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Meta-Analysis

Meta-Analysis of Heavy Metal Contents in Livestock and the Worldwide Potential Exposure to Human for Carcinogenic and Non-Carcinogenic Risks

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Abstract
Livestock products are vital sources of protein and amino acids essential for human health. However, they may also expose consumers to harmful substances, including heavy metals. This study aimed to assess whether heavy metal concentrations, specifically lead, copper, zinc, cadmium, mercury, and arsenic, in various livestock products pose potential carcinogenic or non-carcinogenic risks. A meta-analysis of existing studies on heavy metal concentrations in livestock products was conducted to estimate exposure levels and associated health risks. Non-carcinogenic risk values were below 1, indicating minimal health risk. For lead and arsenic, known carcinogens, the estimated excess cancer risk (ECR) in beef cattle and sheep or goat products did not exceed 1×10^{-4} but was above 1×10^{-6}. These findings suggest that while the probability of cancer incidence is low, there is still potential for carcinogenic harm from lead and arsenic in livestock products. Therefore, it is recommended that livestock products, particularly beef cattle and sheep, undergo contamination analysis before commercial distribution.
Keywords: Carcinogenic Risk, Contamination Level, Heavy Metals, Livestock Products, Meta-Analysis, Non-Carcinogenic Risk.

Introduction

Heavy metals such as lead, cadmium, and arsenic, commonly found in livestock products, are recognized as potential health hazards (Rahman *et al.,* 2012). These metals can accumulate in animal tissues, posing risks to both animals and humans who consume these products (Kabata-Pendias and Mukherjee, 2007). Chronic exposure to heavy metals can lead to bioaccumulation in vital organs such as the liver, kidneys, and brain (Tchounwou *et al.,* 2012). This accumulation may result in severe long-term health effects, including cognitive impairment, immune system dysfunction, organ failure, and even cancer due to DNA damage (Tchounwou *et al.,* 2012; Valko *et al.,* 2005). Previous studies have explored the link between livestock product consumption and cancer risk. Ma and Qi (2023) reported a significant positive correlation between global red meat consumption and cancer incidence. Similarly, Cross *et al.,* (2007) found statistically significant associations between red meat consumption and increased risks of esophageal, colorectal, liver, and lung cancers in individuals over 50 years old.

This study aims to evaluate whether exposure to heavy metals through livestock products poses potential health risks. Given that heavy metal exposure may vary globally due to differences in animal husbandry practices and feed quality, this study employs meta-analysis and literature review to assess heavy metal concentrations in various livestock products. The analysis focuses on estimating both carcinogenic and non-carcinogenic risks associated with the intake of heavy metals, including lead, copper, zinc, cadmium, mercury, and arsenic.

Materials and Methods

Meta-Analysis and Literature Review on Heavy Metal Contents in Livestock

A meta-analysis was conducted to evaluate the concentrations of heavy metals in livestock products. Figure 1 illustrates the process used in the literature review to identify relevant studies reporting heavy metal concentrations, including lead (Pb), copper (Cu), zinc (Zn), cadmium (Cd), mercury (Hg), and arsenic (As).

Google Scholar served as the primary search engine for locating pertinent publications. Keyword combinations related to heavy metals and their levels in livestock tissues were used to identify relevant studies.

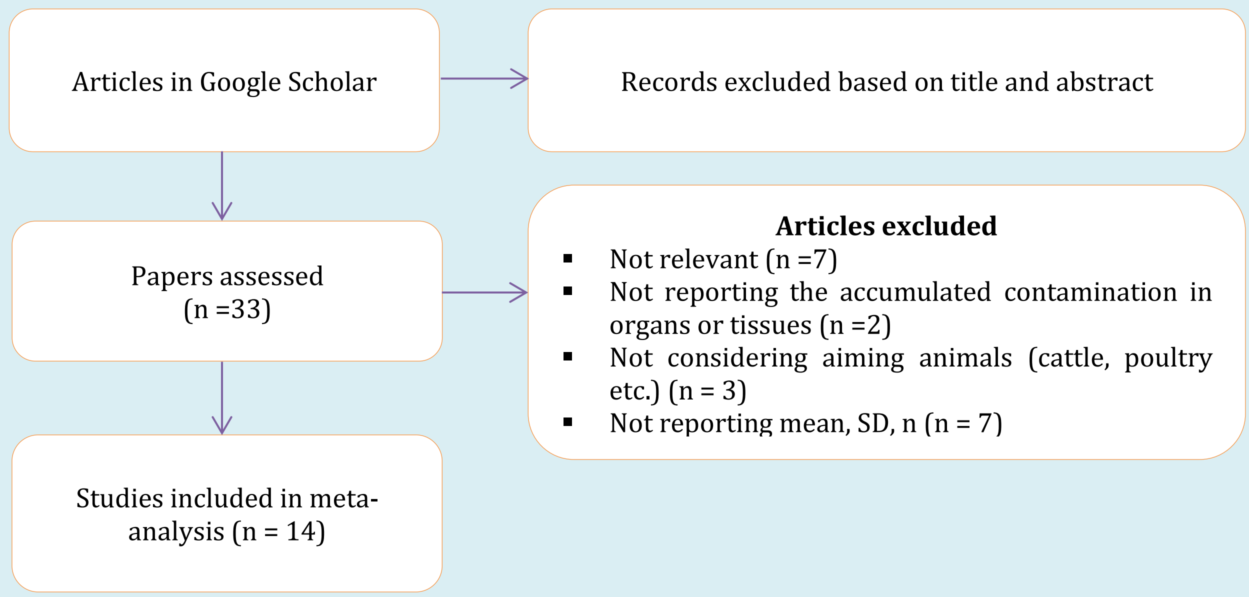

Figure 1. Design for literature review.

The data collected from the selected papers were analyzed through the DerSimonian-Laird random-effects model using Jeffrey's Amazing Statistics Program (JASP) version 0.19.0.0. The program provided the data for the mean concentrations of each heavy metal for products from different livestock such as beef cattle, poultries, swine, goat, and sheep.

Estimation of Exposure

The exposure to the target heavy metals through the intake of livestock products was calculated using the following equation (US-EPA, 2019; Hashemi *et al.,* 2023; Hur, 2024).

$$EDI = C \times IR/BW \qquad \text{(Eq. 1)}$$

EDI (mg/kg-day): Estimated daily intake
C (mg/kg): Concentration of heavy metal in livestock product
IR (kg/day): Ingestion rate of livestock product
BW (kg): The body weight of an individual

The meta-analysis results for the average content of different heavy metals in different livestock products have been used for the value of C. The annual meat consumption per capita for different livestock products, provided by the Food and Agriculture Organization of the United Nations (FAO) was used for estimating the IR value (FAO, 2023; Our World in Data, 2023). As presented in Table 1, the average annual per capita meat consumption data for Africa, America, Asia, Europe, and Oceania during 2017-2021 has been considered. The average meat consumption worldwide was calculated as the mean of the collected data from all selected continents. As for BW, a value of 70kg has been considered the average body weight for an adult.

Table 1. Average meat consumption for different regions (FAO, 2023; Our World in Data, 2023).

Region	**Average meat consumption (kg-meat/year-capita)**			
	Beef	**Poultry**	**Goat/sheep**	**Pork**
Worldwide	16.925	27.768	2.551	17.945
Asia	5.149	11.250	2.128	14.111
Africa	5.577	6.705	2.378	1.594
North America	27.364	46.997	0.650	23.552
South America	29.062	41.159	0.680	12.527
Europe	14.118	25.512	1.689	34.816
Oceania	20.280	34.988	7.778	21.071

Risk Assessment

The non-carcinogenic and carcinogenic risk for intake of the aimed heavy metals, including Pb, Cu, Zn, Cd, Hg, and As in different livestock products have been assessed based on the estimated daily intake. The non-carcinogenic risk has been calculated using the equation below (US-EPA, 1986).

Non-carcinogenic risk = EDI/RfD (Eq. 2)
EDI (mg/kg-day): Estimated daily intake
RfD (mg/kg-day): Reference dose

The equation below was used to estimate the excess cancer risk for carcinogenic elements (US-EPA, 2005).

ECR = EDI × CSF (Eq. 3)
ECR: Excess cancer risk
EDI (mg/kg-day): Estimated daily intake
CSF (per mg/kg-day): Cancer slope factor

For each targeted heavy metal, non-carcinogenic and carcinogenic toxicity information was obtained by reviewing materials and documents presented by authorized organizations, as shown in Table 2.

Table 2. Non-carcinogenic and carcinogenic toxicity of targeted heavy metals.

Targeted heavy metals	Non-carcinogenic toxicity		Carcinogenic toxicity	
	RfD (mg/kg-day)	Reference	CSF (per mg/kg-day)	Reference
Lead (Pb)	0.0036	JECFA, 1994	0.0085	OEHHA, 2009
Copper (Cu)	0.04	US-EPA, 1997	-	-
Zinc (Zn)	0.3	US-EPA IRIS, 2005	-	-
Cadmium (Cd)	0.001	US-EPA IRIS, 1989	-	-
Mercury (Hg)	0.00006	MDEQ, 1995	-	-
Arsenic (As)	0.0003	US-EPA IRIS, 1991	1.50	US-EPA IRIS, 1991

Results and Discussion

Summary of Literature Review

Abdelbasset *et al.,* (2014) investigated the content of lead, copper, zinc, and cadmium in the liver, lung, meat, heart, and kidneys of cattle and sheep in Casablanca, Morocco from March to April 2013. The concentration analysis was done through inductively coupled plasma-atomic emission spectroscopy (ICP-AES). Njoga *et al.,* (2021) investigated arsenic, cadmium, and lead levels in the liver, kidney, and muscle tissues of goats in South-Eastern Nigeria (Enugu State) using flame atomic absorption spectrophotometry.

Several significant studies from Korea have been reviewed. Hwang *et al.,* (2011) conducted a study to analyze lead, cadmium, arsenic, and mercury levels in cattle, swine, and chicken muscle tissues through inductively coupled plasma mass spectrometry (ICP-MS) and a mercury analyzer. The study took place in seven regions across Korea, including Seoul, Gyeonggi, Chung-Cheong, Honam, Kangwon, and Kyung-Sang, from May to October 2008. Kim *et al.,* (2016) conducted a study on the levels of lead and cadmium in the muscle, liver, and kidneys of cattle, swine, and chicken in Korea from 2010 to 2012. They analyzed the concentration using inductively coupled plasma mass spectrometry (ICP-MS) after microwave digestion.

Kim *et al.,* (2017) investigated the content of lead, zinc, cadmium, and arsenic in the muscle of swine from Suncheon, Naju, Chungju, Gangjin, and Yongin cities in Korea. The concentration analysis was done by the ICP-MS method and the inductively coupled plasma-optical emission spectroscopy (ICP-OES) method. Song *et al.,* (2021) investigated the content of lead, zinc, cadmium, and arsenic in the muscles of swine from conventional and animal welfare farms in South Korea from 2018 to 2019. The concentration analysis was done by the ICP-OES and the ICP-MS techniques.

Zeinali *et al.,* (2019) investigated the content of lead, copper, and cadmium in the muscle, liver, and kidney of cattle and sheep from Birjand, Southeast Iran, starting from January 2017 to September 2017. The concentration analysis was done by the ICP-OES method. de Souza Ramos *et al.,* (2019) investigated the content of lead, copper, and zinc in the muscle of cattle and chicken from the city of Campos dos Goytacazes, state of Rio de Janeiro in southeastern Brazil. The samples were obtained between July and December 2014. The concentration analysis was done by ICP-OES.

Badis *et al.,* (2014) conducted a study to analyze the lead, copper, zinc, cadmium, and mercury levels in fresh meat from cattle, sheep, and chickens in Algeria. The samples were collected in 2012 from the north and south regions of the country. They used an atomic absorption spectrophotometer to measure the concentration of contaminants. Ribeiro and Germano (2015) investigated the content of mercury in each cattle swine kidney, and chicken muscle from Brazilian farms. The concentration analysis was done by inductively coupled plasma mass spectrometry (ICP-MS).

Nawrocka *et al.,* (2020) conducted a decade-long study from 2009 to 2018 in Poland. The study focused on analyzing muscle tissues and liver samples from broiler chickens, domestic cattle, and pigs to assess mercury contamination. The detection of mercury was carried out using atomic absorption spectrometry. Ertaş *et al.,* (2021) conducted a study to measure the total arsenic content in poultry and calf meat samples. They utilized a cost-effective and simple method called hydride generation atomic fluorescence spectrometry (HG-AFS). The samples were collected from local markets in the Republic of Türkiye.

Datta *et al.,* (2012) analyzed the arsenic concentration in different organs of poultry birds in India. The samples were collected from Polba, Mitrapur, and Mandal Hat. The birds had been raised for over two years. The total amount of arsenic was determined using an atomic absorption spectrometer. In a study conducted by Makridis *et al.,* (2012), lead, copper, zinc, and cadmium levels in the muscle tissues, liver, and kidneys of cows and sheep in central Greece were analyzed during May and June over three years using atomic absorption spectrometry. The cadmium concentration in sheep's muscle tissues and copper in cow and sheep's muscle tissues was below 0.02 mg/kg. Additionally, lead contamination level was below 0.02 mg/kg for all livestock products.

The results of the literature review for the contents of lead, copper, zinc, mercury, and arsenic in different livestock products are summarized in Table 3 to Table 8.

Table 3. Summary of literature review for lead.

Study	Livestock	Organ	Content of contamination (μg/g)			
			Mean	SD	n	SE
Abdelbasset *et al.,* (2014)	Beef cattle	Liver	1.17	0.34	50	0.05
		Lung	0.74	0.09	50	0.01
		Muscle	0.78	0.02	50	0.003
		Heart	0.76	0.17	50	0.02
		Kidney	0.66	0.11	50	0.02
	Goat/sheep	Liver	1.17	0.19	50	0.02
		Lung	1.13	0.12	50	0.02
		Muscle	0.85	0.08	50	0.01
		Heart	1.28	0.27	50	0.04
		Kidney	1.03	0.25	50	0.04
Badis *et al.,* (2014)	Poultry (North region)	Muscle	8.8	0.37	10	0.12
	Beef cattle (North region)		7.76	0.05	10	0.02
	Goat/sheep (North region)		3.49	0.11	10	0.04
	Poultry (South region)		8.18	1.81	10	0.57
	Beef cattle (South region)		5.85	0.05	10	0.02
	Goat/sheep (South region)		3.57	0.21	10	0.07
Hwang *et al.,* (2011)	Beef cattle	Muscle	0.009	0.008	103	0.0008
	Swine		0.01	0.008	125	0.0007
	Poultry		0.006	0.004	100	0.0004
Kim *et al.,* (2016)	Beef cattle	Muscle	0.003	0.005	69	0.0006
		Liver	0.02	0.01	69	0.001
		Kidney	0.03	0.01	69	0.002
	Swine	Muscle	0.009	0.02	63	0.003
		Liver	0.009	0.01	63	0.001
		Kidney	0.05	0.04	63	0.005
	Poultry	Muscle	0.005	0.01	61	0.001
		Liver	0.004	0.007	61	0.0009
		Kidney	0.007	0.009	61	0.001

Kim *et al.*, (2017)	Swine	Muscle	0.05	0.07	227	0.004
Njoga *et al.*, (2021)	Goat/sheep	Kidney	0.48	8.06	450	0.38
		Liver	0.45	5.09	450	0.24
		Muscle	0.82	8.27	450	0.39
de Souza Ramos *et al.*, (2019)	Beef cattle	Muscle	0.05	0.02	73	0.002
	Poultry	Muscle	0.07	0.06	75	0.006
Song *et al.*, (2021)	Swine (Animal welfare farm A)	Muscle	0.01	0.003	30	0.0005
	Swine (Animal welfare farm B)		0.02	0.02	30	0.003
	Swine (Animal welfare farm C)		0.03	0.04	30	0.007
	Swine (Conventional farm A)		0.02	0.004	30	0.0007
	Swine (Conventional farm B)		0.01	0.003	30	0.0005
	Swine (Conventional farm C)		0.02	0.007	30	0.001
Zeinali *et al.*, (2019)	Beef cattle	Muscle	0.04	0.01	17	0.003
		Liver	0.07	0.01	17	0.003
		Kidney	0.08	0.02	17	0.005
	Goat/sheep	Muscle	0.05	0.03	17	0.007
		Liver	0.10	0.03	17	0.007
		Kidney	0.08	0.03	17	0.008

Table 4. Summary of literature review for copper.

Study	Livestock	Organ	Content of contamination (μg/g)			
			Mean	**SD**	**n**	**SE**
Abdelbasset *et al.*, (2014)	Beef cattle	Liver	22	7.07	50	1.00
		Lung	4.35	1.24	50	0.18
		Muscle	1.42	0.21	50	0.03
		Heart	3.04	0.65	50	0.09
		Kidney	4.52	0.57	50	0.08
	Goat/sheep	Liver	18.6	6.50	50	0.92
		Lung	1.06	0.39	50	0.06
		Muscle	0.8	0.14	50	0.02
		Heart	2.48	0.45	50	0.06
		Kidney	3.1	0.85	50	0.12
Badis *et al.*, (2014)	Poultry (North region)	Muscle	2.3	0.13	10	0.04
	Beef cattle (North region)		12.4	0.29	10	0.09
	Goat/sheep (North region)		2.56	0.15	10	0.05
	Poultry (South region)		2.31	0.15	10	0.05
	Beef cattle (South region)		9.59	0.52	10	0.16
	Goat/sheep (South region)		3.84	0.21	10	0.07
de Souza Ramos *et al.*, (2019)	Beef cattle	Muscle	0.59	0.17	73	0.02
	Poultry		0.26	0.13	75	0.015
Zeinali *et al.*, (2019)	Beef cattle	Muscle	0.72	0.26	17	0.06
		Liver	11.7	14.6	17	3.54
		Kidney	3.42	0.38	17	0.09
	Goat/sheep	Muscle	0.82	0.28	17	0.07
		Liver	24.2	29.4	17	7.13
		Kidney	3.00	0.41	17	0.10

Table 5. Summary of literature review for zinc.

Study	Livestock	Organ	Content of contamination (μg/g)			
			Mean	**SD**	**n**	**SE**
Abdelbasset *et al.*, (2014)	Beef cattle	Liver	9.56	0.47	50	0.07
		Lung	8.72	1.56	50	0.2
		Muscle	9.04	0.17	50	0.02
		Heart	4.35	0.34	50	0.05
		Kidney	5.39	0.99	50	0.14

	Goat/sheep	Liver	8.73	0.31	50	0.04
		Lung	3.3	1.01	50	0.14
		Muscle	6.97	0.17	50	0.02
		Heart	3.54	0.7	50	0.10
		Kidney	6.29	0.45	50	0.06
Badis *et al.*, (2014)	Poultry (North region)	Muscle	27.9	1.11	10	0.35
	Beef cattle (North region)		37.0	3.10	10	0.98
	Goat/sheep (North region)		39.6	3.00	10	0.95
	Poultry (South region)		36.9	1.71	10	0.54
	Beef cattle (South region)		78.2	7.74	10	2.45
	Goat/sheep (South region)		148	6.15	10	1.94
Kim *et al.*, (2017)	Swine	Muscle	3.75	6.04	323	0.34
de Souza Ramos *et al.*, (2019)	Beef cattle	Muscle	47.8	12.7	73	1.49
	Poultry		5.29	1.93	75	0.22
Song *et al.*, (2021)	Swine (Animal welfare farm A)	Muscle	13.5	1.12	30	0.20
	Swine (Animal welfare farm B)		14.8	1.47	30	0.27
	Swine (Animal welfare farm C)		13.0	1.88	30	0.34
	Swine (Conventional farm A)		12.2	0.79	30	0.14
	Swine (Conventional farm B)		14.1	1.93	30	0.35
	Swine (Conventional farm C)		13.5	1.32	30	0.24
Makridis *et al.*, (2012)	Beef cattle	Muscle	38.3	2.6	45	0.39
		Liver	23.5	2.5	60	0.32
		Kidney	13	2.5	63	0.31
	Goat/sheep	Muscle	47.5	4.5	40	0.71
		Liver	11.3	2	39	0.32
		Kidney	13.5	3	39	0.48

Table 6. Summary of literature review for cadmium.

Study	**Livestock**	**Organ**	**Content of contamination (μg/g)**			
			Mean	**SD**	**n**	**SE**
Abdelbasset *et al.*, (2014)	Beef cattle	Liver	0.1	0.1	50	0.01
		Kidney	0.21	0.1	50	0.01
	Goat/sheep	Liver	0.04	0.02	50	0.003
		Lung	0.006	0.009	50	0.001
		Heart	0.006	0.01	50	0.001
		Kidney	0.09	0.06	50	0.008
Badis *et al.*, (2014)	Poultry (North region)	Muscle	1.39	0.05	10	0.02
	Beef cattle (North region)		1.56	0.19	10	0.06
	Goat/sheep (North region)		1.39	0.15	10	0.05
	Poultry (South region)		1.49	0.21	10	0.07
	Beef cattle (South region)		1.71	0.23	10	0.07
	Goat/sheep (South region)		1.31	0.07	10	0.02
Hwang *et al.*, (2011)	Beef cattle	Muscle	0.0004	0.0004	103	0.00004
	Swine		0.0004	0.0002	125	0.00002
	Poultry		0.0005	0.0004	100	0.00004
Kim *et al.*, (2016)	Beef cattle	Muscle	0.0003	0.0005	69	0.00006
		Liver	0.02	0.01	69	0.001
		Kidney	0.06	0.03	69	0.004
	Swine	Muscle	0.0006	0.0009	63	0.0001
		Liver	0.03	0.05	63	0.006
		Kidney	0.13	0.07	63	0.009
	Poultry	Muscle	0.0005	0.0005	61	0.00007
		Liver	0.02	0.05	61	0.006
		Kidney	0.04	0.08	61	0.01
Kim *et al.*, (2017)	Swine	Muscle	0.0006	0.002	323	0.0001
Njoga *et al.*, (2021)	Goat/sheep	Kidney	0.06	6.79	450	0.32
		Liver	0.02	0.02	450	0.001

		Muscle	0.02	0.02	450	0.001
Song *et al.*, (2021)	Swine (Animal welfare farm A)	Muscle	0.0003	0.0005	30	0.00008
	Swine (Animal welfare farm B)		0.0002	0.0002	30	0.00003
	Swine (Animal welfare farm C)		0.002	0.001	30	0.0002
	Swine (Conventional farm A)		0.0002	0.00005	30	0.00001
	Swine (Conventional farm B)		0.00005	0.00007	30	0.00001
	Swine (Conventional farm C)		0.002	0.0009	30	0.0002
Zeinali *et al.*, (2019)	Beef cattle	Muscle	0.01	0.002	17	0.0005
		Liver	0.02	0.01	17	0.003
		Kidney	0.19	0.27	17	0.07
	Goat/sheep	Muscle	0.01	0.002	17	0.0006
		Liver	0.03	0.01	17	0.003
		Kidney	0.13	0.11	17	0.03
Makridis *et al.*, (2012)	Beef cattle	Muscle	1.3	0.3	45	0.04
		Liver	1.4	0.3	60	0.04
		Kidney	1.8	0.4	63	0.05
	Goat/sheep	Liver	1.4	0.3	39	0.05
		Kidney	2.3	0.5	39	0.08

Table 7. Summary of literature review for mercury.

Study	**Livestock**	**Organ**	**Content of contamination (µg/g)**			
			Mean	**SD**	**n**	**SE**
Badis *et al.*, (2014)	Poultry (North region)	Muscle	0.015	0.081	10	0.026
	Beef cattle (North region)		0.051	0.113	10	0.036
	Goat/sheep (North region)		0.027	0.097	10	0.031
	Poultry (South region)		0.009	0.016	10	0.005
	Beef cattle (South region)		0.32	0.113	10	0.036
	Goat/sheep (South region)		0.2	0.065	10	0.02
Hwang *et al.*, (2011)	Beef cattle	Muscle	0.0007	0.001	103	0.0001
	Swine		0.0009	0.001	125	0.0001
	Poultry		0.0007	0.0006	100	0.00006
Ribeiro and Germano (2015)	Beef cattle	Kidney	0.062	0.34	6	0.14
	Swine		0.061	0.35	6	0.14
	Poultry	Muscle	0.063	0.35	6	0.14
Nawrocka *et al.*, (2020)	Beef cattle	Muscle	0.0008	0.0012	1227	0.00003
	Swine		0.0008	0.0014	2368	0.00003
	Poultry		0.0006	0.0007	914	0.00002
	Beef cattle	Liver	0.002	0.002	1227	0.00006
	Swine		0.001	0.002	2368	0.00004
	Poultry		0.0008	0.001	914	0.00004

Table 8. Summary of literature review for arsenic.

Study	**Livestock**	**Organ**	**Content of contamination (µg/g)**			
			Mean	**SD**	**n**	**SE**
Hwang *et al.*, (2011)	Beef cattle	Muscle	0.016	0.015	103	0.0015
	Swine		0.004	0.004	125	0.0004
	Poultry		0.021	0.026	100	0.003
Kim *et al.*, (2017)	Swine	Muscle	0.013	0.054	323	0.003
Njoga *et al.*, (2021)	Goat/sheep	Kidney	0.53	2.12	450	0.10
		Liver	0.57	1.91	450	0.09
		Muscle	0.45	1.70	450	0.08
Song *et al.*, (2021)	Swine (Animal welfare farm A)	Muscle	0.010	0.0007	30	0.0001
	Swine (Animal welfare farm		0.010	0.002	30	0.0004

	B)					
	Swine (Animal welfare farm C)		0.018	0.002	30	0.0003
	Swine (Conventional farm A)		0.010	0.003	30	0.0005
	Swine (Conventional farm B)		0.009	0.001	30	0.0003
	Swine (Conventional farm C)		0.019	0.004	30	0.0007
Ertaş *et al.,* (2021)	Beef cattle	Muscle	0.016	0.0015	3	0.0009
			0.014	0.002	3	0.0012
			0.005	0.0011	3	0.0006
			0.011	0.0009	3	0.0005
			0.015	0.0012	3	0.0007
			0.011	0.0006	3	0.0004
			0.006	0.0009	3	0.0005
			0.015	0.0008	3	0.0005
			0.014	0.0006	3	0.0004
			0.015	0.0025	3	0.0014
			0.011	0.0008	3	0.00046
	Poultry		0.003	0.0002	3	0.00012
			0.004	0.0003	3	0.00017
			0.002	0.0003	3	0.00017
			0.002	0.0002	3	0.00012
			0.001	0.0005	3	0.00029
			0.002	0.0006	3	0.00035
			0.003	0.0001	3	0.00006
			0.006	0.0007	3	0.00040
			0.002	0.0006	3	0.00035
			0.004	0.0006	3	0.00035
			0.004	0.0004	3	0.00023
			0.003	0.0001	3	0.00006
			0.001	0.0002	3	0.00012
			0.003	0.0001	3	0.00006
Datta *et al.,* (2012)	Poultry	Muscle	0.02	0.0268	20	0.006
			0.03	0.031	20	0.007
			0.03	0.031	20	0.007
		Lung	0.02	0.031	20	0.007
			0.04	0.040	20	0.009
			0.02	0.027	20	0.006
		Liver	0.02	0.022	20	0.005
			0.07	0.072	20	0.016
			0.02	0.03	20	0.006
		Kidney	0.03	0.03	20	0.007
			0.098	0.085	20	0.019
			0.053	0.045	20	0.01
		Bone	0.049	0.054	20	0.012
			0.074	0.085	20	0.019
			0.063	0.094	20	0.021
		Heart	0.018	0.022	20	0.005
			0.071	0.081	20	0.018
			0.019	0.027	20	0.006

Results of Meta-Analysis for Content of Contamination, Exposure, and Risk Assessment

1. Lead

The summary of meta-data analysis is presented in Table 9.

Results indicate that the lead concentration in livestock products from beef cattle is the highest among the rest of the target livestock by a concentration of 1.2µg/g, while products from swine had the lowest concentration at 0.018µg/g. Additionally, the results showed a heterogeneity index above 90%.

Table 9. The meta-analysis results for studies targeting lead in livestock products.

Livestock	Content of contamination (μg/g)			I^2 (%)	Remarks
	Mean	SE	95% CI		
Beef cattle	1.200	0.088	1.028-1.372	99.99	Overall value regardless of organs
Poultry	0.189	0.017	0.156-0.222	99.90	
Goat/sheep	1.142	0.173	0.802-1.481	99.94	
Swine	0.018	0.001	0.015-0.021	94.76	

Based on the meta-analysis findings, the average exposure to lead from consuming various livestock products is summarized in Table 10.

Globally, the trend for lead exposure from livestock products is as follows: beef > poultry > goat/sheep > pork. Lead exposure from consuming beef, poultry, goat/sheep, and pork was highest in South America, North America, Oceania, and Europe, respectively.

Table 10. Estimation of regional exposure to lead from ingestion of different livestock products.

Region	Exposure to lead from livestock products (mg/kg-day)			
	Beef	Poultry	Goat/sheep	Pork
Worldwide	7.95×10^{-4}	2.05×10^{-4}	1.14×10^{-4}	1.26×10^{-5}
Asia	2.42×10^{-4}	8.32×10^{-5}	9.51×10^{-5}	9.94×10^{-6}
Africa	2.62×10^{-4}	4.96×10^{-5}	1.06×10^{-4}	1.12×10^{-6}
North America	1.29×10^{-3}	3.48×10^{-4}	2.90×10^{-5}	1.66×10^{-5}
South America	1.36×10^{-3}	3.04×10^{-4}	3.04×10^{-5}	8.83×10^{-6}
Europe	6.63×10^{-4}	1.89×10^{-4}	7.55×10^{-5}	2.45×10^{-5}
Oceania	9.52×10^{-4}	2.59×10^{-4}	3.48×10^{-4}	1.48×10^{-5}

The non-carcinogenic and carcinogenic risk of regional exposure to lead from different livestock products is assessed and presented in Tables 11 and 12, respectively. All non-carcinogenic risk values for different regions and livestock products were below 1, indicating a negligible non-carcinogenic health hazard potential. The excess cancer risk values for all regions and livestock products were estimated to be below 1×10^{-4}, suggesting a low likelihood of carcinogenic health effects from the estimated exposure.

Table 11. Assessment of non-carcinogenic risk of regional exposure to lead from ingestion of different livestock products.

Region	Beef	Poultry	Goat/sheep	Pork
Worldwide	0.223	0.058	0.032	0.004
Asia	0.068	0.023	0.027	0.003
Africa	0.073	0.014	0.030	0.0003
North America	0.360	0.097	0.008	0.005
South America	0.382	0.085	0.009	0.002
Europe	0.186	0.053	0.021	0.007
Oceania	0.267	0.072	0.097	0.004

Table 12. Assessment of excess cancer risk of regional exposure to lead from ingestion of different livestock products.

Region	Beef	Poultry	Goat/sheep	Pork
Worldwide	6.76×10^{-6}	1.75×10^{-6}	9.69×10^{-7}	1.07×10^{-7}
Asia	2.06×10^{-6}	7.07×10^{-7}	8.09×10^{-7}	8.45×10^{-8}
Africa	2.23×10^{-6}	4.22×10^{-7}	9.04×10^{-7}	9.55×10^{-9}
North America	1.09×10^{-5}	2.95×10^{-6}	2.47×10^{-7}	1.41×10^{-7}
South America	1.16×10^{-5}	2.59×10^{-6}	2.58×10^{-7}	7.50×10^{-8}
Europe	5.64×10^{-6}	1.60×10^{-6}	6.42×10^{-7}	2.08×10^{-7}
Oceania	8.10×10^{-6}	2.20×10^{-6}	2.95×10^{-6}	1.26×10^{-7}

2. Copper

As presented in Table 13, the meta-analysis results yield that beef cattle livestock products have the highest copper concentration at 6.24μg/g compared to other targeted livestock, while poultry products have the lowest concentration at 1.62μg/g. The analysis indicated a heterogeneity index exceeding 99%.

Table 13. The meta-analysis results for studies targeting copper in livestock products.

Livestock	Content of contamination (µg/g)			I^2 (%)	Remarks
	Mean	SE	95% CI		
Beef cattle	6.236	0.873	4.524-7.947	99.95	Overall value regardless organs
Poultry	1.622	0.811	0.033-3.212	99.94	
Goat/sheep	3.523	0.431	2.678-4.368	99.78	

According to the meta-analysis, Table 14 summarizes the average exposure to copper from consuming different livestock products. The global trend for exposure to copper from livestock products is as follows: beef > poultry > goat/sheep. The highest exposure to copper from beef ingestion was in South America, while for poultry and goat/sheep ingestion, North America and Oceania had the highest exposures, respectively.

Table 14. Estimation of regional exposure to copper from ingestion of different livestock products.

Region	Exposure to copper from livestock products (mg/kg-day)		
	Beef	Poultry	Goat/sheep
Worldwide	7.95×10^{-4}	2.05×10^{-4}	1.14×10^{-4}
Asia	2.42×10^{-4}	8.32×10^{-5}	9.51×10^{-5}
Africa	2.62×10^{-4}	4.96×10^{-5}	1.06×10^{-4}
North America	1.29×10^{-3}	3.48×10^{-4}	2.90×10^{-5}
South America	1.36×10^{-3}	3.04×10^{-4}	3.04×10^{-5}
Europe	6.63×10^{-4}	1.89×10^{-4}	7.55×10^{-5}
Oceania	9.52×10^{-4}	2.59×10^{-4}	3.48×10^{-4}

The non-carcinogenic risk of regional exposure to copper from different livestock products is assessed and presented in Table 15. All non-carcinogenic risk values for different regions and livestock products were below 1, indicating a low non-carcinogenic health hazard potential.

Table 15. Assessment of non-carcinogenic risk of regional exposure to copper from ingestion of different livestock products.

Region	Beef	Poultry	Goat/sheep
Worldwide	0.103	0.044	0.009
Asia	0.031	0.018	0.007
Africa	0.034	0.011	0.008
North America	0.167	0.075	0.002
South America	0.177	0.065	0.002
Europe	0.086	0.040	0.006
Oceania	0.124	0.056	0.027

3. Zinc

The summary of meta-data analysis, as presented in Table 16, indicates that the zinc concentration in livestock products from goats or sheep is the highest among the rest of the target livestock by a concentration of 25.2µg/g, while products from swine had the lowest concentration at 12.1µg/g. Additionally, the results showed a heterogeneity index above 99%.

Table 16. The meta-analysis results for studies targeting zinc in livestock products

Livestock	Content of contamination (µg/g)			I^2 (%)	Remarks
	Mean	SE	95% CI		
Beef cattle	23.3	1.241	20.9-25.7	99.948	Overall value regardless organs
Poultry	23.4	9.971	3.84-42.9	99.959	
Goat/sheep	25.2	1.002	23.2-27.2	99.934	
Swine	12.1	1.076	10.0-14.2	99.262	

Table 17 summarizes the average exposure to zinc from consuming different livestock products. The worldwide trend for exposure to zinc from livestock products is poultry > beef > pork > goat/sheep. The highest exposure to zinc from beef ingestion was in South America, while for poultry it was in North America and for goat/ sheep it was in Oceania. Finally, Europe showed the highest exposure to zinc from pork ingestion.

Table 17. Estimation of regional exposure to zinc from ingestion of different livestock products.

Region	Exposure to zinc from livestock products (mg/kg-day)			
	Beef	**Poultry**	**Goat/sheep**	**Pork**
Worldwide	1.54×10^{-2}	2.54×10^{-2}	2.52×10^{-3}	8.50×10^{-3}
Asia	4.70×10^{-3}	1.03×10^{-2}	2.10×10^{-3}	6.69×10^{-3}
Africa	5.09×10^{-3}	6.14×10^{-3}	2.35×10^{-3}	7.55×10^{-4}
North America	2.50×10^{-2}	4.30×10^{-2}	6.41×10^{-3}	1.12×10^{-2}
South America	2.65×10^{-2}	3.77×10^{-2}	6.71×10^{-3}	5.94×10^{-3}
Europe	1.29×10^{-2}	2.33×10^{-2}	1.67×10^{-3}	1.65×10^{-2}
Oceania	1.85×10^{-2}	3.20×10^{-2}	7.67×10^{-3}	9.98×10^{-3}

Assessment of non-carcinogenic risk from various livestock products is presented in Table 18. All non-carcinogenic risk values for different regions and livestock products were below 1, indicating low health hazards.

Table 18. Assessment of non-carcinogenic risk of regional exposure to zinc from ingestion of different livestock products.

Region	Beef	Poultry	Goat/sheep	Pork
Worldwide	0.051	0.085	0.008	0.028
Asia	0.016	0.034	0.007	0.022
Africa	0.017	0.020	0.008	0.003
North America	0.083	0.143	0.002	0.037
South America	0.088	0.126	0.002	0.020
Europe	0.043	0.078	0.006	0.055
Oceania	0.062	0.107	0.026	0.033

4. Cadmium

The summary of meta-data analysis for cadmium is presented in Table 19. Results indicate that the cadmium concentration in livestock products from goats or sheep is the highest among the rest of the target livestock by a concentration of 0.28μg/g. This is while products from swine had the lowest concentration at 0.0007μg/g. The results showed a heterogeneity index above 99%.

Table 19. The meta-analysis results for studies targeting cadmium in livestock products.

Livestock	Content of contamination (μg/g)			I^2 (%)	Remarks
	Mean	**SE**	**95% CI**		
Beef cattle	0.027	0.002	0.024-0.030	99.8	Overall value regardless organs
Poultry	0.065	0.003	0.059-0.071	99.9	
Goat/sheep	0.280	0.012	0.256-0.304	99.8	
Swine	0.0007	0.00008	0.0005-0.0008	98.8	

Table 20 presents a summary of the average exposure to cadmium through the consumption of various livestock products. Globally, the trend for cadmium exposure from livestock products is as follows: poultry > goat/sheep > beef > pork. The highest cadmium exposure from beef consumption was reported in South America, while North America showed the highest exposure from poultry consumption and Oceania from goat/sheep consumption. Lastly, Europe exhibited the highest cadmium exposure from pork consumption.

Table 20. Estimation of regional exposure to cadmium from ingestion of different livestock products.

Region	Exposure to cadmium from livestock products (mg/kg-day)			
	Beef	**Poultry**	**Goat/sheep**	**Pork**
Worldwide	1.79×10^{-5}	7.06×10^{-5}	2.80×10^{-5}	4.92×10^{-7}
Asia	5.44×10^{-6}	2.86×10^{-5}	2.33×10^{-5}	3.87×10^{-7}
Africa	5.89×10^{-6}	1.71×10^{-5}	2.61×10^{-5}	4.37×10^{-8}
North America	2.89×10^{-5}	1.20×10^{-5}	7.12×10^{-5}	6.45×10^{-7}
South America	3.07×10^{-5}	1.05×10^{-5}	7.45×10^{-6}	3.43×10^{-7}
Europe	1.49×10^{-5}	6.49×10^{-5}	1.85×10^{-5}	9.54×10^{-7}
Oceania	2.14×10^{-5}	8.90×10^{-5}	8.52×10^{-5}	5.77×10^{-7}

Assessment of the non-carcinogenic risk from cadmium exposure through various livestock products is detailed in Table 21. All non-carcinogenic risk values for different regions and livestock products were below 1, indicating low health hazards.

Table 21. Assessment of non-carcinogenic risk of regional exposure to cadmium from ingestion of different livestock products.

Region	Beef	Poultry	Goat/sheep	Pork
Worldwide	0.018	0.071	0.028	0.0005
Asia	0.005	0.029	0.023	0.0004
Africa	0.006	0.017	0.026	0.0000
North America	0.029	0.120	0.007	0.001
South America	0.031	0.105	0.007	0.0003
Europe	0.015	0.065	0.019	0.001
Oceania	0.021	0.089	0.085	0.001

5. Mercury

The summary of meta-data analysis for the mercury concentration in different livestock products is presented in Table 22. Results indicate that the mercury concentration in livestock products from goats or sheep is the highest among the rest of the target livestock by a concentration of 0.12μg/g, while products from swine had the lowest concentration at 0.0007μg/g. Additionally, the results showed a heterogeneity index above 79%.

Table 22. The meta-analysis results for studies targeting mercury in livestock products.

Livestock	Content of contamination (μg/g)			I^2 (%)	Remarks
	Mean	SE	95% CI		
Beef cattle	0.001	0.0005	0.0003-0.002	98.8	Overall value regardless organs
Poultry	0.0007	0.00007	0.0006-0.0008	79.5	
Goat/sheep	0.115	0.086	-0.055-0.285	95.5	
Swine	0.001	0.0002	0.0006-0.001	97.0	

Table 23 presents a summary of the average mercury exposure through the consumption of various livestock products. The worldwide trend for mercury exposure from livestock products is goat/sheep > poultry > pork > beef. The highest mercury exposure from beef consumption was reported in South America, while North America showed the highest exposure from poultry consumption and Oceania from goat/sheep consumption. Europe exhibited the highest mercury exposure from pork consumption.

Table 23. Estimation of regional exposure to mercury from ingestion of different livestock products.

Region	Exposure to mercury from livestock products (mg/kg-day)			
	Beef	Poultry	Goat/sheep	Pork
Worldwide	6.62×10^{-7}	7.61×10^{-7}	1.15×10^{-5}	7.02×10^{-7}
Asia	2.02×10^{-7}	3.08×10^{-7}	9.58×10^{-6}	5.52×10^{-7}
Africa	2.18×10^{-7}	1.84×10^{-7}	1.07×10^{-5}	6.24×10^{-8}
North America	1.07×10^{-6}	1.29×10^{-6}	2.92×10^{-6}	9.22×10^{-7}
South America	1.14×10^{-6}	1.13×10^{-6}	3.06×10^{-6}	4.90×10^{-7}
Europe	5.53×10^{-7}	6.99×10^{-7}	7.60×10^{-6}	1.36×10^{-6}
Oceania	7.94×10^{-7}	9.59×10^{-7}	3.50×10^{-5}	8.25×10^{-7}

Table 24. Assessment of non-carcinogenic risk of regional exposure to mercury from ingestion of different livestock products.

Region	Beef	Poultry	Goat/sheep	Pork
Worldwide	0.011	0.013	0.191	0.012
Asia	0.003	0.005	0.160	0.009
Africa	0.004	0.003	0.178	0.001
North America	0.018	0.021	0.049	0.015
South America	0.019	0.019	0.051	0.008
Europe	0.009	0.012	0.127	0.023
Oceania	0.013	0.016	0.583	0.014

Assessment of the non-carcinogenic risk from mercury exposure through various livestock products is detailed in Table 24. All non-carcinogenic risk values for different regions and livestock products were below 1, indicating low health hazards.

6. Arsenic

The summary of meta-data analysis is presented in Table 25. Results indicate that the arsenic concentration in livestock products from goats or sheep is the highest among the rest of the target livestock by a concentration of 0.51μg/g, while products from poultry had the lowest concentration at 0.003μg/g. Additionally, the results showed a heterogeneity index above 94% for beef cattle, poultry, and swine.

Table 25. Results of meta-analysis for arsenic.

Livestock	Content of contamination (μg/g)			I^2 (%)	Remarks
	Mean	SE	95% CI		
Beef cattle	0.012	0.001	0.010-0.014	97.5	Overall value regardless organs
Poultry	0.003	0.0002	0.003-0.004	94.9	
Goat/sheep	0.510	0.051	0.41-0.611	0.00	
Swine	0.011	0.001	0.009-0.014	99.4	

In Table 26, the average exposure to arsenic through ingestion of livestock products is presented. The worldwide trend indicates that exposure is highest for goat/sheep, followed by beef, pork, and poultry. The highest exposure for beef consumption was found in South America, while North America showed the highest exposure from poultry consumption, Oceania from goat/sheep consumption, and Europe from pork consumption.

Table 26. Estimation of regional exposure to arsenic from ingestion of different livestock products.

Region	Exposure to arsenic from livestock products (mg/kg-day)			
	Beef	Poultry	Goat/sheep	Pork
Worldwide	7.95×10^{-6}	3.26×10^{-6}	5.09×10^{-5}	7.73×10^{-6}
Asia	2.42×10^{-6}	1.32×10^{-6}	4.25×10^{-5}	6.08×10^{-6}
Africa	2.62×10^{-6}	7.87×10^{-7}	4.75×10^{-5}	6.86×10^{-7}
North America	1.29×10^{-5}	5.52×10^{-6}	1.30×10^{-5}	1.01×10^{-5}
South America	1.36×10^{-5}	4.83×10^{-6}	1.36×10^{-5}	5.39×10^{-6}
Europe	6.63×10^{-6}	3.00×10^{-6}	3.37×10^{-5}	1.50×10^{-5}
Oceania	9.52×10^{-6}	4.11×10^{-6}	1.55×10^{-4}	9.07×10^{-6}

Table 27. Assessment of non-carcinogenic risk of regional exposure to arsenic from ingestion of different livestock products.

Region	Beef	Poultry	Goat/sheep	Pork
Worldwide	0.026	0.011	0.170	0.026
Asia	0.008	0.004	0.142	0.020
Africa	0.009	0.003	0.158	0.002
North America	0.043	0.018	0.043	0.034
South America	0.045	0.016	0.045	0.018
Europe	0.022	0.010	0.112	0.050
Oceania	0.032	0.014	0.518	0.030

Table 28. Assessment of excess cancer risk of regional exposure to arsenic from ingestion of different livestock products.

Region	Beef	Poultry	Goat/sheep	Pork
Worldwide	1.19×10^{-5}	4.89×10^{-6}	7.64×10^{-5}	1.16×10^{-5}
Asia	3.63×10^{-6}	1.98×10^{-6}	6.37×10^{-5}	9.11×10^{-6}
Africa	3.93×10^{-6}	1.18×10^{-6}	7.12×10^{-5}	1.03×10^{-6}
North America	1.93×10^{-5}	8.28×10^{-6}	1.95×10^{-5}	1.52×10^{-5}
South America	2.05×10^{-5}	7.25×10^{-6}	2.04×10^{-5}	8.09×10^{-6}
Europe	9.95×10^{-6}	4.49×10^{-6}	5.06×10^{-5}	2.25×10^{-5}
Oceania	1.43×10^{-5}	6.16×10^{-6}	2.33×10^{-4}	1.36×10^{-5}

The non-carcinogenic and carcinogenic risk of regional exposure to arsenic from different livestock products is assessed and presented in Tables 27 and 28, respectively. All non-carcinogenic risk values for different regions and livestock products were below 1, indicating a negligible non-carcinogenic health hazard potential. The excess cancer risk values for all regions and livestock products were estimated to be below 1×10^{-4}, suggesting a low likelihood of carcinogenic health effects from the estimated exposure.

Discussions

Figure 2 illustrates the funnel plot for each target contamination. The meta-analysis results suggest publication bias for all contaminations as the distribution of studies was not symmetrical.

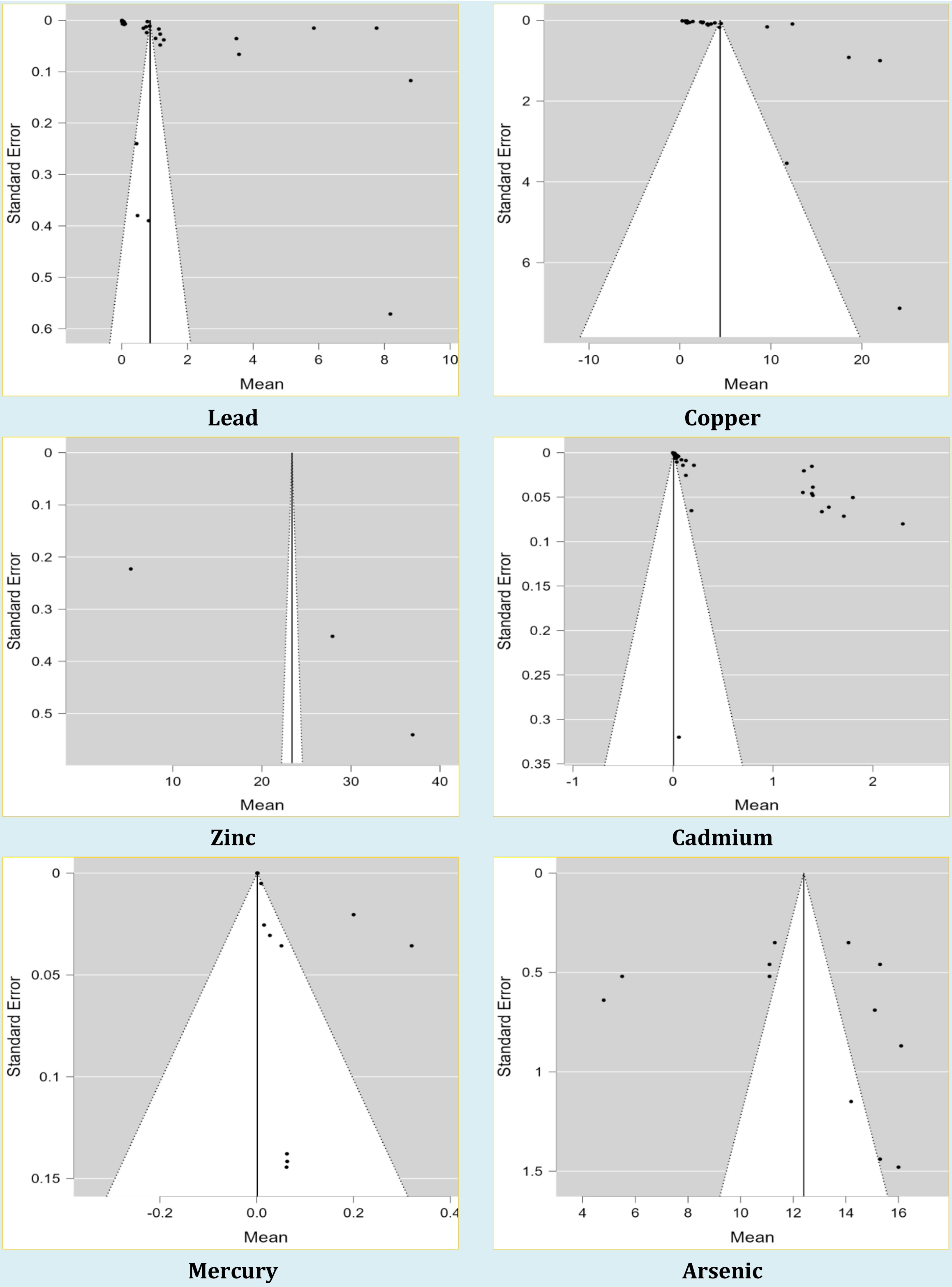

Figure 2. Publication bias for different contaminations.

The result of risk assessments indicated a low potential for non-carcinogenic diseases from the ingestion of livestock products. As for carcinogenic risk assessment, the ECR could be estimated for lead and arsenic. Although the ECR was below 1×10^{-4}, in most cases, it exceeded 1×10^{-6}. Despite it may not contribute significantly, if consumed consistently those heavy metals may cause carcinogenic risks for the human body. Therefore, livestock products with a significantly higher ECR, such as beef cattle or sheep and goat products, should undergo thorough contamination analysis before being distributed in the market, especially in regions with higher ingestion exposure.

This study was conducted with several noteworthy limitations. First, the meta-analysis was based on a limited number of papers. Each paper included only a small number of samples. Therefore, conducting a meta-analysis with a larger number of papers and a wider range of samples might yield different results. Additionally, the study only focused on livestock products from beef cattle, swine, poultry, and goat or sheep, and did not include other commonly consumed animals such as camels or seafood. Consequently, this exclusion may underestimate potential exposure to heavy metals from food.

Conclusion

This study analyzed the contents of lead, copper, zinc, cadmium, mercury, and arsenic in various livestock products, including beef cattle, swine, poultry, and goat or sheep, using meta-analysis. The findings were used to estimate exposure to these heavy metals from consuming the targeted livestock products. The estimated exposure levels were then used to calculate each heavy metal's Hazard Quotient (HQ) and the Excess Cancer Risk (ECR).

The study relied on average concentrations derived from meta-analysis; however, local contamination backgrounds should be investigated for more accurate exposure and risk assessments in specific areas. Future research should expand to include a broader range of edible livestock products, such as camel meat or seafood like fish. Additionally, heavy metal exposure through livestock consumption may vary based on regional cultural, and social factors. Therefore, more detailed, region-specific studies are necessary to accurately reflect the actual heavy metal intake from animal products.

Declarations

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