorption characteristics of Cr (VI) in the soil within sewage irrigation areas. *International Journal of Environmental Research and Public Health, 19*(10), 6309. https://doi.org/10.3390/ijerph19106309

Machado, C. D. C., & Dinis-Oliveira, R. J. (2023). Clinical and forensic signs resulting from exposure to heavy metals and other chemical elements of the periodic table. *Journal of Clinical Medicine, 12*(7), 2591. https://doi.org/10.3390/jcm12072591

Mitra, S., Chakraborty, A. J., Tareq, A. M., Emran, T. B., Nainu, F., Khusro, A., et al. (2022). Impact of heavy metals on the environment and human health: Novel therapeutic insights to counter the toxicity. *J King Saud Univ Sci., 34*(3), 101865. https://doi.org/10.1016/j.jksus.2022.101865

Munir, N., Jahangeer, M., Bouyahya, A., Omari, N. E., Ghchime, R., Balahbib, A., et al. (2021). Heavy metal contamination of natural foods is a serious health issue: A review. *Sustainability, 14*(1), 161. https://doi.org/10.3390/su14010161

Nguyen, T. M., Le Thanh, N. T., Havukainen, J., & Hannaway, D. B. (2018). Pesticide use in vegetable production: A survey of Vietnamese farmers' knowledge. *Plant Protection Science, 54*(4), 203–214.

Nguyen, T. V., Ozaki, A., YiPing, X., Duc, A., & Kurosawa, K. (2017). Contamination of agricultural soils by toxic trace metals in an industrial district in Vietnam. *Science Domain International, 10*(3), 1–9. https://doi.org/10.9734/jgeesi/2017/33235

Palansooriya, K. N., Shaheen, S. M., Chen, S. S., Tsang, D. C., Hashimoto, Y., Hou, D., et al. (2019). Soil amendments for immobilization of potentially toxic elements in contaminated soils: A critical review. *Environment International, 134*, 105046. https://doi.org/10.1016/j.envint.2019.105046

PANAP & IPEN. (2015). Highly toxic pesticides contamination in Cameron Highlands. Pesticide Action Network Asia Pacific. Retrieved from https://ipen.org/news/pesticide-action-network-press-release-highly-toxic-pesticides-contamination-cameron-highlands

Panuwet, P., Siriwong, W., Prapamontol, T., Ryan, P. B., Fiedler, N., & Barr, D. B. (2012). Agricultural pesticide management in Thailand: Status and population health risk. *Environmental Science & Policy, 17*, 72–81.

Parizanganeh, A., Zamani, A., Bijnavand, V., & Taghilou, B. (2014). Human nail usage as a bio-indicator in contamination monitoring of heavy metals in Dizajabaad, Zanjan province-Iran. *Journal of Environmental Health Science and Engineering*. https://doi.org/10.1186/s40201-014-0147-x

Przybylowicz, A., Chesy, P., Herman, M. et al. (2012). Examination of distribution of trace elements in hair, fingernails and toenails as alternative biological materials. Application of chemometric methods. *Central European Journal of Chemistry, 10*, 1590–1599. https://doi.org/10.2478/s11532-012-0089-z

Ramakrishnan, B., Maddela, N. R., Venkateswarlu, K., & Megharaj, M. (2021). Organic farming: Does it contribute to contaminant-free produce and ensure food safety? *Science of the Total Environment, 769*, 145079. https://doi.org/10.1016/j.scitotenv.2021.145079

Reeve, J. R., Hoagland, L., Villalba, J. J., Carr, P. M., Atucha, A., Cambardella, C. A., et al. (2016). Organic farming, soil health, and food quality: Considering possible links. *Advances in Agronomy, 1*, 319–367. https://doi.org/10.1016/bs.agron.2015.12.003

Rice, K. M., Walker, E. M., Wu, M., Gillette, C., & Blough, E. R. (2014). Environmental mercury and its toxic effects. *Korean Society for Preventive Medicine, 47*(2), 74–83. https://doi.org/10.3961/jpmph.2014.47.2.74

Ruttkay-Nedecky, B., Nejdl, L., Gumulec, J., Zitka, O., Masarik, M., Eckschlager, T., et al. (2013). The role of metallothionein in oxidative stress. *International Journal of Molecular Sciences, 14*(3), 6044–6066. https://doi.org/10.3390/ijms14036044

Schweizer, S., Seitz, B., Heijden, M. G. A. V. D., Schulin, R., & Tandy, S. (2018). Impact of organic and conventional farming systems on wheat grain uptake and soil bioavailability of zinc and cadmium. *Science of the Total Environment, 25*(639), 608–616. https://doi.org/10.1016/j.scitotenv.2018.05.187

Şenbayram, M., Gransee, A., Wahle, V., & Thiel, H. (2015). Role of magnesium fertilisers in agriculture: Plant–soil continuum. *Crop & Pasture Science, 66*(12), 1219. https://doi.org/10.1071/cp15104

Sharma, A., Kaur, J., & Nagpal, A. K. (2016). Heavy metals in vegetables: screening health risks involved in cultivation along wastewater drain and irrigating with wastewater. *Springerplus*. https://doi.org/10.1186/s40064-016-2129-1

Sheoran, H. S., Phogat, V. K., Dahiya, R., Dhull, S., & Kakar, R. (2018). Comparative effect of organic and conventional farming practices on micronutrient content in different textured soils of Haryana. *International Journal of Current Microbiology and Applied Sciences., 7*(4), 3399–3407. https://doi.org/10.20546/ijcmas.2018.704.384

Skröder, H., Kippler, M., Nermell, B., Tofail, F., Levi, M., Rahman, S. M., et al. (2017). Major limitations in using element concentrations in hair as biomarkers of exposure to toxic and essential trace elements in children. *Environmental Health Perspectives*. https://doi.org/10.1289/ehp1239

Smith, O. M., Cohen, A., Rieser, C. J., Davis, A. G., Taylor, J., Adesanya, A. W., et al. (2019). Organic farming provides reliable environmental benefits but increases variability in crop yields: A global meta-analysis. *Frontiers in Sustainable Food Systems, 27*, 3. https://doi.org/10.3389/fsufs.2019.00082

Srivastav, A. L. (2020). Chemical fertilizers and pesticides: role in groundwater contamination. Elsevier BV. pp. 143–59. https://doi.org/10.1016/b978-0-08-103017-2.00006-4

Stubblefield, W. A., Genderen, E. V., Cardwell, A. S., Heijerick, D. G., Janssen, C., & Schamphelaere, K. D. (2020). Acute and chronic toxicity of cobalt to freshwater organisms: Using a species sensitivity distribution approach to establish international water quality standards. *Environmental Toxicology and Chemistry, 39*(4), 799–811. https://doi.org/10.1002/etc.4662

Tóth, T., Tomás, J. M., Lazor, P., Bajčan, D., & Jomová, K. (2009). The transfer of heavy metals from contaminated soils into agricultural plants in High Tatras region. *Czech Journal of Food Sciences, 27*(Special Issue 1), 390. https://doi.org/10.17221/600-cjfs

Tsagué Manfo, F. P., Mboe, S. A., Nantia, E. A., Ngoula, F., Telefo, P. B., Moundipa, P. F., & Cho-Ngwa, F. (2019). Evaluation of the Effects of Agro Pesticides Use on Liver and Kidney Function in Farmers from Buea, Cameroon. *Journal of Toxicology, 2020*(1), 2305764. https://doi.org/10.1155/2020/2305764

Vigani, G., & Murgia, I. (2018). Iron-requiring enzymes in the spotlight of oxygen. *Trends in Plant Science, 23*(10), 874–882. https://doi.org/10.1016/j.tplants.2018.07.005

Wahyuningsih, N. E., Setiawan, H. L., Nabiha, P. I., Kartasurya, M. I., & Azam, M. (2023). Heavy metals contamination of local and imported rice in Semarang, Central Java Indonesia. *Political Social Ecolological Engineering, 24*(7), 49–60. https://doi.org/10.12911/22998993/163308

Wang, X., Luo, X., Wang, Q., Liu, Y., & Naidu, R. (2020). Predicting the combined toxicity of binary metal mixtures (Cu–Ni and Zn–Ni) to wheat. *Ecotoxicology and Environmental Safety, 205*, 111334. https://doi.org/10.1016/j.ecoenv.2020.111334

Widowati, H., Sutanto, A., Achyani, T. F., & Hendri, N. (2020). Potential of heavy metal Cd, Pb in affecting non-organic agricultural land levels. *IOP Conference Series Material Science and Engineering, 1594*(1), 012029. https://doi.org/10.1088/1742-6596/1594/1/012029

Witkowska, D., Słowik, J., & Chilicka, K. (2021). Heavy metals and human health: Possible exposure pathways and the competition for protein binding sites. *Molecules*. https://doi.org/10.3390/molecules26196060(2021)

Yang, C., Zhang, Y., & Rheinstädter, M. C. (2014). The structure of people's hair. *PeerJ, 2*, e619. https://doi.org/10.7717/peerj.619

Shahidanasreen, Z. S., Shang, X., Zhanjiang, Xu, X., Li, Y., et al. (2011) Assessment of heavy metals in grain fields with long-term treatment of agrochemicals and organic manure in Hailun City of Northeast China. 18(2):30–35

Zhang, L. (2011). Health risk assessment of mercury exposure for the sensitive populations living along the Di'Er Songhua River region. https://doi.org/10.1109/icmt.2011.6002811

Zhang, J., Li, H., Zhou, Y., Dou, L., Cai, L., Mo, L., et al. (2018). Bioavailability and soil-to-crop transfer of heavy metals in farmland soils: A case study in the Pearl River Delta South China. *Environmental Pollution, 12*(235), 710–719. https://doi.org/10.1016/j.envpol.2017.12.106