Names: Aliyah Oyegbola (T00698070), Maria Alejandra (T00668584)

Experiment title: Determination of Heavy Metals in Cocoa Powder by ICP-MS method after microwave-assisted digestion

CHEM 3170

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1. Abstract

In this experiment, Inductively Coupled Plasma Mass Spectroscopy (ICP-MS) was used to determine the concentration of different trace elements in four different cocoa powder samples. An internal standard technique was used, with the internal standard being chemically similar to the analyte of interest but not present in the sample itself. Argon served as the carrier gas that transported aerosolized sample material into the plasma torch where it could be ionized in the ICP-MS. The hydrogen and oxygen gases in ICP-MS were used to mitigate spectral interferences that arise from polyatomic ions or other matrix components that overlap with the analyte signals. From the results, the elements found in the protein sample powder were arsenic, thallium, copper, molybdenum, antimony, chromium, cobalt, cadmium, magnesium, nickel, manganese, vanadium, aluminum, zinc, barium, and iron. Silver was also found in trace amounts but it was only detectable in sample 2 (PC Organics).

For all four cocoa powder samples, the metal with the highest concentration was magnesium. For the lowest concentration metals, for sample 1, it was arsenic, for sample 2 it was silver, for sample 3 it was arsenic as well and for sample 4 it was antimony. The metals barium (Ba), vanadium (V), chromium (Cr), iron (Fe), copper (Cu), arsenic (As), molybdenum (Mo), antimony (Sb), and thallium (Tl), were below detectable limits or within acceptable daily intake limits, however, magnesium (Mg), aluminum (Al), manganese (Mn), zinc (Zn), nickel (Ni), cobalt (Co), and cadmium (Cd) exceeded recommended thresholds in all samples. Silver (Ag), Lead (Pb), and Selenium (Se) levels could not be determined due to values being under the limit of detection.

2. Introduction

In this experiment, Inductively Coupled Plasma Mass Spectroscopy (ICP-MS) was used to determine the concentration of different trace elements in four different brands of cocoa powder. Five standards of varying concentrations were prepared by diluting a 200 ppb stock solution with a solution containing 2%HNO_3 + 0.5% HCl in 50-mL centrifuge tubes. The blank was created using just the 200 ppb stock solution. The sample solution was created by digesting the cocoa powders with 5-mL of concentrated nitric acid using a microwave digestion equipment. After filtering, the sample solution was diluted using the 200-ppb stock solution in a 50-mL centrifuge tube. All ten centrifuge tubes were then analyzed using an ICP-MS instrument. The Internal Standard (IS) technique was used in the ICP-MS to enhance the accuracy and precision of quantitative analyses. This approach involves adding a known quantity of an internal standard element to the sample before analysis. The internal standard was chemically similar to the analyte of interest but not present in the sample itself. Argon served as the carrier gas that transported aerosolized sample material into the plasma torch where it could be ionized in the ICP-MS. The hydrogen gas in the ICP-MS was used to mitigate spectral interferences that could arise from polyatomic ions or other matrix components that overlap with the analyte signals. Oxygen served a similar purpose but worked through different mechanisms. When combined with hydrogen, it enhanced the removal of certain interferences while also facilitating mass shifts that help distinguish between analytes and their interferences.

3. Experimental Conditions and Procedure

Five standards of varying concentrations were prepared by diluting a 200-ppb stock solution with a solution containing 2%HNO_3 + 0.5% HCl in 50-mL centrifuge tubes. The concentration of each of the standards is as shown in table 1 below. The blank was created using just the 200ppb stock solution as shown in table 1 below.

The four samples used were Hershey's natural unsweetened cocoa powder, PC Organics organic cocoa powder, Cocoa Camino organic cocoa powder, and Fry's cocoa premium cocoa. Each of the cocoa powder samples was prepared by weighing out approximately 0.50g of the cocoa powder directly into a microwave digestion cell, the actual masses of each cocoa powder are shown in Table 2 below. Next, 5 mL of concentrated nitric acid was added to each cocoa powder sample in the fume hood. The cells were placed in the Anton Paar Multiwave GO Digestor for about 35 mins for the sample to digest. When the digestion was complete, the cells were removed from the GO Digester and placed in the fume hood to cool for about 10 mins. Next, the cell lids were opened and vented in the fume hood, while ensuring that the cells were directed away. Next, a filter was set up and water was used to wet the filter paper. Afterwards, about 15 mL of the stock solution was added to the cell and then each solution was filtered into the 50-mL centrifuge tube. Next, the 50-mL centrifuge tube was filled to the mark using the 200-ppb stock solution. Next, all ten centrifuge tubes were taken to the ICP-MS instrument for analysis.

Table 1. Volumes of stock intermediate solution (200.0 ppb) used and the concentrations of each standard.

Standard	Volume (mL) of 200 ppb stock solution	Total Volume (mL)	Concentration of the standard (ppb)
S0	-	50.00	0.0000
S1	0.0250	50.00	0.1000

S2	0.2500	50.00	1.000
S3	2.500	50.00	10.00
S4	12.50	50.00	50.00
S5	25.00	50.00	100.0

Table 2. Masses of the four different commercial cocoa powders used for the heavy metal analysis.

Cocoa Powders	**Samples**	**Mass (g)**
Hershey's cocoa	Sample 1	0.5092
PC Organics	Sample 2	0.5245
Cocoa Camino	Sample 3	0.5012
Fry's Cocoa	Sample 4	0.5009

Table 3. Optimized experimental conditions for ICP-MS analysis of heavy metals

Instrument parameter	**Setting**
RF Powder	1550 W
RF Matching	1.80 W
Carrier Gas	1.00 L/min
Makeup Gas	0.10 L/min
He Gas Flow	5.0 mL/min
H2 Gas Flow	6.0 mL/min
Energy Discrimination	5.0 V
Nebulizer	MicroMist Scott Double
Spray Chamber	Pass

Table 4. Optimized experimental conditions for Anton Paar Multiwave Go Plus digestion system

Steps			
No.	Ramp (mm:ss)	Temp ()	Hold (mm:ss)
1	2:00	100	1:00
2	5:00	180	5:00
Data			
Application Type	Vessel Mode	Temperature Control Mode	Temperature limit ()
Digestion	Multi vessel	Maximum	200
Recipe			
HNO_3			

4. Data and Results

Table 5. Results from ICP-MS analysis, element concentration (ppb) for four cocoa powder samples. Lead, Silver and selenium could not be determined because these fell under the detection limit.

Element	Sample 1 Concentration (ppb)	Sample 2 Concentration (ppb)	Sample 3 Concentration (ppb)	Sample 4 Concentration (ppb)
As - Arsenic	26.77589	18.86269	6.09472	26.41767
Tl - Thalium	30.48514	5.83146	7.10741	10.50402
Ag - Silver	-1.71773	2.06914	-2.68715	-2.60349
Cu - Copper	719.17925	820.34999	1143.07133	353.08488
Mo - Molybdenum	96.05806	93.9954	30.12303	35.40711
Sb - Antimony	92.79949	4.57778	6.98271	1.80757
Cr - Chromium	2073.43641	1807.67305	193.65529	1567.577
Co - Cobalt	1129.82576	1363.84096	675.00044	646.44513
Cd - Cadmium	580.55097	957.6545	396.30444	62.2166
Mg - Magnesium	7197901.505	5500517.004	5447095.37	3608358.32
Ni - Nickel	6159.38964	9249.06266	6862.56083	2782.14782
Mn - Manganese	55279.39881	53229.73372	49361.7644	35147.3696

V - Vanadium	19566.21789	15905.945	3776.46627	17365.7565
Al - Aluminium	19566.218	15905.945	3776.467	17365.757
Zn - Zinc	139846.63	95733.277	103358.061	61760.266
Ba - Barium	15660.62833	19534.31374	13695.0491	8159.66763
Fe - Iron	3961.05109	3227.01883	824.17373	4632.48513
Pb - Lead	-232.10066	-233.96022	-251.94912	-282.19154
Se - Selenium	-4138.60731	-1916.30694	-2153.2993	78.95358

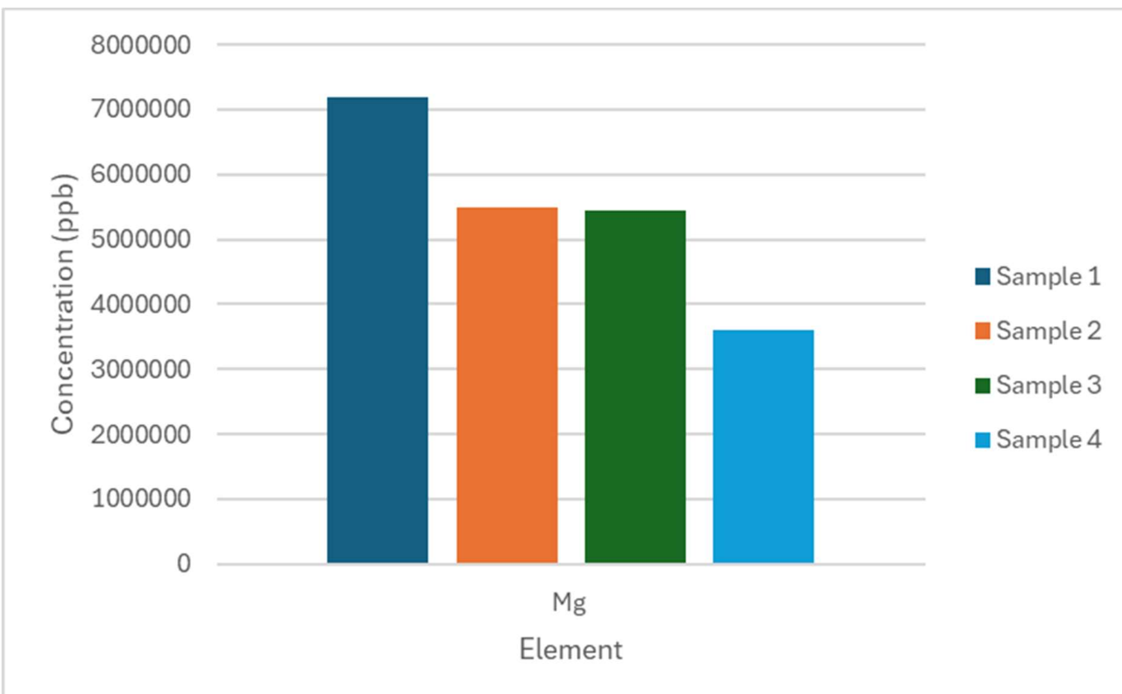

Figure 1. Mg (ppb) concentration from ICP-MS analysis in all four cocoa powder samples.

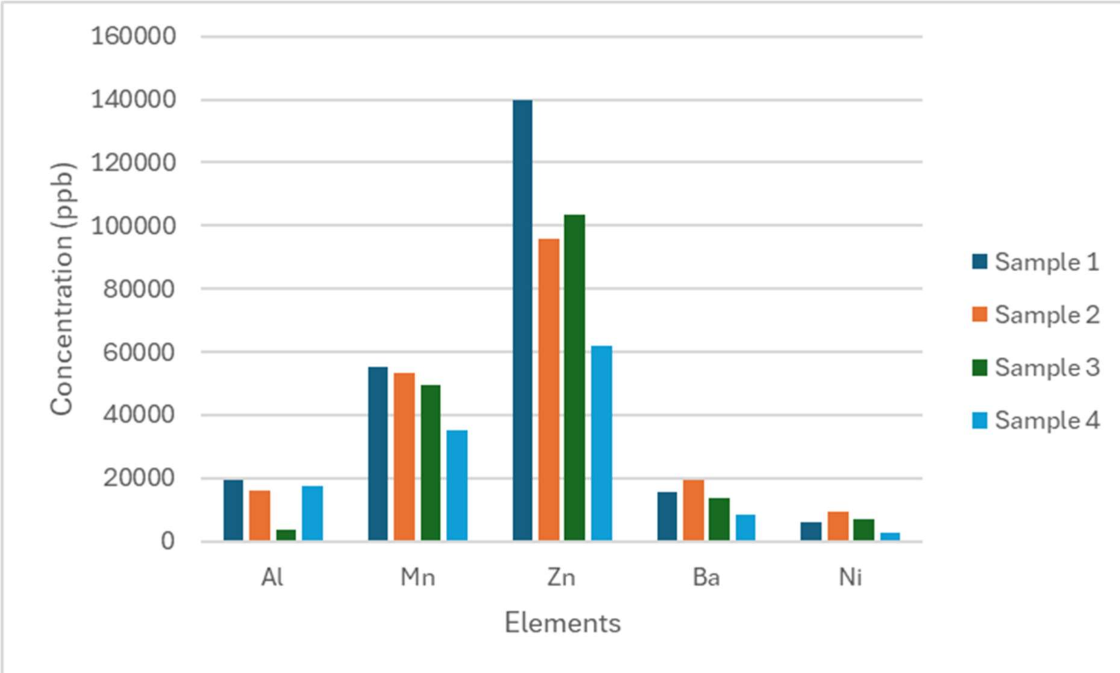

Figure 2. Concentration of heavy metals (Al, Mn, Zn, Ba and Ni)(ppb) from ICP-MS analysis in all four cocoa powder samples. Concentrations between 10000-140000 ppb.

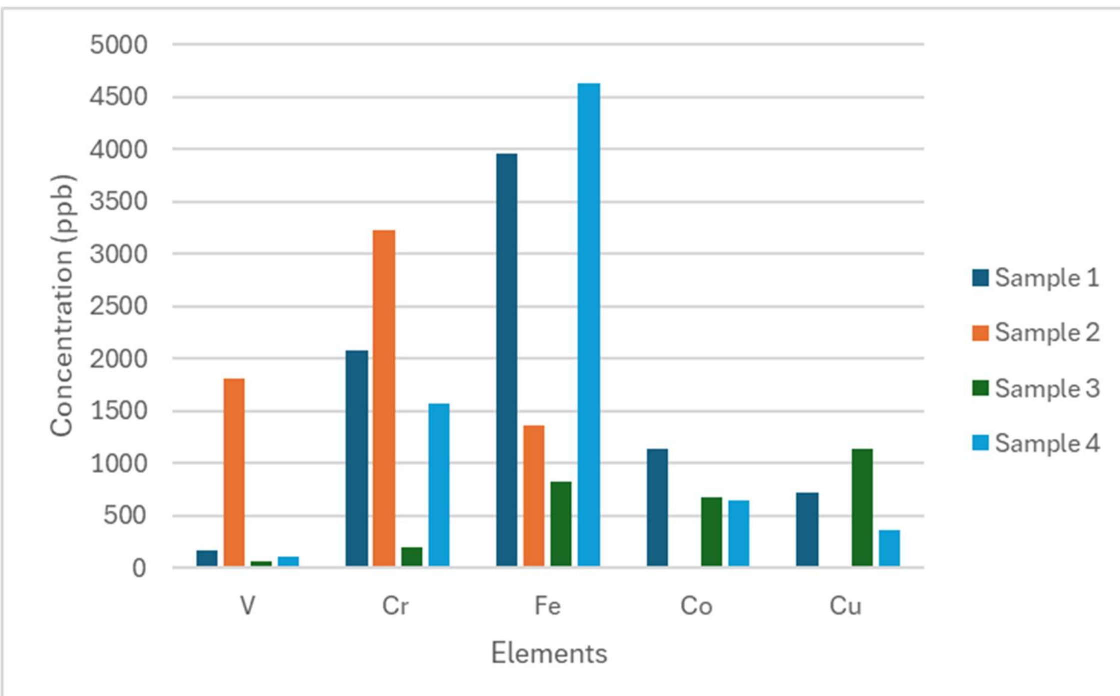

Figure 3. Concentration of heavy metals (V, Cr, Fe and Co) (ppb)from ICP-MS analysis in all four cocoa powder samples. Concentrations between 100-4500 ppb.

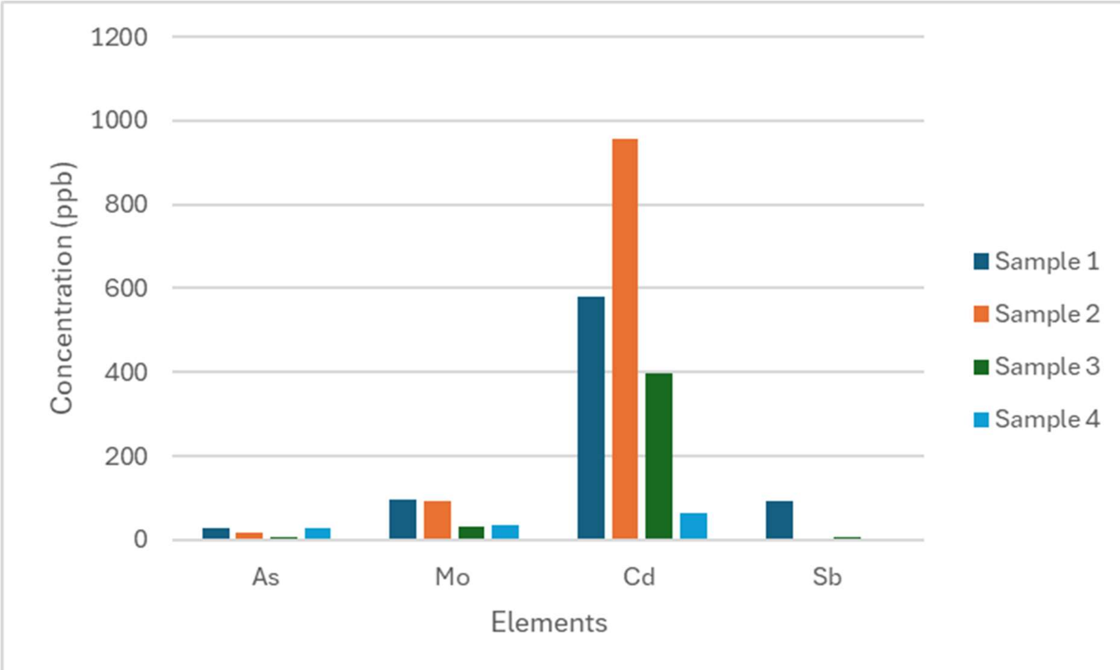

Figure 4. Concentration of heavy metals (As, Mo, Cd, Sb and Tl) (ppb) from ICP-MS analysis in all four cocoa powder samples. Concentrations between 50-1000 ppb.

Table 6. Elements from ICP-MS analysis that exceed the daily intake for adult males in ng for all cocoa powder samples in a 5 gr serving. Sample 4 Cd falls under the daily intake.

Samples (ng)	**Mg (ng)**	**Al (ng)**	**Mn (ng)**	**Zn (ng)**	**Ni (ng)**	**Co (ng)**	**Cd**
Sample 1	3.60E+09	9.78E+06	2.76E+07	6.99E+07	3.08E+06	5.65E+05	2.90E+05
Sample 2	2.75E+09	7.95E+06	2.66E+07	4.79E+07	4.62E+06	6.82E+05	4.79E+05
Sample 3	2.72E+09	1.89E+06	2.47E+07	5.17E+07	3.43E+06	3.38E+05	1.98E+05
Sample 4	1.80E+09	8.68E+06	1.76E+07	3.09E+07	1.39E+06	3.23E+05	-

Table 7. The recommended daily average intake for each heavy metal for an adult male.

Metal	Daily intake ng (adult male)
Arsenic[9]	2.10E+04
Cadmium[11]	6.20E+04[11]
Chromium[11]	2.50E+04[11]
Magnesium [16]	4.20E+08[16]
Aluminum [10]	1.00E+09[10]
Manganese[10]	1.10E+07[10]
Zinc [10]	1.10E+07[10]
Barium [10]	1.10E+07[10]
Nickel [11]	2.31E+05[11]
Iron [16]	8.00E+06[16]
Cobalt [17]	2.90E+04[17]
Vanadium[2]	1.80E+06[2]
Molybdenum [17]	4.50E+04[17]
Antimony [17]	4.20E+06[17]
Thallium[17]	8.20E+04[17]
Cooper [11]	2.50E+07[11]

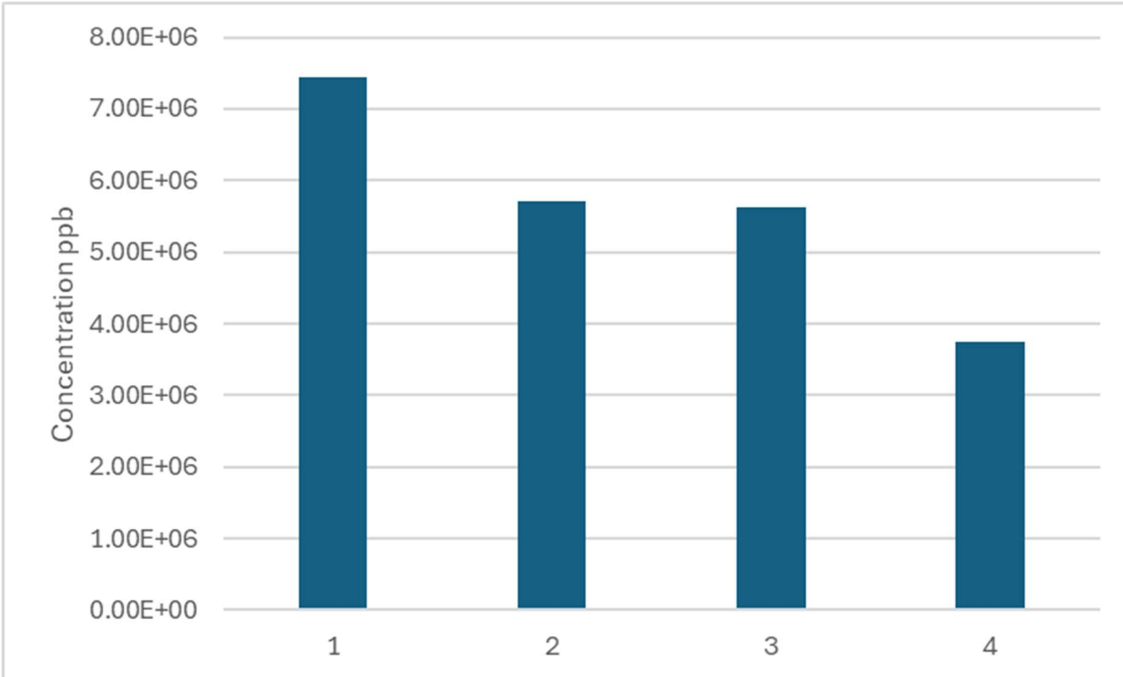

Figure 5. Bar graph for comparison of heavy metals concentrations in cocoa samples. Fry's cocoa powder (sample 4) has the lowest concentration of heavy metals, and Hershey's cocoa powder (sample 1) has the highest concentration of heavy metals.

5. Calculations

5.1 Sample calculation for standard solution 2 of the concentration (ppb) prepared from 200.0 ppb intermediate stock.

C1V1 = C2V2

C1 = 200 ppb, V1 = 0.25 ml
C2 =?, V2 = 50.00 ml

C2 = (200*0.025)/50.00
C2 = 0.1 ppb

5.2 Sample calculation of the amount of Fe (in ug) in sample 1, using the ppb concentration of the metal in the 50.0 mL sample 1.

Fe = 3961.05 µg/L
Then in 50ml = 0.05 L
3961.05 0.05 = 198.05 µg

5.3 Sample calculation of the metal concentration in ng of Fe/gram of Hershey's cocoa powder.

Fe = 198.05 µg in 50 ml
In 1g cocoa powder, there should be:

(198.05 µg)/(0.5092 g) = 388.94 µg/g

5.4 Sample calculation for the amount of Fe (in ng) per 5-gram serving size of Hershey's cocoa powder.

Fe per g = 388.94 µg/g
In 5 grams

388.94 µg/g*5g = 1944.7 µg per serving size
1944.7*1000= 1944700 ng per serving size

6. Discussion

This experiment used ICP-MS to determine the concentration of trace heavy metals in four different cocoa powder samples. The microwave digestion method was used to digest the samples because it significantly reduces the time required for sample preparation. The microwave digestion method has multiple advantages and disadvantages For the advantages, microwave digestion is time-efficient. Microwave digestion significantly reduces the time required for sample preparation. Typical digestion times range from 20 to 40 mins, compared to traditional open acid digestions, which can take 5 to 12 hrs or more. The second advantage is that it makes use of higher temperatures and pressures. The closed system of microwave digestion allows for operation at elevated temperatures (up to 250 – 300°C) and pressures, which enhances the oxidative potential of the acids used and leads to more complete decomposition of complex samples. The final advantage is that it prevents the loss of volatile elements. The closed vessel design prevents the loss of volatile elements such as mercury (Hg) and lead (Pb), which can occur during open digestions. For the cons, microwave digestion has limited applicability for specific analyses. While effective for trace metal analysis, microwave digestion is not recommended for preparing samples for chromatographic techniques like HPLC and GC due to the rapid temperature increase that may degrade sensitive compounds.

The Internal Standard (IS) technique is a widely used method in Inductively Coupled Plasma Mass Spectrometry (ICP-MS) to enhance the accuracy and precision of quantitative analyses. This approach involves adding a known quantity of an internal standard element to the sample before analysis. The internal standard should ideally be chemically similar to the analyte of interest but not present in the sample itself. One significant advantage of using an internal standard is its ability to compensate for matrix effects that may alter ionization efficiency during analysis. Variations in sample composition can lead to differences in signal intensity; however, since both analytes and internal standards are subjected to similar conditions, these variations can be effectively normalized. It also enhances analytical precision by reducing variability between measurements caused by instrumental drift or fluctuations during analysis. In the ICP-MS, argon served as the carrier gas that transports aerosolized sample material into the plasma torch where it can be ionized. The hydrogen gas in ICP-MS was used to mitigate spectral interferences that arise from polyatomic ions or other matrix components that overlap with the analyte signals. Oxygen serves a similar purpose but works through different mechanisms. When combined with hydrogen, it can enhance the removal of certain interferences while also facilitating mass shifts that help distinguish between analytes and their interferences.

From the results, the elements found in the four cocoa powder samples were arsenic, thallium, copper, molybdenum, antimony, chromium, cobalt, cadmium, magnesium, nickel, manganese, vanadium, aluminum, zinc, barium, and iron. Silver was also found in trace amounts but it was only detectable in sample 2 (PC Organics). For all four cocoa powder samples, the metal with the highest concentration was magnesium. For the lowest concentration metals, for sample 1, it was arsenic, for sample 2 it was silver, for sample 3 it was arsenic as well and for sample 4 it was antimony. The analysis of four commercial cocoa powder samples using ICP-MS revealed significant variability in metal concentrations. While most elements analyzed, including barium (Ba), vanadium (V), chromium (Cr), iron (Fe), copper (Cu), arsenic (As), molybdenum (Mo), antimony (Sb), and thallium (Tl), were below detectable limits or within acceptable daily intake limits, magnesium (Mg), aluminum (Al), manganese (Mn), zinc (Zn), nickel (Ni), cobalt (Co), and cadmium (Cd) exceeded recommended thresholds in all samples. Magnesium displayed the highest concentration, with the amount per serving size (5g) ranging from 1.80×10^9 ng to 3.60×10^9 ng. Aluminum levels varied between 1.89×10^6 ng and 9.78×10^6 ng. Manganese concentrations ranged from 1.76×10^7 ng to 2.76×10^7 ng, while zinc levels were detected between 3.09×10^7 ng and 6.99×10^7 ng. Nickel concentrations peaked at 4.62×10^6 ng, and cobalt levels reached up to 6.82×10^5 ng. Cadmium, a toxic heavy metal, exceeded acceptable limits in Sample 1 (2.90×10^5 ng), Sample 2 (4.79×10^5 ng), and Sample 3 ($1.98x10^5$ ng) though Sample 4 being the onçly sample in between the daily intake values for an adult male 3.11×10^4 ng. Metals: Silver (Ag), Lead (Pb), and Selenium (Se), could not be determined due to values being under the limit of detection.

The most toxic metals found in the cocoa powders were antimony, thallium, and arsenic. Thallium is extremely toxic and affects the nervous system. It can be lethal even in small doses. Arsenic is notorious for its ability to cause cancer, skin lesions, developmental effects, cardiovascular disease, neurotoxicity, and diabetes upon chronic exposure. Inhaling antimony can irritate the nose, throat, and lungs, causing coughing, wheezing, and shortness of breath. Chronic exposure can lead to antimony pneumoconiosis, bronchitis, and emphysema.

The different heavy metals have varying effects on human health. Understanding the implications of these metals is crucial for public health, environmental safety, and regulatory measures. Lead is a well-known neurotoxin that can cause severe developmental issues in children, including cognitive deficits and behavioral problems. In adults, lead exposure is associated with hypertension, kidney damage, and reproductive issues. The accumulation of lead in the body can result in long-term health consequences, making it a critical concern for both environmental health and occupational safety. Cadmium is highly toxic even at low concentrations. It primarily affects the kidneys and can lead to renal dysfunction. Chronic exposure to cadmium has been linked to bone demineralization and increased risk of osteoporosis. Additionally, cadmium is classified as a human carcinogen, posing risks for lung cancer upon inhalation. Chromium exists in several oxidation states, with hexavalent chromium being particularly hazardous. Exposure can occur through inhalation or ingestion of contaminated water or food. Hexavalent chromium is known to cause respiratory problems when inhaled and has been linked to lung cancer. It can also induce skin ulcers upon contact. Arsenic is a potent carcinogen that poses significant risks through drinking water contamination. Long-term exposure can lead to skin lesions, developmental effects, cardiovascular disease, neurotoxicity, and an increased risk of various cancers such as bladder and lung cancer. Cobalt is essential in trace amounts for human health but can be toxic at higher levels. Excessive cobalt exposure may lead to respiratory issues and skin irritation. There are concerns regarding its potential carcinogenicity when inhaled over prolonged periods. Copper is vital for various biological functions; however, excessive copper intake can be toxic. High levels may cause gastrointestinal distress and liver damage. Individuals with Wilson's disease cannot properly eliminate copper from their bodies, leading to severe neurological symptoms. Nickel exposure has been associated with allergic reactions and respiratory issues when inhaled as dust or fumes. Prolonged exposure may increase the risk of lung cancer among workers in nickel-refining industries. Nickel compounds are also known irritants that can affect skin health. While some heavy metals play essential roles in human physiology at trace levels, their toxic effects at elevated concentrations pose serious health risks across various systems in the body. Continuous monitoring of these metals in the environment is crucial for preventing adverse health outcomes.

The sources of the heavy metals in the cocoa powders vary. The first could be soil contamination. Heavy metals are naturally present in the earth's crust and can accumulate in soil over time. Agricultural practices, particularly those involving the use of fertilizers and pesticides, can worsen this contamination. For instance, cadmium is often found in phosphate fertilizers, which can leach into the soil and subsequently be absorbed by plants used for the protein powder. A second source could be water supply. Water used for irrigation can also be a significant source of heavy metal contamination. If the water supply contains heavy metals due to industrial runoff or natural deposits, crops grown with this water will absorb these toxins. This is particularly concerning for crops like rice, which is known to accumulate arsenic from contaminated water. The geographical regions can also act as a potential source. The geographical location where crops are grown plays a crucial role in determining their contamination levels. Areas near industrial sites or those with high natural mineral deposits may have higher concentrations of heavy metals in their agricultural products.

There were many potential sources of error during the experiment. The first potential source of error could have been due to interference issues. ICP-MS is susceptible to spectral interferences from other elements present in the sample or from polyatomic ions formed during ionization. These interferences can mask the signals of target analytes, leading to erroneous results. Techniques such as collision/reaction cell technology can help mitigate these issues. The second may have been due to sensitivity variability. Different elements have varying sensitivities in ICP-MS due to differences in ionization energy and mass-to-charge ratios. This variability must be accounted for during method development by selecting appropriate internal standards that compensate for sensitivity differences.

Future research would include looking at heavy metal concentrations in different cocoa powders grown in different geographical regions. This would help to demonstrate if the sources of potential contamination of the cocoa seeds used to make the cocoa powder could be due to the geographical locations being near industrial or mining sites.

7. Conclusion

The analysis of four commercial cocoa powder samples using ICP-MS showed significant variability in metal concentrations. Most elements, including barium (Ba), vanadium (V), chromium (Cr), iron (Fe), copper (Cu), arsenic (As), molybdenum (Mo), antimony (Sb), and thallium (Tl), were either below detectable limits or within acceptable daily intake levels. However, magnesium (Mg), aluminum (Al), manganese (Mn), zinc (Zn), nickel (Ni), cobalt (Co), and cadmium (Cd) exceeded the recommended thresholds in all samples. Magnesium had the highest concentration, ranging from 1.80×10^9 ng to 3.60×10^9 ng per 5g serving. Aluminum levels varied from 1.89×10^6 ng to 9.78×10^6 ng, manganese ranged from 1.76×10^7 ng to 2.76×10^7 ng, and zinc levels were between 3.09×10^7 ng and 6.99×10^7 ng. Nickel concentrations peaked at 4.62×10^6 ng, and cobalt levels reached 6.82×10^5 ng. Cadmium exceeded acceptable limits in Sample 1 (2.90×10^5 ng), Sample 2 (4.79×10^5 ng), and Sample 3 (1.98×10^5 ng), while Sample 4 was within the daily intake limit for adult males at 3.11×10^4 ng. Silver (Ag), Lead (Pb), and Selenium (Se) levels could not be determined due to values being under the limit of detection.

These findings highlight the need for stricter quality control of metal content in cocoa powder, especially for cadmium, nickel, and aluminium, which can pose health risks with long-term consumption. Elevated magnesium levels are nutritionally significant but should be monitored to keep daily intake safe. Further research is needed to evaluate the bioavailability and long-term health effects of these metals in cocoa products.

References

(1) Satarug, S.; Vesey, D. A.; Gobe, G. C. Health Risk Assessment of Dietary Cadmium Intake: Do Current Guidelines Indicate How Much Is Safe? *Environmental Health Perspectives* 2017, *125* (3), 284–288. https://doi.org/10.1289/ehp108.

(2) US), M. *Chromium*. Nih.gov. https://www.ncbi.nlm.nih.gov/books/NBK222329/.

(8) Micronutrients, I. of M. (US) P. on. *Arsenic, Boron, Nickel, Silicon, and Vanadium*. www.ncbi.nlm.nih.gov. https://www.ncbi.nlm.nih.gov/books/NBK222322/#ddd00675.

(9) Canada, H. *Page 6: Guidelines for Canadian Drinking Water Quality: Guideline Technical Document – Arsenic - Canada.ca*. Canada.ca. https://www.canada.ca/en/health-canada/services/publications/healthy-living/guidelines-canadian-drinking-water-quality-guideline-technical-document-arsenic/page-6-guidelines-canadian-drinking-water-quality-guideline-technical-document-arsenic.html (accessed 2024-10-09).

(10) BIEGO, G.; JOYEUX, M.; HARTEMANN, P.; DEBRY, G. Daily Intake of Essential Minerals and Metallic Micropollutants from Foods in France. *The Science of The Total Environment* 1998, *217* (1-2), 27–36. https://doi.org/10.1016/s0048-9697(98)00160-0.

(11)Health Risk Assessment of Cd, Cr, Cu, Ni and Pb in the Muscle, Liver and Gizzard of Hen's Marketed in East of Iran. *Toxicology Reports* 2021, *8*, 53–59. https://doi.org/10.1016/j.toxrep.2020.12.012.

(12) *New Study of Protein Powders from Clean Label Project Finds Elevated Levels of Heavy Metals and BPA in 53 Leading Brands*. Clean Label Project. https://cleanlabelproject.org/blog-post/new-study-of-protein-powders-from-clean-label-project-finds-elevated-levels-of-heavy-metals-and-bpa-in-53-leading-brands/.

(13)Kutscher, D. Six Key Errors to Avoid for Routine Analysis Using Inductively Coupled Plasma-Mass Spectrometry (ICP-MS). *www.spectroscopyonline.com* 2019, *34* (8), 28–3028–30.

(14)Donkor, K. Chemistry 3170 Instrumental Analysis Laboratory Manual, Fall 2024;

(15)Donkor, K. CHEM 3100 Lecture Notes. Thompson Rivers University, Kamloops, B.C. Fall 2024

(16)*Table 6-5, Average Dietary Intake of Barium in Different Age/Sex Groups from the Canadian Total Diet Study (1993–1999)*. Nih.gov. https://www.ncbi.nlm.nih.gov/books/NBK598774/table/ch6.tab5/?report=objectonly (accessed 2024-11-25).

(17)Marini, M.; Angouria-Tsorochidou, E.; Caro, D.; Thomsen, M. Daily Intake of Heavy Metals and Minerals in Food – a Case Study of Four Danish Dietary Profiles. *Journal of Cleaner Production* **2021**, *280*, 124279. https://doi.org/10.1016/j.jclepro.2020.124279.