

## **Chapter One**

### **Introduction**

#### **1.1 Background to the Study**

Indoor dust has increasingly emerged as a significant research focus due to its substantial effects on human health, particularly in urban homes where individuals spend a considerable amount of time. Thus, exposure to contaminants present in indoor dust is both persistent and widespread<sup>1,2</sup>. Globally, environmental exposure to indoor dust has been linked to adverse health effects, especially among children<sup>3,4,5,6,7</sup>. Dust particles in the indoor environment easily settle on several surfaces; hence, they are of concern because they are ubiquitous and may contain contaminants humans are often exposed to across indoor environments<sup>8</sup>. Indoor dust comprises a collection of particles that serve as a significant reservoir for various emerging indoor chemical pollutants<sup>8</sup>. Typically, indoor dust contains organic compounds that are semi-volatile in nature, inorganic elements such as heavy metals, and allergens that can find their way into the human body. Although the primary route for these chemical contaminants in indoor dust into humans is inhalation, exposure may occur through accidental ingestion of dust particles on surfaces, skin or food, or through direct skin absorption<sup>3,9</sup>.

Similarly, indoor dust is also consist of an array of particulate matter, fibres, organic compounds, and biological materials<sup>1,2</sup>. Indoor dust serves as a reservoir for various environmental contaminants, including plastic additives, components of personal care products, pesticides, industrial chemicals, combustion byproducts, and heavy metals.<sup>1,2</sup> Among these, heavy metals and parabens are particularly significant due to their widespread, environmental presence and potential health risks<sup>1</sup>.

Humans are generally exposed to dust through skin contact, ingestion, and inhalation of particles. Several studies have found a direct correlation between harmful substances in dust and related health issues<sup>10,11,12</sup>. For instance, flame retardants have been linked to disruption of the endocrine system in males, polycyclic aromatic hydrocarbons (PAHs) are associated with an increased probability of cancer, and phthalates have been connected to allergies and asthma in young children<sup>3,4,13</sup>. In general, children are more likely to ingest dust from the ground compared to adults due to their proximity as a result of their height, and their frequent oral contact activities with contaminated surfaces during playtime<sup>14,15</sup>.

Usually, potentially toxic elements (PTEs) such as cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), and zinc (Zn), and others can be released into the environmental media due to both natural and human-induced activities<sup>16,17</sup>. Once released, these PTEs can attach to indoor dust particles and may readily find their way into the human body via various routes, including ingestion, inhalation, and skin contact<sup>14,18,19,20</sup>. Typically, PTEs can accumulate in the human body and, over time, may result in various health complications due to their non-biodegradable nature. Similarly, consumer products such as personal care products (PCPs), pharmaceuticals and food utilize parabens, including methylparaben (MeP), ethylparaben (EtP), propylparaben (PrP), and butylparaben (BuP) as preservatives to combat microbial growth<sup>21</sup>.

Despite regulatory restrictions in many developed regions of the world, parabens continue to be used in developing countries like Nigeria, where they are persistently released into the environment through the washoff from personal care products and the discharge of industrial waste from pharmaceutical and paper manufacturing sectors. In many developing countries like Nigeria, parabens are still being included as ingredients in various personal care products (PCPs), including shampoos, moisturisers, deodorants, antiperspirants, shaving gels, lubricants, and

toothpaste<sup>22</sup>. Consequently, consumers are often directly exposed to parabens while using PCPs. Additionally, parabens may also be released into the environment through run-off and improper disposal of used PCP containers. Reports showed that parabens have been implicated in indoor dust, wastewater, river surface water, and marine environments<sup>23</sup>. Concerns have emerged regarding their safety in everyday products and the potential health risks associated with frequent human exposure, given their properties that resemble endocrine-disrupting compounds<sup>24</sup>.

In urban areas such as Ibadan, where growth and industrial operations are on the rise, the potential for indoor dust to serve as a pathway for exposure to these hazardous materials is elevated, highlighting the importance of assessing their concentrations and related health hazards.

## **1.2 Statement of the Problem**

The rapid urban development in Ibadan has led to increased vehicular emissions, heightened industrial activities, and the proliferation of unregulated consumer goods. These elements contribute to the accumulation of pollutants, such as heavy metals and parabens, in indoor dust, thus raising exposure risks for the urban populace<sup>25</sup>. The intricate composition of indoor dust can hold a variety of hazardous materials, such as heavy metals and parabens<sup>26</sup>. These toxins can originate from several sources, both within and outside the home, including construction materials, electronic devices, furniture, personal care products, and household items<sup>26</sup>. They are a global issue and can remain in indoor dust at significant levels due to insufficient air circulation<sup>27</sup>. Once introduced, they continue to exist in the indoor environment, posing long-term exposure risks<sup>28</sup>. Potentially harmful elements are recognised for their toxicity and permanence, while parabens, commonly utilised as preservatives, have been associated with hormonal disruption. Despite their health risks, particularly for children and vulnerable populations, information on the levels of these pollutants in indoor dust, especially in developing urban areas such as those in

Nigeria, remains limited<sup>29</sup>. This knowledge gap hinders effective risk assessment, regulatory measures, and public health initiatives. Therefore, assessing the presence and concentrations of heavy metals and parabens in indoor dust is crucial to identify exposure routes and protect human health.

### **1.3 Justification of the Study**

Indoor dust serves as a significant reservoir and route for human exposure to various environmental pollutants, including potentially toxic elements and emerging organic contaminants, such as parabens. These substances are widely found in the environment due to their extensive use in building materials, consumer goods, cosmetics, electronics, and other human activities, and they persist in various environmental media<sup>30,31</sup>. Continuous exposure to contaminated indoor dust, particularly through inhalation, ingestion, or skin contact, can pose serious health risks, especially for groups who may be more at risk such as children and older adults<sup>30,31</sup>. While the monitoring of elemental and outdoor dust is standard, the assessment of indoor dust, particularly regarding the levels and co-occurrence of parabens alongside potentially toxic elements, remains largely overlooked in many urban areas of Nigeria. Consequently, this study aims to establish baseline data on the levels, distribution, and potential health risks associated with these contaminants in indoor dust from the study area.

### **1.4 Aims and Objectives**

This research aims to evaluate the concentrations and potential health hazards associated with the presence of certain potentially toxic elements and parabens in indoor dust sampled from randomly chosen locations in Ibadan.

The specific objectives are:



- i. Determine the levels of selected potentially toxic elements (Cu, Mn, Pb, Zn, Cr, Ni and Cd) in indoor dust samples collected from residential environments in Ibadan.
- ii. Quantify the levels of parabens (Methylparaben, Ethylparaben, Propylparaben and Butylparaben) in indoor dust.
- iii. Evaluate the average daily dose (ADD) of the studied heavy metals and parabens in the studied indoor dust.
- iv. Assess the potential exposure risks for inhabitants (adults and children).
- v. Assess the contamination source using bivariate and multivariate statistical analysis (Correlation and Principal Component Analysis (PCA) study).
- vi. Assess the ecological risk of the studied contaminants.

### **1.5 Research Questions**

This study seeks to address the following research questions:

1. What are the levels of concentrations of the studied potentially harmful elements (Cu, Mn, Pb, Zn, Cr, Ni and Cd) and parabens (Methylparaben, Ethylparaben, Propylparaben and Butylparaben) in indoor dust samples from the study areas in Ibadan?
2. What are the potential health risks associated with exposure to these contaminants through different exposure pathways?
3. Are there any ecological risks due to the presence and levels of the studied contaminants?

### **1.6 Significance of the Study**

The results of this research will offer important information regarding the simultaneous presence and levels of heavy metals and parabens in indoor dust in selected area in Ibadan. It will contribute to the existing body of knowledge on environmental pollution and public health. Additionally, the study will highlight the potential health risks associated with these

contaminants, serving as a basis for the development of risk assessment models tailored to local contexts<sup>32</sup>. Moreover, this research will help inform policymakers and public health officials in Nigeria on the need for regulations aiming at indoor air quality and consumer product safety, which could ultimately lead to improved indoor environments and reduced exposure to hazardous substances<sup>1</sup>.

### **1.7 Scope of the Study**

This research focuses on examining indoor dust samples gathered from twenty residential sites in Ibadan, Oyo State, Nigeria. It addresses the levels of specific heavy metals (Cu, Mn, Pb, Zn, Cr, Ni, and Cd) as well as parabens (Methylparaben, Ethylparaben, Propylparaben and Butylparaben). Twenty (20) indoor dust samples were collected from each location, making a total of twenty (20) indoor dust samples. These samples were analyzed using atomic absorption spectrophotometer analytical techniques for concentration of heavy metals and extraction by sonification for concentration of parabens<sup>33,34</sup>.

The assessment will focus on determining exposure risks through ingestion, inhalation, and dermal contact, using established models like the U.S. Environmental Protection Agency (USEPA) risk assessment framework<sup>35</sup>.

### **1.8 Limitations of the Study**

This research examines the concentrations of specific potentially toxic elements and parabens in indoor dust samples only. It also assesses the exposure risk to humans using mathematical models. The study locations, twenty in all, were randomly selected within Ibadan, Oyo State, Nigeria.

### **1.9 Operational Definition of Key Terms**

- **Dust:** Dust refers to a fine, dry substance made up of small fragments of soil or debris that can be found on surfaces or suspended in the atmosphere.
- **Indoor Dust:** Indoor dust is a collection or composition of fine particles, including the mixture of soil particles, hair, clothing, fibres (artificial and natural) and other contaminants, found within an indoor environment.
- **Heavy Metals:** Heavy metals are metals that have high density, atomic weight, or atomic number. Some examples are lead (Pb), cadmium (Cd), nickel (Ni), copper (Cu), and zinc (Zn).
- **Parabens:** Parabens are chemical compounds that are used as preservatives in cosmetics and pharmaceuticals. Parabens are also used in certain products to kill bacteria and prevent the product from decaying.
- **Exposure Pathway:** Exposure Pathway is the route through which the exposure, to contaminants, reaches areas of an organism where it has the potential to cause damage.
- **Risk Assessment:** Risk Assessment is a process of identifying what hazards exist, or may appear in the workplace, evaluating the hazards to know how they may cause harm and defining steps to take to minimise harm.

## Endnotes

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## Chapter Two

### Literature Review

#### 2.1 Heavy Metals

The phrase "heavy metals" is commonly used to refer to metals that have an atomic weight exceeding that of iron<sup>1</sup>. They are commonly referred to as a collection of relatively dense and toxic substances, even in minimal amounts<sup>2</sup>. Heavy metals refer to those metals that possess a density exceeding 5 g cm<sup>-3</sup> and atomic masses varying from roughly 60 to 200<sup>2,3,4,5</sup>. Heavy metals are metallic elements with relatively high density and toxicity even at low concentrations. Recently, the phrase "heavy metal" has come to describe a broad category of metals and semimetals that may pose toxicity risks to humans or the environment toxicity<sup>6</sup>. Generally, heavy metals cannot be broken down naturally and are classified into two categories. The first category includes toxic or non-essential metals, with examples such as Lead (Pb), Cadmium (Cd), and Arsenic (As), among others. These non-essential or toxic metals are undesirable, with no biological benefits to human health, but they can be harmful at any level. The second category includes essential metals that are crucial for health, and examples are Copper (Cu), Zinc (Zn), Manganese (Mn), Iron (Fe), Nickel (Ni), Chromium (Cr), and others. These essential metals are sought after and have health advantages to human health in small amounts, but they can become harmful when present in elevated concentrations<sup>7</sup>. Certain heavy metals, including copper, selenium, and zinc, function as essential trace elements that are critical for numerous biological processes, which in turn support overall human metabolism<sup>8,9</sup>. Cobalt, a heavy metal, functions as the central atom in the vitamin B<sup>12</sup> complex and is essential in the reductive branch of the propionic acid fermentation pathway<sup>8,10</sup>. The absence of this specific heavy metal compound would result in the loss of the characteristic flavour of Emmentaler cheese. Heavy metals such as



iron, zinc, tin, lead, copper, and tungsten possess considerable technological value. In recent developments, these metals have been utilised as central atoms in the design of bioinorganic catalysts for specialized chemical applications<sup>11</sup>. Additionally, we encounter precious noble elements like gold, silver, iridium, rhodium, or platinum<sup>8,12</sup>. In opposition, several heavy metals, such as mercury, cadmium, arsenic, chromium, thallium, and lead, are typically associated with the “dark side of chemistry” due to their toxic effects even at low concentrations<sup>8,13</sup>.

## **2.2 Origin of Heavy Metals**

The origins of heavy metals in environmental media such as soil, air, and water are categorised into two, namely:

### **2.2.1 Natural Source**

Heavy metals are generally present in the earth’s crust at low concentrations, ranging from parts per billion for noble metals to as much as 5% for iron. These elements are primarily found chemically bound within carbonate, sulfate, oxide, or silicate rocks, although some may also exist in their metallic, elemental state. Processes such as weathering and erosion facilitate the leaching and migration of heavy metals into soil, river systems, and groundwater<sup>14</sup>. The natural, geogenic, and lithogenic origins of heavy metals in the environment encompass the breakdown of rocks that contain metals, volcanic eruptions, sea-salt spray, forest fires, rock weathering, leaching, decomposition of biogenic sources, seismic activity, and wind-driven soil transport particles<sup>15,16, 17</sup>.

### 2.2.2 Anthropogenic Source

The increase in socio-economic activities resulting from population growth has been linked to the rapid accumulation of heavy metals in the environment. Human activities such as mining, metallurgical operations, agriculture, and energy production are major contributors to the presence of metal contamination<sup>16</sup>. Domestic practices, such as the use of laundry detergents, wastewater, and emissions from chimneys and engines, contribute to the elevated metal concentrations in wastewater. These conditions negatively impact the potential for water reuse in irrigation and during sludge management processes<sup>17,18,19</sup>. The quantity of heavy metals released through these activities can vary due to mining operations, which are known to cause significantly higher contamination rates compared to other activities, leading to long-lasting environmental impacts even after mining has stopped<sup>15</sup>. Heavy metals emitted into the air during mining, smelting, and various industrial processes eventually settle back onto the land through both dry and wet deposition<sup>16,20,21</sup>.

Primary sources of heavy metals include pesticides, paint production, textile printing, the earth's crust, hair dyes, and polyvinyl chloride (PVC) pipes for lead (Pb); rechargeable batteries, tobacco, phosphate fertilizers, pigments, industrial and agrochemical wastes for cadmium (Cd); stainless steel, alloy production, wood preservation, textile dyes, leather tanning, and electroplating for chromium (Cr); kitchen utensils, machine parts, batteries, the earth's crust, cigarettes, and stainless steel for nickel (Ni); volcanic activity, biomass pyrolysis, mining, ship painting, wastewater discharges, and forest fires for mercury (Hg); and volcanic activity, disposal of arsenical chemicals, gold and copper mining, arsenical pesticides, smelting, and fertilizers for arsenic (As)<sup>18</sup>.

## **2.3 Uses of Heavy Metals**

Heavy metals originated from asteroid impacts. In the earth's crust, they are typically present at low concentrations, ranging from parts per billion for noble metals to up to 5% for iron. These metals are primarily found chemically bound in carbonate, sulfate, oxide, or silicate rocks, or in their metallic, elemental form<sup>8</sup>. Certain heavy metals hold significant biological value even in minimal quantities, especially those found in the fourth period of the modern periodic table<sup>22,23</sup>. These metals are biologically significant due to their involvement in enzyme activity (vanadium and manganese), hormone production (selenium), cellular growth (nickel), and metabolic processes (arsenic). However, these metals are needed by humans only in small quantities; excessive levels in the body can lead to adverse health effects<sup>23</sup>. Furthermore, metals are usually very strong, durable and highly resistant to everyday wear and tear. As such, they have been used since ancient times for a lot of things. And even today, with advances in technology and a lot of other things, the uses of metals have broadened greatly. Metals even play a key role in the economy and security as the metals are used in making locks, strong safe, doors etc. In addition, furniture is made from metal these days. Metals also find their uses in the military, where they are used for manufacturing weapons and ammunition. Certain metals are utilised in the galvanizing process to prevent rust. Some important and popular metal uses are given below<sup>24</sup>.

### **2.3.1 In the Construction Industry**

Metals play a pivotal role in the construction sector. Iron and steel, among others, are primary materials utilised in the creation of buildings and residences<sup>24</sup>. Structural building materials commonly include alloy steel, chosen for its strength and flexibility, while copper is utilised for various architectural components, such as roofs and gutters, prized for its durability and aesthetic

appeal<sup>25,26</sup>. Zinc is a widely used metal that serves as a protective coating for other metals. For instance, galvanised steel, which is steel coated in zinc, is prevalent as it helps to prevent rusting<sup>26</sup>. Nickel is another commonly used element, primarily found in the production of stainless steels, where it enhances the metal's strength and resistance to corrosion<sup>26</sup>.

### **2.3.2 In Electronics**

As metals are good conductors of electricity, they are utilised to make wires and parts for equipment and appliances that operate on electrical current. Common examples encompass televisions, mobiles phones, refrigerators, iron, and computers<sup>24</sup>. Copper is frequently employed in electrical wiring; gold is incorporated in various computer technologies and silver is typically used in electronic circuits<sup>25,26</sup>.

### **2.3.3 In Medicine**

If you are wondering how, well, from a biological perspective, metals are found as micro-elements in our bodies. Besides, the presence of metal elements is crucial for several functions, such as the transmission of nerve impulses, oxygen flow, and the reaction between enzymes. Some medicines are therefore combined with metal compounds to treat certain deficiencies or sickness. Metals such as iron, calcium, magnesium, potassium, titanium, and aluminium are commonly used in medicine in the form of antacids<sup>24</sup>. Metals have been widely utilised as medical implants. Stainless steel and titanium alloys are frequently employed in biomedical devices such as joint replacement components, whereas gold, silver, and platinum are often used in dental applications. Various metals are also commonly incorporated in anti-cancer medications used in chemotherapy<sup>25</sup>.

### **2.3.4 Machinery, Refractory and Automobiles**

Most of the equipment and tools are made from metals. This is one of the most common uses of metals. They are used extensively in manufacturing machines for industries, agriculture or farming and automobiles, which include road vehicles, railways, aeroplanes, rockets etc. Here, the commonly used metals are iron, aluminium and steel<sup>24</sup>. Besides these, most of the utensils that are used in the kitchen are made from metals like steel, aluminium, and copper. Due to a high temperature-tolerant nature, metals are preferred the most<sup>24</sup>. Aluminium has emerged as one of the most frequently utilised metals in the production of aircraft, ships, and vehicles in the rail and automotive sectors. As a lightweight and durable material, aluminium helps decrease the weight of vehicles and lowers their fuel usage<sup>25,26</sup>. Magnesium is viewed as an upgrade from aluminium regarding strength-to-weight ratio, and it remains relatively affordable<sup>26</sup>.

### **2.3.5 Decorative Products**

Metals such as platinum, gold, and silver come under the category of precious metals and have high economic value. These metals are widely used in making jewellery sets or for some decorative pieces<sup>24</sup>.

### **2.3.6 Food and Drink Industry**

Stainless steel is the perfect alloy due to its inert properties and ability to withstand various acids commonly found in food. Additionally, it can endure a broad spectrum of temperatures, making it suitable for both heating and freezing, and stainless-steel tools can be sterilized multiple times<sup>25</sup>.

### **2.3.7 Paint Industry**

During the 1800s, the toxic properties of lead were uncovered. This is why it is less prevalent in contemporary times, although it was not too long ago that it was used in products like paints and ammunition. Nevertheless, lead still serves certain purposes today. For instance, it is effective for shielding against radiation. It is also sometimes included in copper alloys to enhance their machinability. The combination of copper and lead is commonly utilised to boost the performance of bearings.

## **2.4 Exposure to Heavy Metals**

Exposure can be defined as the fact of experiencing something or being affected by it because of being in a particular situation or place. Exposure is contact. No matter how dangerous a substance or activity, without exposure, it cannot cause harm<sup>27</sup>. The greater the amount of a substance a person is exposed to, the more likely that health effects will occur. Large amounts of a relatively harmless substance can be toxic<sup>27</sup>. Exposure occurs when people come into contact with a chemical, either directly or through another substance contaminated with the chemical<sup>28</sup>. Exposure can happen when individuals inhale dangerous chemical vapors or air tainted by harmful chemicals or dust<sup>28</sup>. Exposure is described as being dependent on both duration and concentration. Exposure occurs when an individual is exposed to a hazardous substance for a specified period of time and to an amount of hazardous substance greater than the approved intake. Exposure period refers to the duration of time during which an individual is exposed to a specific chemical hazard or mixture of hazards, which is crucial in exposure assessment for evaluating the impact on human health<sup>29</sup>. Exposure concentration refers to the actual amount of a

substance that enters the body and reaches organs and tissues, which determines the toxic effects it may have. It is an important factor in assessing the toxicity of heavy metals<sup>30</sup>. Short-term exposure is referred to as acute exposure; it involves brief contact with a chemical that can occur over a few seconds to hours. For instance, activities like cleaning windows with ammonia, using nail polish remover, or spraying paint can take just a few minutes. The vapors that one may breathe in during these tasks are examples of acute exposures. Long-term exposure is called chronic exposure and is continuous or repeated contact with a toxic substance over a long period of time (months or years). If a chemical is used every day on the job, the exposure would be chronic. Over time, some chemicals, such as PCBs and lead, can build up in the body and cause long-term health effects. Chronic exposures can also occur at home. Some chemicals in household furniture, carpeting or cleaners can be sources of chronic exposure<sup>27</sup>. Both may result in health effects that manifest immediately or after a delay of days or years later<sup>27</sup>.

Heavy metal exposure is widespread due to environmental pollution affecting air, water, and soil, as well as its accumulation in food, tobacco, herbal medicines, and occupational settings<sup>31</sup>. The release of heavy metals into the environment has increased, either directly or indirectly, over the last few decades, particularly in developing nations, as a result of the expansion of specific industries, such as fertiliser production, battery manufacturing, metal plating, and mining operations. The fact that heavy metals do not biodegrade (unlike organic pollutants), their accumulation in living organisms, and their toxic or carcinogenic properties classify them as hazardous materials for both humans and the environment<sup>32</sup>.

#### **2.4.1 Environmental Exposure**

Concerns regarding environmental and public health due to heavy metals contamination have been increasing lately. The risk of human exposure to these metals is increasing as their use in

manufacturing, agriculture, households, and technology expands<sup>33,34</sup>. Although heavy metals are found in nature, human activities like mining, smelting, agriculture, and manufacturing greatly enhance their release into the environment<sup>33,35</sup>. Contamination may also arise from processes such as corrosion, atmospheric deposition, ion erosion, leaching, sediment resurfacing, and the evaporation of metals from polluted water sources into soil and groundwater<sup>33,36</sup>. Additionally, natural occurrences such as volcanic eruptions and weathering contribute to environmental contamination<sup>33,37</sup>. Many heavy metals contribute to environmental and air pollution, and can be fatal to humans. Air pollution, primarily caused by emissions of Particulate Matter (PM), polycyclic aromatic hydrocarbons, and heavy metals (loid)s, is recognised as a major environmental health concern worldwide. Higher levels of air pollution are associated with a wide range of health issues, affecting both children and adults. As urbanisation continues to accelerate, leading to the growth of large metropolitan areas, the increasing number of people moving to cities in search of better opportunities causes pollutant levels in the air to rise, exacerbating the already concerning air quality situation<sup>38,39</sup>. The increasing emission of pollutants from vehicles, factories, and other human activities further worsens the challenges of air pollution in urban areas environments<sup>40,41,42</sup>. Consequently, prolonged exposure to air pollution has emerged as a significant public health concern, particularly for populations residing in major urban areas<sup>40</sup>. The PM, often categorised based on their aero dynamic diameter, includes PM<sub>10</sub>, PM<sub>2.5</sub>, and the finer PM<sub>1</sub> particles<sup>43,44</sup>. These particles can penetrate deep into the respiratory system, leading to respiratory and cardiovascular problems, worsening chronic conditions like asthma, and raising the risk of premature death<sup>40</sup>. Moreover, PM<sub>1</sub>, as the smallest and most inhalable fraction of particulate matter, is considered a particularly harmful component because it can evade natural defense mechanisms and penetrate deeply into the lungs<sup>45,46</sup>. In



addition to particulate matter, potentially toxic metals such as lead, cadmium, nickel, chromium, and arsenic are significant contributors to urban air pollution<sup>45</sup>. Potentially toxic metals (PTMs) commonly known as “heavy metals,” are electropositive elements and metalloids found in various ecosystems. They are characterised by high density and can be harmful even at trace concentrations, posing significant health risks to humans and other organisms<sup>47,48,49</sup>. Toxic elements are released into the atmosphere from various anthropogenic sources, including industrial processes, fossil fuel combustion, and waste management activities<sup>41</sup>. Following inhalation, these metals may accumulate in the body over time, leading to chronic health conditions and disruptions to multiple physiological systems<sup>46</sup>. The carcinogenic properties of specific potentially toxic metals (PTMs), including arsenic (As), cadmium (Cd), hexavalent chromium (Cr (VI)), and nickel (Ni), present significant concerns about their capacity to induce cancer in exposed populations<sup>35,50,51,52</sup>. Heavy metals exhibit significant toxicity when they interact with environmental elements such as water, soil, and air. These metals can subsequently enter the food chain, leading to exposure in humans and other living organisms<sup>53</sup>. Metal-contaminated environments lead to the accumulation of heavy metals within the human food chain, ultimately affecting the human body<sup>53</sup>. The health effects of heavy metals on humans vary based on the level and length of exposure<sup>53</sup>.

## **2.5 Physiological Routes of Exposure**

Exposure routes are the ways an agent or contaminant enters a person or individual or population after contact. The route of exposure is crucial in an exposure event<sup>54,55</sup>. There are three major means by which a heavy metal can come into contact with or enter the body. These are called routes of exposure<sup>27</sup>.

### **2.5.1 Inhalation Exposure**

Inhalation is the most rapid and common route of exposure<sup>25,54</sup>. Inhaling contaminated air can occur when breathing in particles (such as dust), vapors (like volatile or semi-volatile substances), or aerosols and mist<sup>27,55</sup>. People may encounter exposure through inhalation while participating in various activities both outside and indoors. Additionally, individuals inside buildings may be exposed to outdoor pollutants that enter and affect the indoor air quality<sup>54</sup>. Chemicals can enter and irritate the nose, air passages and lungs. They can become deposited in the airways or be absorbed through the lungs into the bloodstream. The blood can then carry these substances to the rest of the body<sup>27,55,56</sup>. Signs of chemical exposure via inhalation may include irritation of the eyes, nose, and throat, as well as coughing, trouble breathing, headaches, dizziness, confusion, and even fainting<sup>56</sup>.

### **2.5.2 Dermal Exposure**

Dermal exposure refers to direct contact with the skin or eyes. Certain substances can penetrate the skin and enter the bloodstream. If the skin is broken, cut, or cracked, it can facilitate the entry of these substances into the body<sup>27</sup>. Chemicals can rapidly reach the bloodstream, potentially leading to additional harm, alongside the immediate effects that may occur to the eyes and skin<sup>56</sup>. Dermal exposure can result from skin contact with contaminated environmental sources such as water during bathing, washing, or swimming, as well as contact with sediment (e.g., while wading, fishing); soil or dust from outdoor sources (for instance, during leisure activities,

gardening, or construction work); and dust that has accumulated indoors on carpets, flooring, clothing, countertops, or various other surfaces<sup>55</sup>.

Water can become polluted through direct discharges into surface water (i.e., point sources), indirect releases, and movement into groundwater or other water sources where people may be exposed through skin contact. Soil, household dust, or other materials may become contaminated due to deliberate applications (e.g., pesticide usage), deposition of particulates (e.g., from airborne pollutants), or transfer from different mediums (e.g., water). Human receptors might also come into contact with chemicals from consumer products directly (e.g., during use) or indirectly (e.g., chemicals that have settled on indoor or outdoor surfaces)<sup>55</sup>. Symptoms of exposure to chemicals in the eyes can include itching or burning sensations, blurred vision, discomfort, and potential blindness<sup>56</sup>.

### **2.5.3 Ingestion Exposure**

Ingestion exposure can occur through the consumption of contaminated food, water, or other beverages. Contaminated food may contain chemical residues as a result of this exposure<sup>27,55</sup>. Substances that come into contact with food, cigarettes, utensils, or hands can be ingested. Exposure through ingestion can happen either intentionally or unintentionally due to the ingestion of soil, dust, or chemical residues present on contacted surfaces or objects through non-dietary means and then brought to the mouth (this is particularly concerning for young children). Soil can become polluted due to direct releases into the ground, deposition from the atmosphere, or movement from other sources (such as water). Contaminated soil can also be brought indoors, contributing to polluted household dust<sup>55</sup>. Chemical exposure via ingestion happens when substances are absorbed through the digestive system. Chemicals can be ingested both directly

and indirectly. Direct ingestion may happen accidentally by ingesting or drinking a chemical; proper labeling and housekeeping can reduce the likelihood of this occurring. The risk of chemical exposure increases with indirect ingestion. This scenario arises when food or beverages are taken into a chemical lab, where they can absorb chemical contaminants (from vapors or dust in the air), leading to exposure when consumed. Similarly, this can happen if food or drink is kept alongside chemicals, such as in a refrigerator. Ingestion may also occur if a lab worker who handles chemicals neglects to wear gloves or maintain good personal hygiene, such as frequent handwashing, and then goes outside the laboratory to eat, drink, or smoke. In all such instances, chemical exposure can occur, although the effects of prolonged exposure might remain undetected for many years<sup>56</sup>. Children are at greater risk of ingesting substances found in dust or soil because they often put their fingers or other objects in their mouths. Lead present in paint chips exemplifies this process. Such substances may be absorbed into the bloodstream and subsequently distributed throughout the body. The route of exposure can determine whether or not the toxic substance has an effect. For example, breathing or swallowing lead can result in health effects, but touching lead is not usually harmful because lead is not readily absorbed through the skin<sup>27,54</sup>. Signs of chemical ingestion may include unusual or metallic flavors in the mouth, stomach pain, nausea, difficulties with swallowing, and an overall sense of unwellness<sup>56</sup>.

## **2.6 Specific Heavy Metals and their Risks**

As trace elements or at low concentrations, Certain heavy metals, including copper, iron, selenium, zinc, and manganese, are considered essential elements to maintain the metabolism of the human body and human survival. However, at higher concentrations they can become toxic agents and lead to poisoning<sup>58,59</sup>. Heavy metals such as arsenic, cadmium, lead, thallium, and mercury have no biological function but can enter the human body through environmental

exposure. Like essential metals, they become toxic when their concentrations exceed certain thresholds<sup>59,60</sup>.

### 2.6.1 Copper (Cu)

Copper is a fundamental element required for the survival of organisms ranging from bacteria and fungi to plants and animals. In humans, copper serves as an indispensable trace metal and is a necessary cofactor for various biological processes<sup>61</sup>. An intake of 0.8 mg per day of copper is adequate to maintain and regulate copper homeostasis in the human body<sup>62</sup>. Most dietary copper is in the form of  $\text{Cu}^{2+}$ , which cannot be directly absorbed by cells. Digestive tract cells process  $\text{Cu}^{2+}$ , reducing it to  $\text{Cu}^+$  with the help of Divalent Metal Transporter 1 (DMT1).  $\text{Cu}^+$  then binds to Copper Transporter 1 (CTR1) to enter cells. Once inside,  $\text{Cu}^+$  is transferred to the copper chaperone protein antioxidant 1 (Atox1), which interacts with copper transport ATPase  $\beta$  (ATP7 $\beta$ ) through the Golgi complex pathway from preceruloplasmin and subsequently acts on organs and tissues throughout the body<sup>63</sup>. Copper exhibits significant redox activity, enabling it to participate in diverse biochemical reactions through electron transfer. As a trace element, copper is broadly distributed in biological tissues, contributes to protein synthesis, and is essential for physiological regulation and human health<sup>63</sup>. Copper, in conjunction with specific proteins and enzymes, plays a crucial role in essential physiological processes, including energy metabolism, oxidative detoxification, and mitochondrial respiration. The absorption, transport, storage, and excretion of copper ions constitute the fundamental mechanisms that maintain copper homeostasis in the body<sup>64,65</sup>. Copper binds to enzymes, facilitating blood clotting, hormone maturation, and cellular energy metabolism. The distinct redox properties of copper

confer both beneficial and harmful effects on cells. Excess copper induces cytotoxicity and leads to cell death, whereas copper deficiency impairs its absorption and transport, resulting in abnormal intracellular copper distribution<sup>66</sup>. Both excess and deficiency of copper disrupt normal cellular function. Since tumor growth and metastasis require increased copper, copper-based diagnostic and therapeutic approaches are well-suited for cancer<sup>66</sup>. The average daily copper intake in adults, as determined by balance studies, should be interpreted with caution due to uncertainties in copper concentrations across various foods and water sources. Additionally, homeostatic mechanisms regulating copper absorption and excretion may influence the adequacy of copper supplied to the blood and liver<sup>67,68,69</sup>. Although the beneficial effects of copper as an essential trace element are well understood, there is uncertainty regarding copper reference values for humans due to differing recommendations from various national authorities<sup>67</sup>. Proposed reference ranges for copper are as follows: blood free serum copper, 1.6–2.4  $\mu\text{mol/L}$  or 10–15  $\mu\text{g/dL}$ ; blood total copper, 10–22  $\mu\text{mol/L}$  or 63.7–140.12  $\mu\text{g/dL}$ ; serum ceruloplasmin, 2.83–5.50  $\mu\text{mol/L}$  or 18–35  $\mu\text{g/dL}$ ; total 24-hour urine copper, 0.3–0.8  $\mu\text{mol}$  or 20–50  $\mu\text{g}$ ; and liver copper, 0.3–0.8  $\mu\text{mol/g}$  of tissue or 20–50  $\mu\text{g/g}$  of tissue<sup>68,69</sup>. Normal urinary copper excretion is assumed to be less than 70  $\mu\text{g}$  per day, while fecal copper output, primarily from bile, is estimated to be 1 to 2 mg per day. While copper is a vital trace element for many biological functions, including those in humans, elevated concentrations of these metals in water bodies caused by pollution can result in negative health impacts for aquatic life and humans who consume them<sup>71,72</sup>. Copper, which is crucial for various enzymatic activities and bodily functions, can lead to gastrointestinal problems, abdominal disorders, disruptions in metabolic processes, damage to the liver and kidneys, and neurotoxic effects when present in high concentrations<sup>23,73,74,75,76</sup>. Copper (Cu) is an essential micronutrient for human health.

Nevertheless, elevated concentrations of Cu may result in toxicity and adverse health outcomes<sup>77</sup>. Copper accumulation induces mutations and aggregation of mitochondrial proteins, leading to a reduction in the activity of primary antioxidant enzymes and an increase in the production of toxic reactive oxygen species<sup>78</sup>. An association between increased copper (Cu) levels and the development of fibrosis in renal tissues has been demonstrated<sup>79</sup>. Copper exposure adversely affects male reproductive function, resulting in reduced sperm count and motility<sup>80</sup>. A correlation has been identified between copper exposure and the prevalence of obesity<sup>81</sup>. Copper influences the homeostasis of essential elements, including calcium, iron, and manganese. Disruption of these elements is associated with the induction of oxidative stress. Consequently, this process may contribute to the onset of neurodegenerative disorders<sup>82</sup>.

### **2.6.2 Manganese (Mn)**

Manganese is a grayish-red transition metal and ranks among the most abundant elements in the Earth's crust at an average concentration of 950 mg kg<sup>-1</sup> or 0.095% in proportion. Manganese primarily occurs in mineral ores such as pyrolusite (MnO<sub>2</sub>), rhodocrosite (MnCO<sub>3</sub>), manganite (Mn<sub>2</sub>O<sub>3</sub>·H<sub>2</sub>O), hausmannite (Mn<sub>3</sub>O<sub>4</sub>), biotite mica (K(Mg,Fe)<sub>3</sub>(AlSi<sub>3</sub>O<sub>10</sub>)(OH)<sub>2</sub>), and amphibole ((Mg,Fe)<sub>7</sub>Si<sub>8</sub>O<sub>22</sub>(OH)<sub>2</sub>)<sup>83,84,85,86</sup>. Manganese (Mn) functions as a cofactor for multiple enzymes and is essential for the physiological processes of humans, plants, and animals. Additionally, manganese serves as a critical raw material and alloying element in various industrial applications. However, widespread industrial use results in excessive emissions into the environment, posing a significant threat to both ecosystems and public health. Generally, Manganese exhibits valence states of +2, +3, +4, +6, and +7. In aqueous environments with pH values between 4 and 7, manganese predominantly exists as Mn<sup>2+</sup>. At higher pH levels or in the presence of microbial oxidation, higher oxidation states of manganese are observed<sup>87</sup>.

Manganese confers beneficial effects primarily by facilitating the incorporation of metal ions into metalloproteins. Additionally, it is incorporated into the enzymes arginase, glutamine synthetase, phosphoenolpyruvate decarboxylase, pyruvate carboxylase, and manganese superoxide dismutase<sup>88</sup>. For example, the regulation of ammonia levels in the body depends on manganese, which modulates the enzymatic activity of arginase. Furthermore, manganese significantly influences bone health due to its ability to interact with glycosyltransferases<sup>89</sup>. A recent study demonstrated that manganese enhances the body's defense against DNA viruses by increasing the sensitivity of the DNA sensor cGAS and its downstream adaptor protein STING. Additionally, manganese plays a significant role in the innate immune sensing of tumors and enhances adaptive immune responses against tumors<sup>90</sup>. Furthermore, several studies have indicated that manganese (Mn) bioavailability is a significant regulator of long-term litter decomposition rates<sup>91</sup>. Manganese (Mn) is an essential element for the production of manganese peroxidase (MnP), a key enzyme involved in the degradation of lignin and humification products. This relationship likely explains the observed phenomenon<sup>92</sup>. Manganese in nature is primarily sourced from deep-sea ore clusters, rock crust, soil, and freshwater. Crustal rocks and mining ores formed by volcanic eruptions, forest fires, and diverse plant life on land and in water are the main contributors to manganese reserves in the biosphere<sup>93</sup>. Diet constitutes the main source of manganese (Mn) intake in non-occupational settings. Adults typically consume between 1 and 10 mg of Mn per day, with approximately 1 to 5% absorbed in the gastrointestinal tract<sup>94</sup>. Manganese (Mn) is abundant in wheat germ, green vegetables, tea, and highly refined bread and cereals produced from crops grown in fertile soil. Furthermore, manganese concentrations are elevated in most dried fruits, particularly pine nuts<sup>95,96</sup>. While manganese (Mn) metal has significantly advanced industrial development and regional economic growth, it has also resulted



in substantial environmental pollution and degradation, particularly due to emissions from electrolytic manganese residue (EMR)<sup>97,98,99,100</sup>. EMR is a waste residue produced during electrolytic manganese processing, following sulfuric acid leaching, ammonia neutralization, and plate filter pressing<sup>101,102</sup>. Primary sources of airborne manganese (Mn) include industrial emissions from foundries and ferro-manganese facilities, combustion of fossil fuels, and the entrainment of Mn-containing soils<sup>103</sup>. Individuals who accidentally inhale Mn may absorb it directly into the brain via olfactory or trigeminal nerve pathways, bypassing the liver. In the brain, Mn disrupts dopamine, serotonin, and glutamine signaling, increasing the risk of manganism<sup>104,105,106</sup>.

The World Health Organization (WHO) recommends that manganese (Mn) levels in drinking water not exceed 0.1 milligrams per liter (mg/L). Sidoryk-Wegrzynowicz et al. suggest that excessive Mn accumulation in the central nervous system can cause neurotoxicity, leading to a neurological disorder known as manganism<sup>106</sup>. During the early stages of the disease, patients exhibit psychotic symptoms. Over time, these symptoms progress to chronic disturbances in extrapyramidal circuits, resulting in postural instability, dystonia, bradykinesia, micrographia, mask-like facial expression, and speech disturbances<sup>107,108</sup>. The neurological impact of manganese (Mn) is influenced by both the route of exposure and the extent of accumulation. Inhalation of Mn is typically linked to oxidative stress and increased neuronal apoptosis. In contrast, ingestion of Mn tends to produce more subtle effects, primarily altering neurochemistry and cognitive function. Currently, manganese (Mn) toxicity is primarily linked to occupational exposure among welders, miners, and steel workers who are exposed to chronic high concentrations of airborne particulate Mn. Inhalation of manganese may result in pulmonary inflammation and the gradual onset of respiratory symptoms, including cough, bronchitis,

pneumonitis, and reduced pulmonary function<sup>89</sup>. Manganese smelters and miners are at increased risk of developing occupational manganism and Amyotrophic Lateral Sclerosis (ALS)<sup>89</sup>.

### 2.6.3 Lead (Pb)

Natural lead comprises four stable isotopes: <sup>204</sup>Pb (1.4%), <sup>206</sup>Pb (24.1%), <sup>207</sup>Pb (22.1%), and <sup>208</sup>Pb (52.4%)<sup>31</sup>. The element is characterised by a bluish-white, lustrous appearance and exhibits both malleability and ductility. Its advantageous characteristics, such as resistance to corrosion, high density and low melting point make it suitable for use in pipes, solder, and storage batteries<sup>31</sup>. Sources of lead vary among countries, depending on the historical and current applications of lead-containing products. These sources extend beyond gold ore processing and the recycling of used lead materials. Studies have demonstrated a reduction in blood lead levels among populations in countries where unleaded gasoline is used<sup>23</sup>. A recent study reported elevated blood lead levels among pregnant women in a rural village in Bangladesh. More than 30% of the sampled women had blood lead concentrations exceeding 5 µg/dL. The primary source of lead exposure for these women was identified as food storage cans. Nearly 18% of the tested cans contained lead solder, contributing to lead contamination among the women<sup>109</sup>. A study conducted in China measured blood lead levels (BLLs) in children receiving treatment at lead specialty clinics and reported BLLs ranging from 5 to 126 µg/dL. This phenomenon can be attributed to both industrial sources and the widespread use of folk medicine in China<sup>110</sup>. Lead poisoning has been reported in Zamfara State, Nigeria, an area known for gold mining. According to Mahuta, sources of lead exposure in Nigeria include gold mining, the use of lead pipes for drinking water, and cultural practices involving lead<sup>111</sup>. Exposure occurs primarily through inhalation and ingestion, specifically via the respiratory tract and through the consumption of contaminated water and soil<sup>23</sup>. Sharma et al indicated that lead present in soil can

infiltrate the human food supply through plants growing in the contaminated soil<sup>112</sup>. Lead is a hazardous environmental pollutant with significant toxic effects on multiple organ systems. Although lead (Pb) can be absorbed through the skin, the primary routes of absorption are the respiratory and digestive systems. Exposure to Pb may result in neurological, respiratory, urinary, and cardiovascular disorders through immune modulation, oxidative stress, and inflammatory processes. Furthermore, lead (Pb) may disrupt the balance of the oxidant–antioxidant system and trigger inflammatory responses in multiple organs. Exposure to Pb alters physiological functions and is linked to various diseases<sup>113</sup>. Lead (Pb) is highly toxic and adversely affects neurological, biological, and cognitive functions in humans. The internationally recognised threshold for lead poisoning is 10 µg/dl in blood<sup>114</sup>. In 2021, the Centers for Disease Control and Prevention (CDC) revised the public health action level for blood lead (Pb) to 3.5 µg/dL (0.17 µmol/L) for children under six years of age, while maintaining the threshold at 5 µg/dL (0.24 µmol/L) for individuals aged six and older (18). The 3.5 µg/dL (0.17 µmol/L) threshold was established based on data from the National Health and Nutrition Examination Survey (NHANES) for the 2015–2016 and 2017–2018 cycles<sup>115</sup>. The adulteration of opium with lead (Pb) has emerged as a significant threat to human health in recent years<sup>116</sup>. The lead toxicity in humans causes intestinal cancer, a serious effect on mental health (Alzheimer’s disease), lung cancer, and central nervous system<sup>23</sup>. Lead induces oxidative damage in various organs by directly promoting membrane lipid peroxidation and decreasing antioxidant parameters<sup>117</sup>. Low levels of lead exposure have been reported to stimulate immune responses, whereas higher exposures typically result in immunosuppression<sup>118,119</sup>.

#### **2.6.4 Zinc (Zn)**

Zinc (Zn) is among the most abundant transition elements in the Earth's crust and is recognised as an essential trace element for all living organisms<sup>120,121,122</sup>. It is an essential component of many proteins and serves as a cofactor or coenzyme for over 300 enzymes. It plays a key role in regulating enzymes, proteins, DNA, immune function, and cell metabolism<sup>123</sup>. It also helps reduce the formation of free radicals and Reactive Oxygen Species (ROS), supporting protein stability and the activity of antioxidative enzymes<sup>124</sup>. In natural environments, zinc occurs as a divalent cation ( $\text{Zn}^{2+}$ ) and interacts with a range of negatively charged ions ( $\text{CO}_3^{3-}$ ,  $\text{OH}^-$ ,  $\text{C}_2\text{O}_4^{4-}$ ). Zinc (Zn) is primarily found in nature as the mineral sphalerite ( $\text{ZnS}$ ) and possesses five stable isotopes ( $^{64}\text{Zn}$ ,  $^{66}\text{Zn}$ ,  $^{67}\text{Zn}$ ,  $^{68}\text{Zn}$ , and  $^{70}\text{Zn}$ ). Among these,  $^{64}\text{Zn}$  is the most abundant<sup>125</sup>. In humans, zinc is essential for the synthesis of hormones and their corresponding receptors<sup>126,127</sup>. The human body contains approximately 2 to 3 grams of zinc, with over 80% found in the bones and muscles. Within the circulatory system, enzymes such as superoxide dismutase and carbonic anhydrase, which are present in red blood cells, transport the majority of zinc in the bloodstream. The majority of transported zinc in plasma is bound to albumin, with an approximate concentration of 12–16  $\mu\text{M}$ . Moreover, zinc regulation in the human body is closely linked to cellular proliferation, apoptosis, differentiation, and the production of cytokines and antibodies. These processes are essential for maintaining the homeostasis of both innate and adaptive immune systems<sup>128,129,130</sup>. Zinc supplementation has been recommended to reduce viral activity and to ameliorate tissue damage and inflammation in various viral infections, including COVID-19<sup>131,132</sup>. Human zinc intake depends on diet, which varies by age and gender. The German Nutrition Society recommends a daily intake of 1.5 mg for infants aged 0 to 4 months, 11 mg for adolescent males, and 14 mg for adolescent females aged 15 to 19 years. For adults aged 19 years or older, the Food and Nutrition Board of the United States recommends an average intake

allowance of 11–16 mg/day and 7–10 mg/day, respectively, depending on the amount of phytate consumed<sup>132,133</sup>. Zinc intake, particularly in excessive amounts, has been reported to influence the modulation of gastrointestinal microbiota and the immune system<sup>134</sup>. Excessive intake of this element may cause adverse effects, including disruption of other elemental levels, particularly copper. This disruption can lead to copper deficiency anaemia, decreased copper-dependent enzyme activity, and dysregulation of cholesterol metabolism<sup>135,136</sup>. At elevated concentrations, Zn can become toxic to cells by disrupting essential biological functions. This occurs when Zn blocks protein thiols through mismetallation with other metals<sup>137,138,139</sup>. Environmental emissions of large quantities of zinc (Zn) from both natural and anthropogenic sources have facilitated its unchecked entry into food chains, leading to biomagnification in living organisms. Zn is commonly present in soil due to weathering and in water bodies as a result of industrial effluent discharge. Zinc (Zn) is among the most prevalent heavy metals in soil. Excessive concentrations can induce phytotoxicity, significantly reducing crop quality and yield. Furthermore, the accumulation of Zn in edible plant tissues may pose health risks to humans upon consumption due to absorption or deposition<sup>138,139,140,141,142</sup>. Moreover, elevated concentrations of Zn in soil inhibit and alter soil microbial communities due to its bioavailability as ionic Zn and within organometallic complexes, as previously established<sup>143,44,145,146,147,148,149</sup>. In humans, zinc toxicity primarily manifests through oral exposure, dermal contact, or accidental inhalation<sup>150</sup>. Zinc is essential for regulating many biological functions, including immune response, wound healing, enzymatic activity, and metabolism. However, excessive zinc levels have been linked to prostate cancer, possibly through the regulation of the Zip1 transporter, which affects zinc accumulation in prostate cells. High zinc intake may also contribute to gastrointestinal disorders, kidney issues such as nausea and vomiting, immune system disruption, and abnormal liver function<sup>23,151,152</sup>.

### 2.6.5 Chromium (Cr)

Chromium (Cr) is a naturally occurring heavy metal present in the earth's crust and seawater, and is commonly utilised in various industrial processes<sup>153</sup>. Chromium exhibits several oxidation states from  $-2$  to  $+6$ , with the trivalent and hexavalent forms being the most common and stable<sup>154</sup>. Chromium can enter the human body through inhalation, ingestion, and dermal absorption. Occupational exposure to chromium constitutes a substantial health risk<sup>153</sup>. Chromium is widely utilised in the production of stainless steel, chrome plating, leather tanning, and as a dye in printing and textile manufacturing, as a cleaning solution, and as an anticorrosive in cooling systems. Industrial exposures with Cr can be to the trivalent and hexavalent forms, which exhibit different toxicokinetics and toxicodynamics in the body<sup>154</sup>. Chromium (VI) is associated with various diseases and pathologies, whereas chromium (III) is essential in trace amounts for lipid and protein metabolism and functions as a cofactor in insulin activity<sup>155,156,157</sup>. According to the International Agency for Research on Cancer (2018), hexavalent chromium is classified as a group I occupational carcinogen<sup>155</sup>. For non-occupational human populations, the primary exposure pathways to chromium are the ingestion of chromium-contaminated food and water, and dermal contact with chromium-containing products. In addition, metallurgical, refractory, and chemical industries discharge significant quantities of chromium into soil, groundwater, and air, resulting in adverse health effects on humans, animals, and marine life<sup>158</sup>. Chromium (Cr) can induce a range of diseases through bioaccumulation in the human body. These include dermal, renal, neurological, and gastrointestinal disorders, as well as various cancers affecting the lungs, larynx, bladder, kidneys, testicles, bone, and thyroid<sup>158</sup>. A recent meta-analysis indicated that exposure to Cr (VI) might lead to higher mortality rates and the incidence of multiple cancer types, including lung, laryngeal, bladder, kidney, testicular, bone,

and thyroid cancers in humans<sup>159</sup>. An ecological study conducted in Greece in 2011 reported elevated concentrations of Cr (IV) in drinking water, ranging from 41 to 156 µg/L, and a corresponding increase in the incidence of liver ( $p < 0.001$ ), lung ( $p = 0.047$ ), and genitourinary cancers ( $p = 0.025$ ) among women<sup>155,160,161,162,163</sup>. A 2012 study conducted in India reported a higher incidence of gastrointestinal and dermatological complications among populations exposed to groundwater contaminated with hexavalent chromium (Cr(VI))<sup>159,164</sup>. DNA damage, genomic instability, and reactive oxygen species (ROS) generation are recognised mechanisms underlying chromium (Cr) toxicity and carcinogenicity. Both Cr (VI) and Cr (III) can induce ROS production<sup>165</sup>. Chromium carcinogenicity is associated with DNA damage, disruption of transcriptional regulation, lung disorders such as bronchitis and cancer, and adverse effects on the renal and reproductive systems<sup>23</sup>. Chromium (Cr) accumulation in body organs may pose significant risks to human health<sup>164</sup>. Cr negatively affects bronchial epithelial cells, possibly by disrupting proteins involved in apoptosis, the cytoskeleton, and energy metabolism<sup>167</sup>. The effects of chromium (Cr) on fetal growth during pregnancy have been examined<sup>167</sup>. The study's findings indicate that chromium (Cr) may exert toxic effects on fetal growth. Chromium is classified as a carcinogen and has been associated with the development of lung cancer<sup>168</sup>. Hyperpigmented skin often results from exposure to elevated levels of chromium<sup>170</sup>.

#### **2.6.6 Nickel (Ni)**

Nickel (Ni) is a silver-white metal with notable antioxidative properties. It ranks as the fifth most abundant metal on Earth, following iron, oxygen, silicon, and magnesium<sup>169,170</sup>. Nickel in the environment primarily originates from soil migration resulting from rock weathering, soil deposition, riverbed sedimentation, and volcanic eruptions. Although nickel can exhibit multiple valence states under certain conditions, nickel compounds are most commonly present in the

environment as  $\text{Ni}^{2+}$ , which exhibits low solubility in water<sup>170</sup>. Nickel offers greater antioxidative properties than iron and is widely used in electroplating, coatings, alloys, and industrial equipment<sup>172</sup>. Human activities, including industrial wastewater discharge, fossil fuel emissions, and the use of nickel compounds in manufacturing and electroplating, have increased nickel levels in water, soil, and air<sup>173</sup>. Organisms in these environments may be impacted by elevated nickel levels and accumulation<sup>170</sup>. Nickel primarily exists as  $\text{Ni}^{2+}$ . In biological systems, all forms of nickel intake, except for nickel carbonyls, involve the independent action of  $\text{Ni}^{2+}$ . The solubility of  $\text{Ni}^{2+}$  influences its toxicity mechanisms<sup>174</sup>. Nickel is an essential element for certain plant species; however, its biological role in humans remains unclear. Although most soluble nickel compounds are excreted in human feces, exposure to different forms of nickel can still cause health issues. Acute exposure, especially by inhalation, may result in severe conditions. Chronic Ni exposure can occur through various pathways, most commonly affecting the digestive tract<sup>175</sup>. Nickel exposure through drinking water and food can harm the human body, affecting the reproductive system and skin, and may lead to fatal toxicity<sup>173,174,176</sup>. In addition, alloys containing nickel, commonly utilised in food processing, can leach into food through direct contact or during sterilization<sup>177,178,179</sup>. These results emphasize the necessity of tracking nickel contamination in food. The US Environmental Protection Agency (USEPA) has established a reference dose (RfD) of 20  $\mu\text{g}/\text{kg}$  body weight per day. In 2015, the European Food Safety Authority set a tolerable daily intake (TDI) of 2.8  $\mu\text{g}/\text{kg}$  body weight, which was subsequently revised to 13  $\mu\text{g}/\text{kg}$  body weight<sup>175,180</sup>. Nickel (Ni) is widely present in air, water, and soil<sup>181</sup>. The negative effects of nickel (Ni) on human health have been extensively investigated, with a particular focus on its impact during pregnancy. Studies have demonstrated a positive correlation between Ni exposure in pregnant women and the incidence of preterm



delivery<sup>182</sup>. Patients with diabetes demonstrated higher urinary concentrations of nickel (Ni) compared to non-diabetic individuals<sup>183</sup>. Maternal exposure to Ni has been associated with an increased risk of congenital heart defects in offspring<sup>184</sup>. Nickel has been linked to immunological disorders, including Type I hypersensitivity and Type IV immune reactions, in individuals with chronic systemic symptoms related to nickel exposure<sup>185</sup>.

### **2.6.7 Cadmium (Cd)**

Cadmium (Cd), a relatively rare element, is naturally present in soil and in minerals including sulfide, sulfate, carbonate, chloride, and hydroxide salts, as well as in water. Elevated concentrations of cadmium (Cd) in water, air, and soil often result from industrial activities, leading to significant human exposure to Cd<sup>185,186, 87</sup>. Cadmium commonly occurs alongside other heavy metals, including zinc, copper, and lead, and is widely present in the environment<sup>188</sup>. Environmental cadmium concentrations are increasing as a result of soil disruption, volcanic activity, and industrial processes that utilize cadmium in alloys, pigments, stabilizers, and batteries<sup>189,190</sup>. Cadmium is primarily used in electroplating and the manufacture of nickel-cadmium batteries<sup>189</sup>. As a result, cadmium frequently contaminates municipal solid waste landfills, electronic waste, soils, and various plant tissues, including leaves, stems, and roots<sup>191,192,193</sup>. Human exposure to cadmium may occur through inhalation, including cigarette smoking, and through the consumption of contaminated food. Contamination can result from cadmium uptake by plant roots or rhizomes, or through horizontal transfer, affecting crops such as potatoes, grains, seeds, and mushrooms. Additional dietary sources include crustaceans, mollusks, shellfish, mussels, cocoa powder, and dried seaweed. The presence of cadmium (Cd) in contaminated water may disrupt essential physiological mechanisms, potentially leading to both acute and chronic health disorders<sup>186,187,188</sup>. Cadmium, in its ionic form as  $\text{Cd}^{2+}$ , is a non-

essential divalent metal that exhibits toxicity in eukaryotic cells<sup>194</sup>. As a result, cadmium does not participate in any known biological processes, including those involving enzymes. Therefore, cadmium is not physiologically eliminated from the human body, as mechanisms responsible for cadmium homeostasis and regulation of its uptake and release are absent. Infants may possess cadmium in their bodies from birth, as cadmium crosses the placental barrier and readily reaches the fetus<sup>195</sup>. Ingestion of contaminated food is a primary source of cadmium (Cd) exposure. Additional exposure can occur through smoking, which increases blood and urine Cd concentrations. Inhalation of industrial dust leads to more efficient pulmonary absorption of Cadmium. As individuals age and are continuously exposed to cadmium through inhalation and ingestion, cadmium accumulates in the body and can persist for 20 to 30 years as a non-biodegradable metal<sup>195,196,197</sup>. Cadmium (Cd) is classified by the International Agency for Research on Cancer (IARC) as carcinogenic to humans (Group 1)<sup>198</sup>. This toxic heavy metal poses significant risks to human health<sup>199</sup>. Cadmium exposure affects the vascular endothelium by stimulating the release of antithrombolytic substances, which subsequently increases the production of inflammatory markers<sup>200</sup>. Vijayakumar et al. investigated the biological effects of cadmium (Cd) on the proliferation and metastasis of prostate cancer and basal breast tumors<sup>201</sup>. Breast tumour cells may have reduced anti-oxidative defences, which can trigger ROS formation when exposed to Cd. The proximal tubule is also the primary site of Cd accumulation and nephron damage<sup>202</sup>.

## **2.7 Trace Metal Exposure Pathways**

Trace metals are minerals found in living organisms in minor quantities. Certain ones are recognised as nutritionally vital, while others could be essential, and the rest are regarded as non-

essential. Trace metals primarily act as catalysts in enzyme systems; some metal ions, like iron and copper, are involved in oxidation-reduction reactions related to energy metabolism<sup>204</sup>. Trace metals are present in a wide range of aqueous environments, geological materials, and biological systems. Trace metals exhibit toxicity when consumed in excessive quantities over prolonged periods<sup>205</sup>. It is widely recognised that trace metals can readily penetrate the human body because of their tiny particles and high mobility through three primary routes: ingestion, skin contact, and inhalation<sup>206</sup>. The small size and widespread presence of dust pose risks to both urban environmental quality and human health. Inhalation of dust is one of the exposure pathways in which humans are exposed to trace metals as the dust may be contaminated by heavy metals. Humans are also exposed to trace metals from the consumption or ingestion of contaminated food and drinks. When compared to adults, young children might present a greater risk of exposure to food and drinks contaminated with heavy metals due to their repetitive hand/finger sucking and mouthing non-food objects<sup>206,207</sup>. Humans are exposed to trace metals by direct contact with the eye or skin. Heavy metals are commonly found in colored cosmetics, either as intentional additives or as impurities introduced during the manufacturing process through raw materials<sup>208</sup>. The presence of heavy metals, including cadmium (Cd), lead (Pb), arsenic (As), nickel (Ni), chromium (Cr), and mercury (Hg), in cosmetic products poses significant risks to human health<sup>209</sup>. Certain elements are incorporated into cosmetics to promote optimal metabolic and physiological functions of the skin. Products containing the metals mentioned earlier include those applied to the mucous membranes, such as lipsticks, lip glosses, beauty creams, lotions, and hair care preparations<sup>210,211,212</sup>.

## **2.8 Effect of Trace Metals on Human Health**

Heavy metals can enter the human body through the gastrointestinal tract, skin, or inhalation. These toxic metals represent a significant threat to human health due to their capacity to damage cellular membranes and DNA, as well as disrupt protein and enzyme function<sup>213</sup>. The pathways of exposure and the associated health effects of heavy metals are illustrated in Figure 2.1. The primary pathways of exposure, the health consequences of toxic metals, and the strategies for risk mitigation are critical considerations. These adverse effects arise from direct environmental exposure to toxic metals as a result of human activities<sup>213</sup>.

### **2.8.1 Cadmium**

At low levels, cadmium compounds are highly toxic and can accumulate in the environment. The disease known as "Itai-Itai" (which involves osteoporosis and kidney dysfunction) results from the accumulation of cadmium in rivers, leading to weakened bones and fractures in people. It may also have the potential to lead to lung cancer, in addition to harming the respiratory system, liver, and kidneys<sup>214,215</sup>. Cadmium significantly contributes to the risk of cardiovascular diseases associated with smoking, including peripheral artery disease and coronary heart disease and infertility caused by reproductive system failure<sup>216</sup>. Cadmium leads to mental health issues, digestive problems, complications in the Central Nervous System, weaknesses in the immune system, damage to DNA, and Cancer<sup>217</sup>.

### **2.8.2 Chromium**

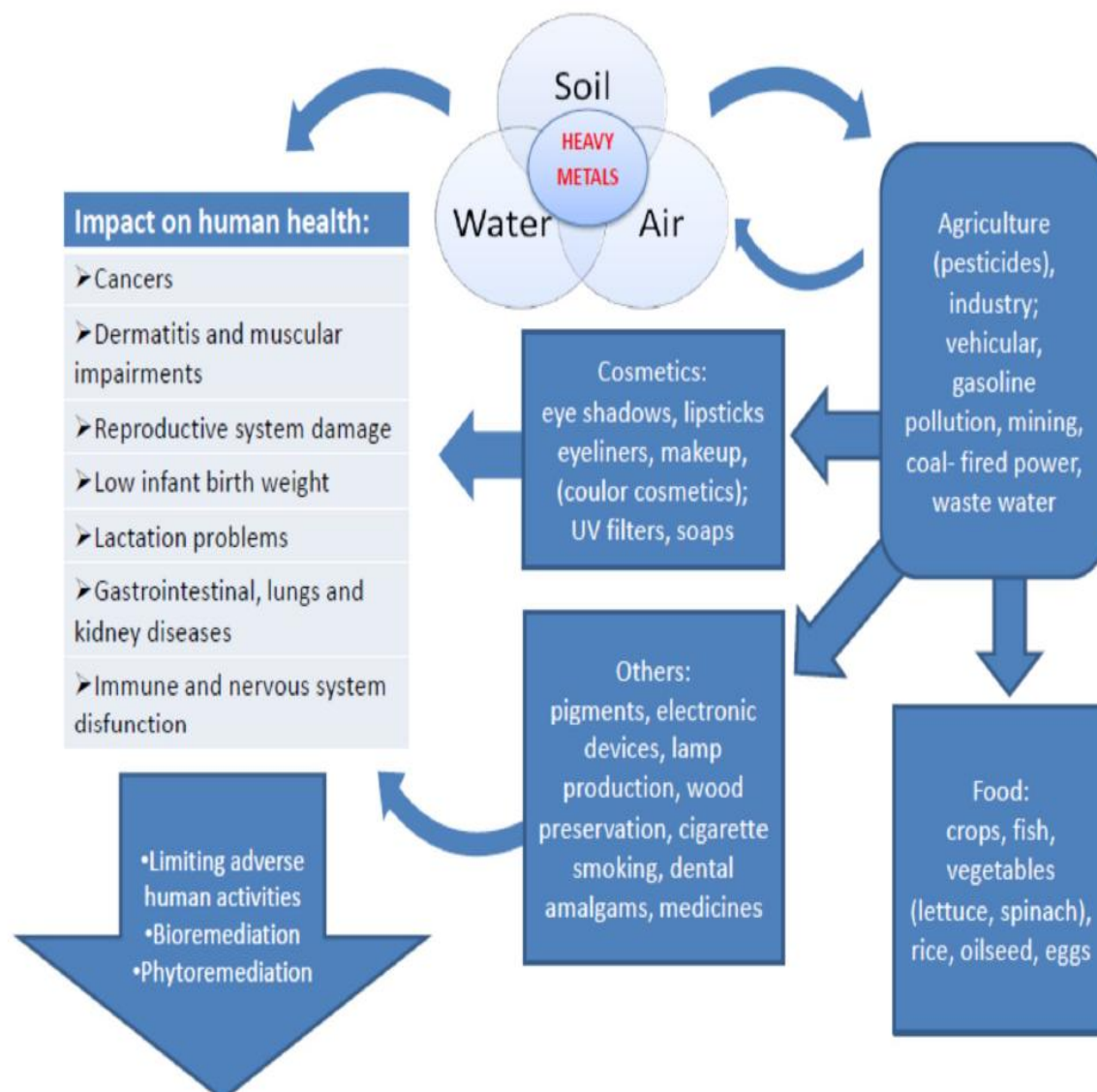
Elevated levels of chromium can damage the liver and kidneys, cause skin ulcers, and impact the human nervous system. Chromium (VI) poses a greater risk to human health compared to chromium (III)<sup>218,219</sup>. Cr (VI) induces oxidative stress and elevated production of reactive oxygen species (ROS), which target cellular DNA and lipids, resulting in DNA damage and lipid peroxidation, respectively. Additionally, various other cellular injuries and cell death, including both apoptosis and necrosis, may occur. At medium to low concentrations, ROS production in cells can contribute to tumour formation and progression<sup>220</sup>. Ingestion of chromium (VI) typically results in acute poisoning, manifesting as gastrointestinal ulceration, nausea, vomiting, fever, diarrhoea, vertigo, toxic nephritis, liver damage and death (usually at 1–3 g). Exposure to chromium (VI) through inhalation or repeated skin contact results in chronic poisoning. Chromium (VI) exposure is associated with allergic contact dermatitis, eczema, gingivitis, mucous membrane irritation, bronchitis, liver and kidney disease, sinusitis, pneumonia, lung cancer, and the development of chrome holes, particularly on the forearms, hands, fingers, and nose<sup>221,222</sup>.

### **2.8.3 Lead**

Lead (Pb) poisoning poses significant risks to human health. Elevated levels of Pb can adversely affect the fetus and negatively impact the central nervous system<sup>223</sup>. This exposure leads to various health issues, including damage to the renal and neurological systems, intellectual disabilities, and cancer<sup>224,224,226</sup>. Lead exposure can result in hypertension, reproductive complications, renal impairment, neurological damage, abdominal pain, peripheral nerve damage, iron deficiency, and cognitive impairment. In children, lead exposure impairs brain and central nervous system development, lowers intelligence, reduces educational achievement and attention span, and increases antisocial behaviour<sup>227,228,229</sup>.

#### **2.8.4 Copper**

Copper leads to hair loss, anaemia, kidney damage, and headaches, and it can also result in death when it builds up in the liver, brain, and pancreas, leading to fatal outcomes<sup>230</sup>. Excess copper exposure has been associated with insomnia, anxiety, agitation, and restlessness. In cases such as Wilson's disease, where copper accumulates in organs due to impaired biliary excretion, clinical manifestations may include lack of appetite, fatigue, jaundice, Kayser-Fleischer rings, speech impairment, difficulty swallowing, uncontrolled poisoning, brain damage, demyelination, and hepatic cirrhosis<sup>231</sup>.



**Figure 2.1:** Pathways for exposure and the effects of heavy metals on human health<sup>213</sup>.

### **2.8.5 Zinc**

While zinc is essential for humans in small amounts, elevated levels can lead to symptoms such as vomiting, skin irritation, fever, and anaemia<sup>232</sup>. Zinc may cause nausea, vomiting, stomach cramps, decreased HDL cholesterol, pancreatic complications, fatigue, epigastric pain, copper deficiency, anemia, impaired immune function, and neutropenia<sup>233</sup>.

### **2.8.6 Nickel**

Small amounts of nickel may not adversely affect biological cells, but long-term exposure to elevated levels can be damaging to cells, lead to weight loss, and negatively impact the heart and liver. Nickel toxicity could lead to impaired cell growth and an increased risk of cancer<sup>234</sup>. Nickel exposure has been linked to lung embolisms, asthma, allergic reactions from jewelry, respiratory failure, heart disorders, dizziness after gas exposure, and a higher risk of cancer. Nickel sulphide, nickel oxide, and soluble nickel compounds are classified as carcinogenic. Occupational exposure to inhaled nickel compounds in the nickel industry is associated with an increased risk of lung and nasal cancer<sup>235,236</sup>.

## **2.9 Parabens**

Parabens are a class of compounds that are frequently utilised as preservatives due to their ability to inhibit microbial growth. They are typically included in cosmetics and various personal care items to stop the development of mould, bacteria, and yeasts. Methylparaben and propylparaben are the two most widely utilised parabens<sup>237</sup>. Other names for these are methyl 4-hydroxybenzoate and propyl 4-hydroxybenzoate<sup>238</sup>. Parabens are widely recognised preservatives that help extend the shelf life of many foods, cosmetics, and pharmaceutical items by preventing the growth of microorganisms. They work to inhibit or minimize the proliferation



of mould and harmful bacteria. Their purpose is to safeguard both the product and the consumer<sup>239</sup>. Parabens constitute a widely recognised class of synthetic chemicals employed as preservatives in foods, cosmetics, and pharmaceutical products<sup>239</sup>. Parabens (PBs) are ester derivatives created by replacing the alkyl groups of para-hydroxybenzoic acid with methyl, ethyl, or benzyl groups<sup>241,242</sup>. These compounds are alkyl or aryl homologs of p-hydroxybenzoic acid (PHBA)<sup>243</sup>. Producers incorporate parabens to enhance the stability of various personal care and food products, thereby extending their shelf life. In the absence of a reliable preservative, numerous products, when used regularly, can become tainted and turn into a habitat for bacteria, yeast, and mould. Parabens are odourless, tasteless and chemically stable, making them perfect for incorporation into food and personal care items. Parabens have been commonly used in personal care items, as well as in food and drink, since the 1920s. Individuals face continuous exposure to parabens over their lives, due to the consistent use of products that include these chemicals or the regular consumption of certain widely-used food and beverage items. Parabens are classified as endocrine disruptors, which could lead to reproductive issues, impact birth results, and elevate the risk of cancer<sup>244</sup>. Parabens are frequently present in personal care products and cosmetics like lotions, sunscreens, antiperspirants, and makeup, moisturisers, shaving cream, conditioner, shampoo, diaper rash ointment, baby wipes, facial scrubs, mascara, cream, powder blush, liquid and powder foundation, stain removal and hair products<sup>243,243,245,246,247</sup>. Parabens may also be found in chewing gum and mouthwash<sup>248</sup>. Food items that include parabens consist of beer, soft beverages, sauces, syrups, jams, jellies, desserts, frozen dairy items, pickles, processed vegetables, trail mix, and packaged tortillas<sup>249</sup>. Although these chemicals have been widely used since the 1920s, numerous aspects of their effects on human health remain unclear. For example, the combined impact on the endocrine system and

potential disruptions to homeostasis are not yet fully understood. Numerous studies have evaluated the effects of both acute and chronic exposure to parabens. The findings from these investigations have resulted in the classification of parabens as Endocrine Disrupting Chemicals (EDCs)<sup>250</sup>. Previous studies have investigated the potential role of parabens as causative agents in diseases associated with hormonal disorders<sup>251</sup>.

## **2.10 Characteristics of Parabens**

Parabens are structurally based on para-hydroxybenzoic acid (PHBA) and are distinguished by the nature of their substituent, which can be either an alkyl chain or an aromatic ring. The most common parabens possess a linear alkyl chain as the substituent<sup>243</sup>: methylparaben (MeP), ethylparaben (EtP), propylparaben (PrP), butylparaben (BuP), and pentylparaben (PeP).

Iso-propylparaben (iso-PrP) and iso-butylparaben (iso-BuP) are parabens with branched-chain substituents. Benzylparaben (BzP) represents an aromatic ester derived from PHBA<sup>243</sup>. Cosmetic products typically contain substances that provide a favorable environment for the growth of microorganisms such as bacteria and fungi. These substances include amino acids, peptides, protein hydrolysates, polysaccharides, plant extracts, and vitamins. In the absence of preservatives, cosmetics are prone to rapid spoilage, which leads to alterations in both aroma and appearance of the product<sup>252,253</sup>. Antimicrobial ingredients are incorporated during cosmetic production to extend product shelf life and inhibit microbial growth. Preservatives are classified as agents that inhibit the growth and development of microorganisms, such as fungistatic and bacteriostatic compounds, or as substances that kill microorganisms by causing cell damage, including bactericidal and fungicidal preservatives<sup>254</sup>. Widely used preservatives include derivatives of benzoic acid. In cosmetics, esters of parahydroxybenzoic acid (PHB), also known

as 4-hydroxybenzoic acid or parabens, are particularly significant. Parabens primarily exhibit fungistatic activity by inhibiting the growth of fungi such as mould. They also exert a lesser inhibitory effect on bacteria. In addition to parabens, other preservatives such as phenoxyethanol are used specifically to inhibit bacterial growth<sup>255</sup>. The group of PHB preservatives includes compounds such as parasept, Nipagin, and Aseptin<sup>256</sup>. Paraben concentrations in cosmetics typically range from 0.3% to 0.5%, with a maximum of 0.4% permitted in the European Union. These esters exhibit poor solubility in water. Benzyl para-hydroxybenzoate demonstrates the lowest solubility, while methyl para-hydroxybenzoate has the highest solubility among the group. Although parabens share structural similarities with salicylic acid (2-hydroxybenzoic acid) and benzoic acid, their toxicological and chemical properties differ significantly.

The use of parabens in cosmetics remains a subject of considerable debate. Despite extensive testing over recent decades and their legal status in production, public concerns persist regarding the potential effects of these compounds on human health. In 2007, parabens were classified as compounds that may disrupt the endocrine system. Some experts also caution that they can trigger allergic reactions. Some parabens are also naturally occurring. For example, methyl paraben is present in blueberries. Additionally, many medical professionals assert that the current acceptable dose of parabens in cosmetics is insufficient to cause harm<sup>257</sup>. Parabens are esters primarily used as preservatives. They inhibit the growth of yeasts and bacteria that may proliferate in cosmetic products over time. Parabens significantly extend the shelf life of creams and masks. The durability of a cosmetic product and the selection of an appropriate preservative are critical factors in ensuring cosmetic safety. In the absence of preservatives, water-based cosmetics typically exhibit a significantly reduced shelf life and generally require refrigeration

for storage. Cosmetics require preservatives because their primary ingredient is water, which supports the growth of microorganisms<sup>258</sup>.

Parabens, which are esters of p-hydroxybenzoic acid and related compounds, have been widely used as preservatives in cosmetic products for several decades and remain the most prevalent preservatives in this industry. These substances are extensively utilised in the cosmetics, pharmaceutical, and food industries. They are also present in products designed for children's care and in cosmetics labeled as hypoallergenic. They exhibit both antifungal and antibacterial activity, with greater effectiveness against Gram-positive bacteria than against Gram-negative bacteria<sup>259,260</sup>. In addition to exhibiting antimicrobial properties, these compounds are incorporated into soaps as antiperspirant agents and into shampoos as anti-dandruff substances. They also demonstrate the ability to penetrate the skin.

Based on penetrative ability, parabens are ranked as follows: butylparaben, propylparaben, ethylparaben, and methylparaben. A minor risk exists for paraben accumulation in adipose tissues<sup>261</sup>. Parabens help protect cosmetics from microbial infections, but they have also been linked to potential health risks. While they are among the most sensitising contact substances, they are generally considered weak allergens. Allergic reactions are typically mild, manifesting as pruritus and erythema, but can also result in the development of atopic dermatitis. Parabens are classified among compounds with extremely low oestrogenic activity.

The potency of parabens is between 1,000 and 1,000,000 times lower than that of natural oestrogen. The Scientific Committee on Consumer Safety (SCCS) report states that parabens, when used within acceptable concentrations, are considered safe and do not exhibit toxic, carcinogenic, genotoxic, or teratogenic effects<sup>262</sup>. However, there is a growing body of concern that these substances may cause skin irritation, allergic reactions, cancer, and reduced male

fertility. According to the EU Commission Regulation of 18 September 2014, propylparaben, butylparaben, their isomers, and salts are banned in products intended for children under three years of age due to their potential effects on the endocrine system<sup>263</sup>. The concentration of these substances has been restricted to 0.14% when used individually or in mixtures. In addition, the EU Commission Regulation of 9 April 2013 prohibits the use of isoparabens (isopropylparaben, isobutylparaben, pentylparaben, benzylparaben, phenylparaben) in cosmetics due to insufficient safety data. Parabens are solid compounds that appear as fine, odorless crystals. Various groups of parabens are illustrated in Figure 2.2. Common parabens utilised in cosmetic formulations include methylparaben, ethylparaben, propylparaben, isopropylparaben, butylparaben, isobutylparaben, and their respective potassium and sodium salts, such as potassium methylparaben and sodium isobutylparaben<sup>264</sup>.

## **2.11 Structures of Parabens**

### **2.11.1 Ethylparabens**

Ethylparaben (ethyl para-hydroxybenzoate) is the ethyl ester formed from p-hydroxybenzoic acid through the process of condensing the carboxy group of 4-hydroxybenzoic acid with ethanol. The IUPAC name of Ethylparaben is ethyl 4-hydroxybenzoate. Its formula is (C<sub>9</sub>H<sub>10</sub>O<sub>3</sub>). It is used as an antifungal agent, antimicrobial preservative, a plant metabolite, and as a food additive<sup>265</sup>. Table 2.1 shows the molecular structure of Ethylparaben<sup>265</sup>.

### **2.11.2 Methylparabens**

Methylparaben is an aromatic substance. It appears as a white, odourless crystalline powder and is the methyl ester of p-hydroxybenzoic acid with the chemical formula of C<sub>8</sub>H<sub>8</sub>O<sub>3</sub>. The IUPAC designation for Methylparaben is methyl 4-hydroxybenzoate. It is used as a preservative in

cosmetics, medicine and foods. It's known for its effectiveness and cost-effectiveness in preventing microbial contamination. It has anti-bacterial and anti-fungal properties<sup>265</sup>. Also, Table 2.1 illustrates the structural configuration of methylparaben<sup>265</sup>.

### 2.11.3 Propylparabens

Propylparaben is the propyl ester derived from 4-hydroxybenzoic acid. Its formula is ( $C_{10}H_{12}O_3$ ). The IUPAC designation for Propylparaben is sodium 4-propoxycarbonylphenolate. It is a benzoate ester and is functionally connected to both propan-1-ol and 4-hydroxybenzoic acid. It is used as preservative, mostly used in water-based cosmetics, such as shampoos, lotions, creams, an antifungal agent and an antimicrobial agent<sup>265</sup>. Similarly, Table 2.1 illustrate the structural configuration of Propylparaben<sup>265</sup>.

### 2.11.4 Butylparabens

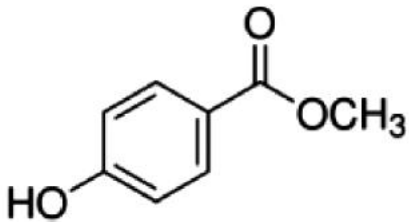
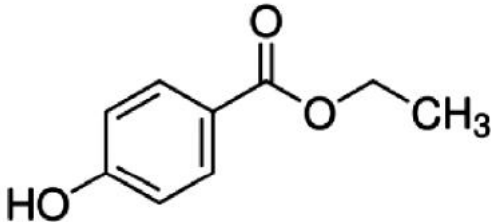
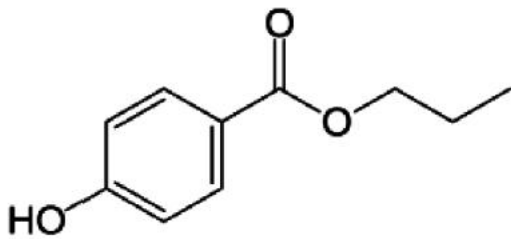
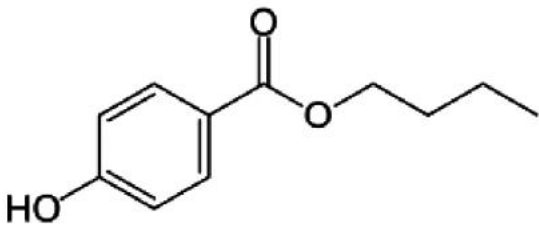
Butylparaben is an organic compound with the formula ( $C_{11}H_{14}O_3$ ). The IUPAC name of Butylparaben is butyl 4-hydroxybenzoate. Butylparaben serves as an antimicrobial preservative in cosmetic products, as it prevents the growth of bacteria and fungi in personal care items, in medication suspensions and as a flavouring additive in food <sup>265</sup>. Likewise, Table 2.1 shows the the structural configuration of Butylparaben<sup>265</sup>.

## 2.12 Physicochemical Properties of Parabens

Parabens, which are esters of p-hydroxybenzoic acid, are widely used as preservatives in cosmetics, pharmaceuticals, personal care products, and food due to their low cost, chemical stability, and high water solubility<sup>242,266,267</sup>. The physicochemical properties of parabens are significantly influenced by the nature of the substituent group. Parabens are odorless, tasteless,

and colorless compounds. Parabens do not alter the characteristics of cosmetics or food, so the color, aroma, and density remain unchanged. The general physicochemical properties of parabens are presented in Table 2.2. Parabens vary according to the type of alkyl group, which influences both their solubility in water and their antimicrobial activity<sup>268</sup>. These compounds are chemically stable and lipophilic. Depending on the alkyl chain length, their solubility in water is weak or very weak, as indicated in Table 2.3. Because these preservatives are effective only in the aqueous phase, solubilizing aids such as propylene glycol, glycerol, or ethanol should be added. These aids maintain antimicrobial activity across a pH range of 4 to 8. The antimicrobial efficacy of parabens decreases in the presence of certain surfactants due to hydrogen bond formation or the incorporation of paraben molecules into micelles. Parabens utilised on an industrial scale are typically synthetic compounds. However, several parabens, particularly methylparaben and propylparaben, also occur naturally in various commercial plants<sup>265</sup>.

**Table 2.1: Molecular Structure of Parabens<sup>265</sup>**

| Paraben             | Molecular Structure                                                                  |
|---------------------|--------------------------------------------------------------------------------------|
| Methylparaben (MeP) |    |
| Ethylparaben (EtP)  |    |
| Propylparaben (PrP) |  |
| Butylparaben (BuP)  |  |



**Table 2.2 Physicochemical Properties of Parabens<sup>\*265</sup>**

| Property                  | Methyl           | Ethyl                         | Propyl                        | Butyl                          |
|---------------------------|------------------|-------------------------------|-------------------------------|--------------------------------|
| 1                         | 2                | 3                             | 4                             | 5                              |
| Molecular weight          | 152.16           | 166.18                        | 180.21                        | 194.23                         |
| Melting point (T)         | 131              | 116–18                        | 96.2–98                       | 8–69                           |
| Boiling point (“C)        | 125–128          | 115–118                       | 95–98                         | 68–72                          |
| Density                   | 270–280          | 297–298                       | –                             | –                              |
| Refractive index          | –                | –                             | 1.0630                        | –                              |
| *max” in H <sub>2</sub> O | 1.5250           | 1.5050                        | 1.5050                        | –                              |
| PKa                       | –                | 256 (1.5 x 10 <sup>-2</sup> ) | 256 (1.5 x 10 <sup>-2</sup> ) | 256 (1.55 x 10 <sup>-2</sup> ) |
|                           | 8.17             | 8.22                          | 8.35                          | 8.37                           |
| Inorganic impurities**    |                  |                               |                               |                                |
| As                        | 1 ppm            | –                             | 1 ppm                         | 1 ppm                          |
| Pb                        | 10 ppm           | –                             | 10 ppm                        | 10 ppm                         |
| Ash                       | 0.1%             | 0.1%                          | 0.1%                          | 0.1%                           |
| Residue on ignition* (%)  | 0.05             | 0.05                          | 0.05                          | 0.05                           |
| Loss on drying* (%)       | 0.5              | 0.5                           | 0.5                           | 0.5                            |
| Acidity* (mEq/750 mg)     | 0.02             | 0.02                          | 0.02                          | 0.02                           |
| Solubility                |                  |                               |                               |                                |
| Alcohol                   | very soluble     | very soluble                  | soluble                       | soluble                        |
| Water                     | slightly soluble | slightly soluble              | insoluble                     | insoluble                      |
| Ether                     | very soluble     | very soluble                  | soluble                       | soluble                        |
| Acetone                   | very soluble     | soluble                       | soluble                       | soluble                        |
| Benzene                   | slightly soluble | –                             | –                             | –                              |
| Carbon tetrachloride      | slightly soluble | –                             | –                             | –                              |
| Glycerin                  | slightly soluble | slightly soluble              | –                             | slightly soluble               |

\*\*Maximum recommended; no information available on organic impurities

**Table 2.3: Parabens have a restricted solubility in Water<sup>265</sup>**

| <b>Property</b>   | <b>Methylparaben<br/>sol. g/100 mg</b> | <b>Ethylparaben<br/>sol. g/100 mg</b> | <b>Propylparaben<br/>sol. g/100 mg</b> | <b>Butylparaben<br/>sol. g/100 mg</b> |
|-------------------|----------------------------------------|---------------------------------------|----------------------------------------|---------------------------------------|
| Water 18°C        | 0.16                                   | 0.08                                  | 0.023                                  | 0.005                                 |
| Water 25°C        | 0.25                                   | 0.11                                  | 0.04                                   | 0.015                                 |
| Water 80°C        | 3.2                                    | 0.86                                  | 0.45                                   | 0.15                                  |
| Ethanol           | 22                                     | 25                                    | 26                                     | 110                                   |
| Propylene, Glycol | 1.7                                    | 0.5                                   | 0.4                                    | 0.3                                   |
| Peanut Oil        | 0.5                                    | 1                                     | 1.4                                    | 5                                     |
| Mineral Oil       | 0.01                                   | 0.025                                 | 0.03                                   | 0.1                                   |

### 2.13 Occurrence of Parabens

Parabens are widely present in the human environment. Certain parabens are synthesized by plants and bacteria, leading to their presence in natural ecosystems. Parabens occur naturally in bacteria, plants, and fruits, and have been synthesized and used by industry since the 1920s<sup>269,270,271</sup>. Members of the *Microbulbifer* family synthesize para-hydroxybenzoic acid (PHBA) and its esters. Methyl paraben (MeP) has been detected in berries at concentrations up to 0.15 ppm and is also present in *Oxalis tuberosa* and *Andrographis paniculata*<sup>257,272,273</sup>. PrP was isolated from the aerial parts of *Stocksia brahuica*, a species in the family *Sapindaceae*. Parabens synthesized by plants and microorganisms may function as protective agents that inhibit the growth of fungi and Gram-positive bacteria<sup>257,274</sup>. The substantial presence of parabens in the human environment is attributable to compounds produced through industrial-scale chemical synthesis. The high efficiency and low cost of this synthesis process have facilitated the widespread use of parabens<sup>257,274</sup>. Furthermore, parabens are widely used due to their broad-spectrum antibacterial and antifungal properties, which include the inhibition of yeast growth<sup>257,274</sup>. Parabens were considered safe for many years, which led to a systematic increase in their production that continues to rise annually<sup>257,274</sup>. The substantial increase in paraben production has contributed to the contamination of potable water and subsequent absorption of parabens by aquatic organisms<sup>269,275</sup>. A recent study documented the widespread presence of parabens and their metabolites in fish, seagrasses, invertebrates, marine macroalgae, seawater, mangroves, and ocean sediments<sup>275</sup>. Furthermore, parabens have been detected in both dust and indoor air, thereby increasing overall exposure to these endocrine-disrupting chemicals (EDCs)<sup>269</sup>. Parabens are typically synthesized via acid-base reactions or esterification processes that involve p-hydroxybenzoic acid and an alcohol (R-OH) in the presence of catalysts such as

thionyl chloride, dodecatungstophosphoric acid, or montmorillonite K10 clay. This reaction yields parabens and water<sup>276,277</sup>. Methylparaben and propylparaben are synthesized through the esterification of p-hydroxybenzoic acid with methanol for methylparaben and n-propanol for propylparaben, both of which utilize sulfuric acid as a catalyst<sup>257</sup>. Alternatives to parabens include formaldehyde, quarternium-15, imidazolidinyl urea, diazolidinyl urea, and dimethyloldimethyl hydantoin. Natural preservatives such as thymol, cinnamaldehyde, allyl isothiocyanate, citric acid, ascorbic acid, and rosemary extract are also available<sup>278</sup>. However, the use of natural preservatives presents challenges, including potential allergenic reactions and other health concerns. Furthermore, current research is insufficient to conclusively demonstrate the efficacy and safety of these products<sup>279</sup>. Cosmetic products may also contain preservatives, including formic acid, propionic acid, sorbic acid, benzoic acid, salicylic acid, benzyl alcohol, 2-phenoxyethanol, sodium benzoate, triclosan, bronopol, DMDM hydantoin, methylisothiazolinone, and methylchloroisothiazolinone<sup>280</sup>.

#### **2.14 Application of Parabens**

These compounds are widely utilised due to their effective preservation and antimicrobial properties, as well as their chemical stability and low production costs, making them suitable for industrial applications<sup>278,280</sup>. Furthermore, the low incidence of sensitization, adequate water solubility for solution preparation, chemical inertness, stability in product consistency and color, and lack of perceptible odor or taste are properties that make parabens valuable compounds<sup>279</sup>. Increasing the alkyl chain length in parabens enhances their antimicrobial effectiveness, but it also reduces their water solubility. Parabens are more effective as preservatives against fungi than against bacteria, and are more effective against Gram-positive bacteria than against Gram-negative bacteria. The range of effectiveness may increase when different parabens are used in

combination<sup>257</sup>. Furthermore, these compounds demonstrate efficacy at neutral and acidic pH levels, as well as in alkaline solutions with a pH of up to 8. Above this threshold, their preservative functions diminish<sup>276</sup>. Since the 1990s, the use of parabens has increased annually, and they are now utilised in diverse fields, including pharmaceuticals, food production, cosmetics, and medicine<sup>279</sup>. Within industrial contexts, methylparaben (MP) is designated as E-218, ethylparaben (EP) as E-214, and propylparaben (PP) as E-216. The use of parabens has significantly increased, particularly within the food industry. Since 2013, parabens have been incorporated into the majority of canned and packaged food products<sup>279</sup>.

#### **2.14.1 Food**

Analysis of various commercially available food ingredients and additives revealed that MeP is the most commonly used paraben. The levels of MeP frequently correlate with those of PrP<sup>243</sup>. Parabens are commonly added to processed vegetables, spices, dairy products, bread, and juices. As reported by Liao et al., approximately 99% of the 282 food samples examined contained parabens<sup>241</sup>. The average concentration of parabens detected in food products was roughly 39.3 ng g<sup>-1</sup>. Analysis of paraben levels in various food categories revealed that vegetables contained the highest concentrations (109 ng g<sup>-1</sup>), followed by condiments (75.4 ng g<sup>-1</sup>) and cereals (25.2 ng g<sup>-1</sup>)<sup>241</sup>.

#### **2.14.2 Pharmaceuticals**

In China, parabens were also detected at high levels in pharmaceutical products, with a detection rate of approximately 97%. Zhao et al., reported that the geometric mean and median concentrations for the sum of measured parabens (MeP, EtP, PrP, BuP, BzP, and HeP) were 94.8 ng g<sup>-1</sup> and 119 ng g<sup>-1</sup>, respectively<sup>282</sup>. The maximum concentration of the sum of parabens ( $\Sigma$ )

was 1256 ng g<sup>-1</sup>. Among the pharmaceutical samples analyzed, methylparaben (MeP) was the predominant compound, representing 54% of the total measured parabens (EtP–24.6%; PrP–20.7%)<sup>282</sup>. The geometric mean concentration of MeP (28.7 ng g<sup>-1</sup>) was approximately 3.8 times higher than that of EtP (7.49 ng g<sup>-1</sup>) and 3.6 times higher than that of PrP (7.95 ng g<sup>-1</sup>)<sup>282</sup>. Furthermore, a strong positive correlation was observed between the concentration of MeP and the concentration of PrP in the pharmaceutical samples ( $r = 0.316$ )<sup>281</sup>. A US-based study found that only 20% of the analyzed pharmaceutical products contained parabens. The most frequently detected parabens in these products were MeP, PrP, and EtP<sup>284</sup>. Zhao et al., analyzed the presence of parabens in pharmaceutical products, categorizing them by therapeutic use such as throat, anti-inflammatory, gastrointestinal, cold, protective, and other medicines<sup>282</sup>. However, the study did not demonstrate significant differences between the groups and failed to categorize pharmaceutical samples according to their physical states, such as solid or liquid <sup>282</sup>. Nevertheless, a previous study reported a rising prevalence of parabens in liquid pharmaceutical products<sup>282</sup>. The results may be attributed to the higher moisture content of the liquids, which requires the addition of greater quantities of preservatives to inhibit microbial growth<sup>238</sup>.

### 2.14.3 Personal Care Products

Esters of PHBA have been detected in various Personal Care Products (PCPs), including shampoos, balsams, conditioners, creams, soaps, deodorants, make-up products, wet wipes, and lotions<sup>283</sup>. Analysis of 52 personal care product (PCP) samples in previous studies indicated that among six measured parabens, methylparaben (MeP, 77%), propylparaben (PrP, 73%), ethylparaben (EtP, 46%), and butylparaben (BuP, 25%) were most frequently detected<sup>238,283</sup>. A study conducted in Denmark detected parabens in 36% of 751 analyzed cosmetic product samples intended for children<sup>244</sup>. In Sweden, BuP was detected in 9% of cosmetic products

collected for children. In a comparable study conducted in Norway, analysis of 117 cosmetic products intended for children revealed that parabens were present in 32% of the samples. Methylparaben (MeP) and propylparaben (PrP) were the most frequently detected parabens in these products<sup>284</sup>.

## 2.15 Metabolism of Parabens

Extensive research has investigated the metabolism of parabens in living organisms. Studies indicate that parabens are absorbed through dermal application, dietary intake, and inhalation<sup>244,284</sup>. A previous study on parabens and their hydrolysis product in indoor dust reported that parabens and their common hydrolysis product, 4-HB, were detected in all dust samples collected from the four countries studied<sup>285</sup>. The geometric mean concentrations of the sum of six parabens in dust decreased in the following order: Korea (2320 ng g<sup>-1</sup>), Japan (2300 ng g<sup>-1</sup>), United States (1390 ng g<sup>-1</sup>), and China (418 ng g<sup>-1</sup>). The substantially lower concentrations of parabens detected in dust samples from China may be attributed to differences in per capita consumption of cosmetics and personal care products. Korean and Japanese women exhibited similar per capita consumption of cosmetics and skin care products, a level five times greater than that of American women and 50 times greater than that of Chinese women<sup>286,287</sup>. MeP and PrP were the most prevalent parabens, exhibiting a 100% detection rate in dust samples collected from all four countries<sup>285</sup>. MeP represented 42 to 73% of total paraben concentrations, with geometric mean concentrations ranging from 226 to 1670 ng g<sup>-1</sup>. PrP represented 12 to 46 percent of total paraben concentrations, with a geometric mean concentration ranging from 123 to 761 ng g<sup>-1</sup>. The concentrations measured in this study demonstrate that cosmetics and personal care products represent a significant source of indoor dust contamination by parabens.

Additionally, dust ingestion constitutes an important exposure pathway for certain environmental chemicals in humans<sup>285</sup>.

In another literature, the absence of data regarding the use rate of personal care products among the Vietnamese population precludes estimation of the risk of parabens exposure via dermal absorption. In this study, human exposure to parabens was quantified through the dust ingestion pathway<sup>288</sup>. Among the analyzed parabens, methylparaben (MeP) exhibited the highest detection frequency in dust samples ( $n = 58$ ) at 96.6 percent, followed by propylparaben (PrP) at 89.7 percent and ethylparaben (EtP) at 84.5 percent. In contrast, isopropylparaben (IPrP) was detected at the lowest frequency, with a detection rate of 34.5 percent. MeP exhibited the highest concentrations in the dust samples, with a mean of  $304 \text{ ng g}^{-1}$  and a median of  $188 \text{ ng g}^{-1}$ , followed by PrP ( $58.0/33.6 \text{ ng g}^{-1}$ )<sup>288</sup>. These findings are consistent with previous reports indicating that MeP is the predominant paraben detected in dust samples<sup>289</sup>. The median concentrations of MeP, EtP, PrP, and BuP detected in indoor dust samples from Oregon, USA were 1920, 180, and 965 and  $80 \text{ ng g}^{-1}$ , respectively<sup>108</sup>. These results indicate that MeP was listed as an ingredient in all labelled PCPs and was present in both labelled and non-labelled products. The total concentrations of parabens in dust samples ( $n=58$ ) collected in Hanoi, Vietnam, ranged from below the detection limit to  $1650 \text{ ng g}^{-1}$  (mean/median:  $285/403 \text{ ng g}^{-1}$ ). The results align with those obtained from dust samples collected in Beijing, Jinan, Guangzhou, Shanghai, Qiqihaer, and Urumchi, China (mean/median:  $418/573 \text{ ng g}^{-1}$ )<sup>289</sup>. Paraben concentrations in dust samples from developed nations, including Canada, Spain, Japan, South Korea, and the USA, were significantly higher than those in samples from developing countries such as Vietnam and Algeria. These results suggest that consumer products, such as personal care products containing parabens, are more commonly used in developed countries. Recent findings indicate an upward



trend in paraben concentrations in Vietnamese house dust samples over the past several years. The average and median concentrations of parabens in indoor dust collected from Vietnamese residences in 2014, 2017, and 2019 were 183/132, 310/264, and 513/379 ng g<sup>-1</sup>, respectively. This observation indicates a shift in the consumption patterns of products containing parabens among Vietnamese consumers. The relatively small sample sizes in 2014 (n = 16) and 2017 (n = 15), as well as the use of different sampling sites across the three campaigns, introduce potential uncertainty in the analytical results. The exposure doses estimated in this study were 5 to 10 times lower than those reported in other publications from China and the USA<sup>290</sup>. Overall, human exposure doses to parabens via dust ingestion decreased with increasing age. Exposure through dust ingestion was substantially lower than exposure via dermal absorption and food ingestion<sup>288</sup>.

Multiple studies in the scientific literature have documented the presence of parabens in dust samples<sup>285,288</sup>. Both scientists measured the concentration of parabens in the dust samples as well as the route of exposure, which indicates humans are exposed to parabens in the indoor environment. However, the potential risk assessment of the parabens to human health was not conducted. In addition, in Africa, especially in developing countries like Nigeria, there is a scarcity of data on air contamination, and when available, it is limited to the outdoor air environment contamination. Furthermore, in Nigeria, there is a scarcity of monitoring and risk assessment data on the co-occurrence of these chemical residues in indoor dust. In this research, we aim to evaluate the levels and possible health hazards posed by certain heavy metals and parabens present in indoor dust from specific locations in Ibadan.

## **2.16 Legislation of Parabens**

In the United States, parabens are permitted in cosmetics without restriction. However, some manufacturers are reducing their use or switching to alternative preservatives in response to growing concerns<sup>280,291</sup>. The Cosmetic Ingredient Review Organization has recommended implementing restrictions on the use of parabens in the USA and Canada that align with those established by the European Union<sup>280</sup>. The United States and Canada do not have specific legislation governing the use of parabens in cosmetics. However, regulatory authorities in both countries recommend paraben concentration limits consistent with those established by the European Union<sup>244</sup>.

Several organizations, including ECORCER (France), BDIH (Germany), NaTrue (Belgium), Soil Association (United Kingdom), ICEA (Italy), and BIOCOSC (Switzerland), have adopted EU measures and do not permit parabens in their products. Additionally, CosmeBio has prohibited parabens in cosmetics since 2002<sup>280</sup>. Since 2011, Denmark has restricted the use of propylparaben, butylparaben, isopropylparaben, and isobutylparaben in products intended for children under three years old<sup>244</sup>.

The US Food and Drug Administration (FDA) classifies methylparaben (MP) and propylparaben (PP) as inactive ingredients in dentifrices, contraceptives, analgesics, injectable drugs, inhalation and intranasal solutions, as well as ophthalmic, oral, topical, rectal, and vaginal pharmaceuticals<sup>257</sup>. The FDA has approved parabens as food additives and considers methylparaben and propylparaben safe for use at concentrations up to 0.1%<sup>257,294</sup>. Furthermore, the Joint FAO/WHO Expert Committee established a combined daily intake limit for MP, EP, and 10 mg per kg of PP<sup>292</sup>. Obtaining information on the use of parabens in pharmaceuticals, cosmetics, and food products from the USA and China is challenging. The FDA has not updated its regulations regarding parabens. As previously noted, there are no restrictions on their use in

cosmetics, and no evidence contradicts the values reported by Soni et al. for food applications<sup>257,292</sup>. No relevant academic publications or official sources were identified for China. However, one website indicates that the most recent update to cosmetic legislation occurred in 2015, permitting the use of MP, EP, PP, BuP, iso-PP, iso-BuP, and their sodium and potassium salts in cosmetics<sup>293</sup>. A 2018 website update presents a list of ingredients proposed for regulatory amendment, specifying only MeP, EtP, PrP, BuP, and their salts as authorized substances under the same restrictions as the European Union<sup>294</sup>. If confirmed, China has revised its regulations concerning the use of parabens in the cosmetic industry.

In Japan, ethyl, propyl, isopropyl, butyl, and n-butyl parabens are permitted as food additives, and the permissible limits are regulated based on the total quantity of p-hydroxybenzoic acid. In cosmetic products, the maximum allowed paraben concentration is 1%<sup>244,292</sup>.

Based on the preceding information, there is a notable absence of significant action. Despite increasingly stringent legislation regulating the industrial use of parabens, these compounds remain present in the environment. Several studies continue to identify parabens as potential contributors to various human health issues. Additional restrictions on the use of parabens should be implemented. Further research on the risks associated with parabens is necessary to provide robust scientific evidence for informed decision-making.

### **2.17 Estimated Daily Intake of Parabens**

Given the limited and frequently contradictory findings regarding dietary and transdermal absorption of parabens, researchers are working to consolidate data on precise paraben exposure levels. The measured concentrations of parabens in the analyzed products provide a foundation for determining the Estimated Daily Intake (EDI) in terms of  $\text{ng kg}^{-1} \text{ b.w./24 h}$ <sup>243,276,283,285</sup>. A comparative analysis of estimated daily intake (EDI) of parabens across multiple countries

identified the average daily intake of total parabens via dust ingestion among adults in four nations to be between 0.2 to 1.2 ng kg<sup>-1</sup> bw/day<sup>287</sup>. Children's exposure to parabens from dust ingestion was approximately five times higher than that of adults. In the four countries examined, estimated paraben intake through dust ingestion was higher among children in Japan, Korea, and the United States compared to those in China<sup>290</sup>. In the United States, toddlers experience paraben exposure through dust ingestion at levels twice those estimated for children and 13 times those estimated for adults<sup>290</sup>. Although the intakes of parabens through alternative exposure routes such as diet, inhalation, and dermal absorption from cosmetics remain undetermined, dietary and dermal exposures are likely significant contributors to total daily paraben exposure<sup>291</sup>. Findings from human biomonitoring studies indicate elevated exposure levels to parabens among the U.S. population.

## **2.18 Exposure Pathway of Parabens**

Humans primarily encounter parabens through oral and dermal routes, with food and personal care items being the key sources<sup>295,296</sup>. These substances are eliminated from the body chiefly via urine, and the urinary biomarkers that can be detected indicate exposure from all routes: oral, inhalation, and dermal<sup>283,297</sup>. Pharmaceutical products and cosmetics represent the primary sources of human exposure to parabens<sup>244</sup>.

## **2.19 Human Health Impact of Parabens Exposure**

Paraben compounds exhibit both estrogenic and anti-androgenic activities. These molecules have been linked to the development of tumors, particularly breast tumors, and to male infertility. Parabens have been identified as potential risks to human health. The primary sources of human exposure to parabens are pharmaceutical products and cosmetics<sup>244,298,299,300</sup>.

Parabens and other xenobiotic chemicals disrupt the hypothalamo-pituitary-gonadal axis by mimicking female hormones. This interference disrupts normal hormonal regulation and negatively affects male reproductive function<sup>300</sup>. Endocrine disruptors interfere with the action, synthesis, metabolism, and transport of endogenous hormones. These compounds may disrupt the central nervous system, immune system, lipid and glucose regulation, and thyroid function. They can also act as epigenetic modulators, leading to transgenerational effects<sup>244</sup>. Propylparaben does not irritate or sensitize normal skin. However, medicines containing parabens have shown sensitizing effects when applied to damaged or broken skin<sup>294</sup>. The Ophthalmic Drug Panel of the United States Food and Drug Administration Bureau of Drugs determined that MeP and PrP are unsuitable for use in ophthalmic solution preparations due to their potential to cause eye irritation<sup>257</sup>.

Sabalitschka and Neufeld-Crzellitzer found that taking 2000 mg of PrP daily for one month did not produce visible toxic effects. Similarly, another study using 2000 mg of MeP for an unspecified duration also reported no adverse effects<sup>294</sup>. Current data do not establish a clear link between paraben use and allergic reactions, though some individuals have reported allergies after ingesting products containing parabens<sup>294</sup>.

Previous research has examined human skin irritation associated with products containing parabens at 0.1–0.8%<sup>276</sup>. Overall, irritation was not observed in most cases; however, moderate irritation occurred in some instances. In a summary of tests involving parabens in 27,230 patients with dermatitis, only 2.2% developed sensitization following patch testing with 1–30% parabens<sup>276</sup>. Individuals with intact skin did not exhibit sensitization reactions to parabens<sup>276</sup>.

Parabens are recognised as endocrine disruptors that can replicate estrogen's effects in the body. The endocrine system is a sophisticated network of internal organs responsible for producing

hormones. Hormones act as signalling molecules that travel through the circulatory system to their target locations. The effective operation of the endocrine system is crucial for maintaining homeostasis in the human body. Hormonal function disorders can arise from both internal and external factors<sup>301</sup>.

Numerous studies indicate that parabens may interfere with the functioning of normal breast cells and possibly contribute to their irregular growth, which could heighten the risk of developing breast cancer.

**Enhanced cell proliferation:** Numerous research studies indicate that parabens can imitate estrogen and, as a result, increase breast cell growth<sup>302,303</sup>. Cell-based studies of parabens' effects on the estrogen receptor do not address other systems that influence the development of breast cancer. One cell-based study tried to mimic the conditions of cells and tissues by adding proteins called growth factors, which stimulate the expression of HER2, found in 25 percent of breast cancers. The authors found that the presence of a growth factor called heregulin leads parabens to stimulate the estrogen receptor at levels that had been considered non-toxic in cell-based research<sup>303</sup>.

**Reduced cellular apoptosis:** Research indicates that certain levels of parabens might diminish programmed cell death, which is one mechanism the body employs to handle damaged cells<sup>302</sup>.

**Metastasis:** Research conducted in vitro has demonstrated that cells treated with parabens for more than 20 weeks could elevate factors linked to metastasis<sup>302</sup>.

**Inhibition of chemotherapy drugs:** Methylparaben might reduce tamoxifen's effectiveness in blocking estrogen's impact, which could lead to diminished efficacy of this widely used chemotherapy medication in treating breast cancer<sup>302</sup>.

Parabens have been associated with various health issues, including allergies, and could also interfere with thyroid function levels<sup>304,305</sup>. The thyroid gland is an endocrine organ responsible for the synthesis and storage of thyroxine (T4) and triiodothyronine (T3). Diverse biological functions, including the regulation of protein activity and active hormones are characterised by their roles in carbohydrate synthesis, initiation of fatty acid catabolism, enhancement of bone metabolism and nervous tissue growth, and regulation of kidney and cardiovascular function<sup>306</sup>. Urine samples from women at 16–20 and 24–28 weeks of gestation were analyzed for thyroid hormones and parabens, including MeP, PrP, and BuP. Results showed a correlated increase in BuP and free thyroxine (FT4) levels. An increase in FT4 levels was observed at 16 to 20 weeks of gestation, followed by a decrease at 24 to 28 weeks, concurrent with rising MeP levels. The measured FT4 levels corresponded with the anticipated physiological hormonal changes observed during pregnancy, indicating that the findings are unlikely to be attributable to paraben exposure<sup>307</sup>.

## **2.20 Dust**

Dust is any microscopic, powder-like particle or collection of powder-like particles that is made up of sand, soil, fragments of organic tissue or manufactured materials, or some combination of these sources and is both light enough to be carried by the wind and heavy enough to be deposited on a surface. Individual dust particles can be large enough to be observed by the unaided eye, and large concentrations of dust driven by wind are often conspicuous as dust devils and dust storms, which can impair normal visibility and make breathing difficult<sup>308,309</sup>. Dust consists of tiny, dry particles, including pollen, bacteria, smoke, ash, and salt crystals from the sea, along with small fragments of dirt or rock, such as sand. It includes a wide range of particles of varying origins, such as soil, pollen, pollutants, dead skin cells, and cosmic particles<sup>310</sup>. Dust

may also comprise small particles of human and animal skin cells, pollutants, and hair. Dust is everywhere in both natural environments and human-made settings. It is small enough to be suspended in the air and settle slowly under gravity or collects on virtually all surfaces, including the surfaces of individual plants, between hair-like structures of animals, and on the ground in cultivated and uncultivated landscapes, as well as on furniture and other elements of the indoor environment. Suspended dust that floats gently in the air may be almost unnoticeable unless light from a sunbeam reflects off individual particles<sup>308,310</sup>. Dust plays a substantial role in various environmental and atmospheric processes. For example, it contributes to the Earth's radiative balance by scattering and absorbing solar radiation, affecting weather and climate patterns<sup>310</sup>. Dust particles can also serve as nuclei for cloud formation, impacting precipitation patterns and the hydrological cycle<sup>311</sup>. Dust particles and other aerosols aloft perform critical roles in weather. Most importantly, they serve as condensation surfaces that facilitate the formation and growth of raindrops and snowflakes. In larger concentrations, dust particles help reflect incoming sunlight into space, which slows the heating of Earth's surface<sup>308</sup>. Microscopic particles of dust significantly contribute to Cloud Condensation Nuclei (CCN). These nuclei consist of tiny solid materials present within clouds. CCN might arise from a dust storm moving through a cloud or an updraft carrying dust particles. In the clouds, water vapour condenses around CCN, transforming into liquid. Often, the invisible dust serves as the core of every raindrop<sup>309,311</sup>. Dust particles range in size from 1 to 400 micrometres ( $\mu\text{m}$ ;  $1\ \mu\text{m} = 0.001\ \text{mm}$  [about 0.00004 inch]). Particles larger than about  $100\ \mu\text{m}$  ( $0.1\ \text{mm}$  [0.004 inch]), which is about the width of a human hair, are visible to the unaided eye. Depending on their size and composition, dust particles can remain airborne for long periods and can be transported over large distances by wind<sup>308</sup>. Human lungs are capable of filtering out particles as small as  $1\ \mu\text{m}$ . However, smaller particles, which



include allergens, some types of smoke and ash particles, soot, and dust that remains suspended in the air, can lodge in the lungs and enter the circulatory system<sup>310</sup>. Dust can be inorganic or organic. Inorganic components of dust include small bits of rock, salts, and pollutants, such as insecticides and fumes given off by heavy metals such as copper, iron, and mercury. Organic components include pet dander, hair or fur, skin fragments, textile fibres, and ash, as well as tiny living things such as pollen, mites, and mould spores<sup>310</sup>. The inhalation of dust is responsible for several lung and respiratory disorders, whose symptoms and severity depend on the particles' composition and size, the amount of dust inhaled, and the length of exposure. Larger allergens, such as pollen (which ranges in size from 20 to 100  $\mu\text{m}$ ), skin fragments (which range in size from 1 to 40  $\mu\text{m}$ ), and mould spores (which range in size from 3 to 10  $\mu\text{m}$ ), can trigger allergic reactions and asthma. In addition, lung diseases known as the pneumoconioses result when certain inhaled mineral dusts are deposited in the lungs, where they cause a chronic fibrotic reaction that leads to decreased capacity for exercise and increasing breathlessness, cough, and respiratory difficulty. Such larger particles can deliver into the lungs smaller agents, such as heavy metals, viruses, and bacteria, which can later enter the bloodstream. Soot and tobacco smoke particles (which range in size from 0.01 to 0.15  $\mu\text{m}$  and from 0.01 to 1  $\mu\text{m}$ , respectively), known for their ability to cause cancer and raise the risk of heart attack and stroke in human beings, are small enough to easily pass the body's blood-gas barrier<sup>310</sup>.

### 2.20.1 Types of Dust

**Mineral Dust:** This is primarily created from natural sources such as deserts, dry lake beds, and other waterless regions where wind erodes soil and rocks. These particles are mostly composed of silicates, clays, quartz, and carbonates. It plays a crucial role in atmospheric processes by influencing the Earth's radiative balance, serving as cloud condensation nuclei, and fertilizing

ocean ecosystems through long-range transport. Exposure to mineral dust usually leads to respiratory problems and visibility reduction<sup>311,312</sup>.

**Industrial Dust:** This is dust generated in various industrial processes and manufacturing operations, and human activities such as construction, mining, and manufacturing processes. Industrial dust often contains a wide range of particles, including metals, chemicals, minerals, and pollutants. Examples are coal dust, metal particles such as nickel (Ni), Cadmium (Cd), Lead (Pb), silica dust, chemical dust and other toxic substances. Exposure to industrial dust can lead to serious health conditions like silicosis, lung cancer and pneumoconiosis. Industrial dust may lead to occupational health hazards<sup>313,314</sup>.

**Organic Dust:** This dust is comprised of particles resulting from biological sources such as plant fibres, fungal spores, animal dander, bacteria, and debris of insects. It is common in agricultural settings and indoor environments. Organic Dust can cause respiratory issues such as hypersensitivity pneumonitis, asthma, and allergic reactions<sup>309,315,316</sup>.

**Pollen Dust:** Pollen dust is a type of fine powder produced by plants, including flowers, trees, and grasses. Pollen dust is released as part of their reproductive process and consists of tiny grains that are dispersed by wind, insects, or animals and can become airborne. Pollen is typically dominant during specific seasons, depending on the plants in the area. Exposure to pollen dust can trigger allergic reactions in sensitive individuals, leading to symptoms such as sneezing, asthma, hay fever, itching, and congestion<sup>316,317</sup>.

**Combustion Dust:** This is also called Soot/Black Carbon dust. This type of dust results from the incomplete combustion of organic materials, including fossil fuels, wood and biomass. It is rich in carbon and has a distinguishing black colour. Due to the potent climate-forcing agent of combustion dust, it absorbs sunlight and adds to atmospheric warming. In addition, it has effect

on air quality and visibility. Owing to the smallness of the dust particles of combustion dust, they can infiltrate deep into the respiratory system, leading to cardiovascular and respiratory diseases<sup>318,319,320</sup>.

**Household Dust:** This is also called Indoor dust, and it is the most common type of dust found in homes. Household dust consists of a mixture of materials such as dead cells, including skin cells, textile fibres, pet dander, pollen, insect debris, dust mite waste and particles brought from the outdoors and found within the indoor environment. Household dust can harbour allergens, microorganisms, as well as chemical contaminants like flame retardants, potentially impacting indoor air quality and contributing to respiratory problems<sup>321,322</sup>.

## 2.21 Indoor Dust

Indoor dust can be defined as a combination or complex mixture of fine inorganic and organic materials that can originate from both indoor and outdoor environments. It includes organic and inorganic materials such as soil particles, textile fibres, skin flakes, pollen, and residues from building materials<sup>323,324,325</sup>. Indoor dust is defined as particulate matter (PM) that accumulates on floors, carpets, surfaces, and other objects within indoor environments<sup>326</sup>. Indoor dust can be described as a heterogeneous mixture that includes soil brought in from outside, settled particles, dander from humans and animals, insect remnants, and various other debris, complicating the extraction and identification of specific compounds while presenting multiple pollutants. Furthermore, Indoor dust contains semi-volatile organic compounds, heavy metals, and allergens. These substances can enter the body through inhalation, non-dietary ingestion from contaminated surfaces, or direct skin absorption<sup>327,328,329,330</sup>.

### 2.21.1 Sources and Composition of Indoor Dust

The sources of particulate matter found in indoor air can be categorised into two primary types: The first type is outdoor sources, which include particles from the outdoor atmosphere that come in through doors, windows, ventilation systems, and the movement of residents entering and exiting the space. The second type comprises indoor sources, such as smoke from cigarettes, cooking, and various other indoor activities<sup>331,332,333,334,335,336</sup>. Indoor air particulate matter comes from outdoor sources, the movement of residents in and out of the space, and various indoor activities such as cooking and smoking<sup>335,336,337,338</sup>. Within the household, opening the door and entering from the outdoors can ferry dirt and pollen to join the dust accumulating inside. Some research suggests that about two-thirds of household dust comes from outdoor sources, such as outdoor dust and air pollution, while the remaining one-third derives from indoor inorganic sources<sup>310</sup>.

The composition of indoor dust is influenced by the surrounding environment, human activities, household products, and outdoor air quality. Dust serves as a sink for various contaminants, including heavy metals and organic chemicals like parabens, which can adhere to dust particles due to their small size and surface properties<sup>339</sup>. As a result, indoor dust plays a crucial role in human exposure to environmental contaminants. Other components of dust include colonies of mould, shreds of paint, and traces of soot. Dust also contains small fibres of cloth pulled from clothes and furniture. Dangerous chemical pollutants, such as the toxic insecticide Dichloro-Diphenyl-Trichloroethane (DDT), have persisted in U.S. household dust as recently as 2022. Though DDT was banned in most countries in the 1970s due to its dangerous properties, the insecticide has persisted in nature and in households, where it may endanger children and other vulnerable groups<sup>310</sup>. While human skin cells and hair are not the only components of indoor dust, these materials do make up a significant portion of the mixture. Each human sheds about

500 million skin cells per day. Estimates of the percentage of dust composed of flakes of human skin vary, with one study placing the figure as high as 75 to 90 percent. However, the portion of dust derived from living things does not necessarily come from humans alone. Traces of fur, dander, and feathers from pets add to the mix. Such cast-off cells are not the only contribution pets make to dust in the house. Research has indicated that households with dogs have more types of bacteria in their dust than pet-free households do. Other biotic substances, such as small living and dead insects, can also appear in dust. Dust mites, household pests that live in dust, can cause allergies<sup>310</sup>.

## **2.22 Role of indoor dust as a carrier of pollutants, including heavy metals and organic compounds like parabens**

The concern over indoor dust is especially pronounced in urban areas, where high population density and industrialization can exacerbate pollutant levels. This is particularly relevant in developing regions like Nigeria, where regulatory frameworks and environmental management practices may lag behind those of developed countries. Thus, understanding the role of indoor dust in pollutant accumulation and exposure is critical for public health<sup>340</sup>.

## **2.23 Indoor Air Quality**

Indoor air quality pertains to the condition of the air within residential, educational, workplace, or other indoor spaces<sup>340</sup>. Various studies have shown that we spend up to 90% of our time indoors, whether at home, workplaces, educational institutions, public spaces, commercial establishments such as shops and restaurants, and vehicles. Chemical exposures within indoor environments play a crucial role in shaping the exposome, which encompasses all environmental exposures experienced by an individual over a lifetime<sup>337</sup>. Indoor dust refers to settled particulate

matter (PM) that accumulates on floors, carpets, surfaces, and various objects within indoor environments. It is a heterogeneous mixture of particles, including artificial and natural fibers, atmospheric particulate matter, hair, biological materials such as molds, pollen, bacteria, animal fur, and dander, as well as ash, soot, skin particles, and components from building and consumer products<sup>337</sup>. Settled house dust particles typically range in size from micrometers to millimeters, with the majority measuring between 30 and 300 micrometers<sup>337</sup>. Particles smaller than 10  $\mu\text{m}$  typically remain airborne instead of settling as surface dust and account for less than 10% of the total indoor dust mass<sup>337</sup>. Reported indoor dust shows significant variation in particle size distribution, partly due to differences in sampling methods. However, a significant portion is due to variations in human behavior, indoor environments, building materials, consumer products, and the transfer of materials from outdoors to indoors. Particle size distribution varies within individual studies. For instance, the mass contribution of 25-63  $\mu\text{m}$  particles in researcher-collected dust from UK homes ranged from less than 20% to more than 70%<sup>341</sup>. Indoor residential dust generally contains about 35 percent material originating from outdoor soil<sup>337</sup>. Outdoor soil is often introduced into indoor environments via shoes and clothing. The proportion of outdoor soil in indoor dust can vary substantially, ranging from 30% to 70%, depending on factors such as the presence of pets and whether shoes are worn indoors. There is even greater variation across other indoor microenvironments. For example, in child daycare centers, outdoor shoes are not worn inside, whereas in vehicles, outdoor shoes are always worn. Organic content varies according to the specific microenvironment and typically ranges from 5% to 40%<sup>337</sup>. Finer particles contain more organic material, which significantly increases the ability of indoor dust to absorb organic contaminants. For example, particles smaller than 63  $\mu\text{m}$  have an organic fraction of 68%, compared to 42% in particles between 63  $\mu\text{m}$  and 2 mm. Coarser fractions have the

highest silica content. Fibrous particle concentrations range from 9 to 89 percent, depending on room type and furniture. Kitchens typically have lower levels of air quality than bedrooms, and carpets and sofas can increase the amount of fibrous dust. The highest concentrations are found in homes with pets<sup>337</sup>. Particles are classified based on their diameter for air quality regulations. Particles that measure 10 microns or less in diameter (PM<sub>10</sub>) can be inhaled into the lungs and may cause negative health effects. Particulate matter that is 2.5 microns or less (PM<sub>2.5</sub>) is referred to as fine particulate matter. Consequently, PM<sub>2.5</sub> is a subset of PM<sub>10</sub>. PM<sub>10</sub> and PM<sub>2.5</sub> often originate from different sources of emissions and possess distinct chemical compositions. The combustion of gasoline, oil, diesel, or wood is responsible for a large share of the PM<sub>2.5</sub> pollution in the outdoor environment, as well as a considerable amount of PM<sub>10</sub>. Furthermore, PM<sub>10</sub> includes particulate matter originating from construction activities, landfills, agriculture, wildfires, brush or waste burning, industrial processes, windblown dust from open areas, pollen, and bacterial fragments<sup>333</sup>. Particulate matter is either directly emitted as primary particles or formed in the atmosphere as secondary particles through chemical reactions involving gases like sulfur dioxide, nitrogen oxides, and certain organic compounds. These compounds originate from natural sources such as trees and vegetation, as well as from human activities including industry and vehicle emissions. The size of dust particles is a key factor in evaluating the risk of human exposure to heavy metals in indoor environments<sup>334</sup>. Finer particles settle more slowly than larger ones, allowing them to stay suspended in the air for extended periods, which can potentially affect human respiratory health<sup>342</sup>. Particles that are less than 10  $\mu\text{m}$  in size are especially dangerous due to their small dimensions, which enable them to penetrate the lungs<sup>343</sup>. Industrial dust, like that from solvent-based paints, consists of very fine particles (less than 1  $\mu\text{m}$ ) and typically contains high levels of lead and zinc<sup>336</sup>. The primary

concern regarding human exposure is not the dust matrix itself, but the diverse range of chemicals present on or within dust particles. These chemicals originate from the surrounding environment, including building materials, furnishings, and consumer products such as electronics, outdoor air, aerosols, and human activities such as cooking, heating, and cleaning<sup>327</sup>.

## **2.24 Contaminants in Indoor Dust**

Indoor dust comprises a diverse array of chemical compounds, with concentrations varying according to the specific sources of the dust. An extensive literature review by Dong et al. identified 355 distinct chemicals present in indoor dust, of which only four were of biological origin, such as fatty acids<sup>337</sup>. Additionally, chemicals adsorbed onto dust particles, although susceptible to degradation under direct sunlight, generally degrade or dissipate more slowly indoors than outdoors or in indoor air. This slower rate is attributed to stable indoor temperatures, lower humidity, reduced microbial populations, and limited exposure to solar radiation<sup>338</sup>. Commonly identified chemical mixtures present in indoor dust include the following:

**2.24.1** Polymer constituents include bisphenols, such as bisphenol A, F, S, and AF, as well as alkylphenols<sup>339</sup>.

**2.24.2** Plastic additives, specifically flame retardants (FRs), include substances like the prohibited Polybrominated Diphenyl Ethers (PBDEs), alternative ‘novel’ halogenated FRs and organophosphate esters (OPEs) FRs; plasticisers such as phthalate esters<sup>341</sup> and their replacements<sup>339,340,341,342,343</sup>.

**2.24.3** Ingredients found in personal care products, cleaning agents include parabens, synthetic fragrance chemicals, triclosan, siloxanes, and ultraviolet (UV) filters<sup>343,345,346</sup>.

**2.24.4** Perfluorinated alkyl substances and related fluorinated compounds<sup>347</sup>.



**2.24.5** Pesticides encompass both banned legacy compounds, such as DDT and hexachlorocyclohexanes, as well as currently used agents, including chlorpyrifos and permethrin<sup>348,349</sup>.

**2.24.6** Industrial compounds such as polychlorinated biphenyls (PCBs) and chlorinated paraffins<sup>349,350</sup>

**2.24.7** Combustion and degradation by-products include polycyclic aromatic hydrocarbons (PAHs), polychlorinated and polybrominated dibenzo-p-dioxins and dibenzofurans, as well as related compounds such as nicotine<sup>349</sup>.

**2.24.8** Heavy metals, significantly, lead<sup>351</sup>.

Concentration levels differ by several orders of magnitude across various compound groups and microenvironments. Typically, PCDD/Fs, PCBs, OCPs, and PBDEs are found at concentrations ranging from picograms to nanograms per gram. Parabens, synthetic musks, PAHs, and alternative halogenated flame retardants are generally present at nanogram-per-gram levels. Phthalate esters, OPEs, chlorinated paraffins, and siloxanes are usually detected at the highest concentrations, reaching milligrams per gram<sup>351,352</sup>.

## **2.25 Transfer of Heavy Metals and Parabens from Sources to Dust**

Chemicals enter the indoor environment through direct application, as exemplified by pesticides, unintentional production, as observed with polycyclic aromatic hydrocarbons (PAHs), and emissions from products such as flame retardants (FRs) and plasticizers<sup>353</sup>. Gas-phase chemicals can partition onto airborne particles, which subsequently settle or adhere to indoor surfaces, forming dust layers<sup>353</sup>. Due to their high surface area-to-mass ratio, settled dust acts as a significant reservoir for chemicals. Consumer products contribute chemicals to dust through three primary processes: volatilization, followed by partitioning into dust; direct transfer through

contact with dust; and abrasion, which generates dust particles<sup>353</sup>. The primary transfer pathways are determined by both the type of product and its chemical properties. For instance, in the case of BDE-209, volatilization is negligible while abrasion and direct transfer are the predominant mechanisms<sup>353</sup>.

## **2.26 Human Exposure Routes to Dust**

The main human exposure pathways to dust are dermal contact and ingestion, which occur through hand-to-mouth behavior and consumption of food contaminated with settled dust. The rates of dust ingestion and the sizes of ingested dust particles remain uncertain. Finer dust particles adhere to hands, increasing the risk of both ingestion and dermal exposure. There is no consensus on the minimum particle size required for adherence to hands, with reported diameters ranging from less than 10  $\mu\text{m}$  to less than 246  $\mu\text{m}$ <sup>354</sup>. Children have significantly higher rates of dust ingestion than adults due to their frequent floor play and the increased likelihood of placing hands and non-food objects in their mouths. This behavior, together with the smaller body size of children, results in significantly greater exposure to chemicals via dust for children compared to adults. Estimated dust ingestion rates are 30 to 140 mg per day for children and 2 to 30 mg per day for adults<sup>355</sup>. In certain scenarios, dermal contact represents a greater source of exposure than dust ingestion<sup>356</sup>. Dermal exposure is quantified according to the body surface area in contact with dust, ranging from conservative estimates involving only the hands to assessments that include the entire body for young children. Dermal exposure is influenced by the degree of dust adherence to the skin, as outlined in guidelines for dermal contact with soil. For children indoors, dust adherence ranges from 0.004 to 0.01  $\text{mg}/\text{cm}^2$  across different body parts. For adults, values range from 0.02 to 0.80  $\text{mg}/\text{cm}^2$ , depending on activity<sup>354,357</sup>.

Ingestion and dermal adherence rates for dust exposure remain highly uncertain. Most estimates rely on soil ingestion rates, which may not accurately reflect indoor environments due to differences in behavior and activity. Furthermore, dermal absorption factors vary depending on the specific chemical and are determined by the extent of soil contact<sup>356</sup>. The bioaccessibility of chemicals present in dust remains insufficiently characterised and is expected to vary among different chemical compounds<sup>353</sup>. Consequently, exposure estimates based on these ingestion and dermal exposure rates remain highly uncertain<sup>353</sup>.

Although often overlooked, inhalation exposure to resuspended indoor dust can represent a significant pathway under certain conditions, contributing to overall exposure to airborne particulate matter with a diameter of less than 10 micrometers<sup>358</sup>. Human activities, such as walking and vacuuming, re-entrain dust into indoor air, resulting in a 'personal cloud' where particulate matter (PM) concentrations exceed ambient levels both indoors and outdoors. The composition of indoor airborne PM typically correlates with indoor dust levels, indicating that resuspended indoor dust significantly contributes to indoor airborne PM<sup>358</sup>.

## **2.27 Evidence of Exposure to Heavy Metals and Parabens through Dust**

Although quantifying exposure through dust remains uncertain, the significance of this pathway is well established. Multiple studies have demonstrated associations between chemical concentrations in indoor dust, biomarkers of exposure, and, in certain instances, health outcomes. The association was established for lead, as lead-contaminated house dust was identified as the primary source of lead exposure among children<sup>359</sup>. Initial environmental modelling indicated that dust is a significant exposure pathway for PBDEs. Subsequent dust measurements and exposure estimates corroborated this finding<sup>340,360</sup>. Additional evidence for this exposure pathway is provided by observed correlations between contaminant concentrations in dust and

corresponding levels in the human body, such as the association between dust and blood (serum, plasma) concentrations of PBDEs<sup>361</sup>. There is evidence of a direct association between contaminant dust levels and specific health outcomes. For example, flame retardants in house dust have been linked to endocrine disruption in men, while phthalates in house dust are associated with allergic diseases in children<sup>362,363</sup>.

## **2.28 Factors Influencing Indoor Dust Contamination**

Geographic variations in indoor dust concentrations are well documented and result from multiple factors. The predominant factor appears to be differences in chemical usage among countries. Polybrominated diphenyl ether (PBDE) concentrations in dust are higher in North America compared to other regions, primarily due to the greater use of PBDEs in consumer products. In contrast, the predominant organophosphate ester (OPE) compounds found in dust from Europe and North America differ from those commonly detected in Asian dust<sup>342,343,363,364</sup>. Income level serves as a key determinant of country-specific differences in compound use and sources. FR and PCB concentrations are generally elevated in high-income countries, while pesticide and PAH concentrations tend to be higher in middle-income countries<sup>359</sup>. Restrictions on chemicals and their subsequent replacement with alternatives are evident in the composition of indoor dust. For instance, concentrations of Firemaster 550 components increased significantly from 2006 to 2011 in California indoor dust, while levels of the phased-out PBDEs decreased concurrently<sup>365</sup>. The type of indoor environment also affects the levels of contaminants in dust<sup>366</sup>. For example, vehicle dust and dust in public spaces with higher flame-retardancy standards often contain higher levels of flame retardants<sup>367</sup>. Significant heterogeneity in contaminant levels in dust is frequently observed within individual rooms, primarily due to the proximity of dust to chemical sources. This spatial variability can result in substantial differences

in human exposure, depending on the specific dust encountered within an indoor environment<sup>368</sup>. Additional factors that influence heavy metal contamination include seasonal variation, the presence of heavily polluting industries, housing characteristics, traffic volume, and specific spatial areas<sup>369</sup>.

## **2.29 Evaluation of Health Risk**

Dust has a significant impact on human health due to its complex chemical composition and potential for re-emission. Heavy metals present in indoor dust serve as key predictors of heavy metal concentrations in biological markers<sup>370,371</sup>. Chromium levels in industrial indoor dust and in the urine and saliva of workers exposed in the surgical instrument manufacturing industry showed significant positive correlations<sup>370</sup>. Zinc concentrations in indoor dust served as reliable predictor variables for toenail zinc content<sup>371</sup>. Lead present in household dust was a significant predictor of blood lead concentrations in young children. Potential human health risks from heavy metals present in dust are typically evaluated using the United States Environmental Protection Agency (US EPA) health risk assessment model<sup>372,373</sup>. Potential human health risks from heavy metals in indoor dust exhibit significant variation across different locations. In Hubei, China, non-carcinogenic risks (hazard quotient, HQ) and carcinogenic risks (cancer risk, CR) for children in urban areas were 1.59 to 1.95 times higher than those for children in rural areas<sup>374</sup>. Residents living in industrial areas face greater potential health risks compared to those residing in urban or rural regions<sup>375</sup>. Additionally, substantial differences exist in the health risks linked to heavy metals present in dust of varying ages<sup>376</sup>. Children are at greater risk than adults of exposure to heavy metals through indoor dust intake due to their more frequent hand-to-mouth

behaviors<sup>377</sup>. In urban areas of Hubei, China, the hazard quotient (HQ) and cancer risk (CR) values for children aged 3 to 5 years were 1.40 to 1.47 times higher than those for children aged 6 to 9 years<sup>378</sup>. Exposure to heavy metals through dust may present considerable health risks to populations residing in e-waste recycling regions<sup>378</sup>. The hazard quotient (HQ) values for lead (Pb) were 2.27 for adults and 9.52 for toddlers in e-waste workshops<sup>379</sup>. An HQ value of 1.56 for children's exposure to Pb in dust from electronic workshops indicated a significant non-carcinogenic risk<sup>380</sup>. Heavy metal exposure from dust ingestion in young children residing near an e-waste recycling area presents significant risks, as indicated by hazard quotient (HQ) values for Pb (11.10), Cu (2.78), and Cd (1.16)<sup>381</sup>. Lead (Pb) was identified as the most prominent pollutant presenting a substantial risk in the e-waste recycling sector, indicating the need for further investigation<sup>382</sup>. Certain industrial sectors may also experience considerable health risk implications. The cancer risks (CRs) of chromium (Cr) and cadmium (Cd) in workers exposed to the manufacturing of surgical instruments were  $3.0 \times 10^{-1}$  and  $4.1 \times 10^{-2}$ , respectively. These values substantially exceed the safety limits ( $1 \times 10^{-6} < CR < 1 \times 10^{-4}$ ) established by the US EPA<sup>370</sup>.

Hand-to-mouth behaviors are now a leading non-dietary way people are exposed to indoor environmental contaminants through accidental ingestion of dust. This study calculated the estimated daily intake (EDI, ng g<sup>-1</sup> bw/day) of parabens from dust ingestion for various populations, following the method described by Wang et al. (2021)<sup>383</sup>. The equation is as follows (1).

$$EDI_{\text{ingestion}} = \frac{C \times DIR}{BW} \quad (1)$$

Where C denotes the concentration of parabens in dust, expressed in nanograms per gram ( $\text{ng g}^{-1}$ ). The Dust Ingestion Rate (DIR) is 0.03 grams per day for infants and adults, and 0.06 grams per day for toddlers, children, and teenagers. The average body weights are as follows: infants, 6 kg; toddlers, 15 kg; children, 25.2 kg; teenagers, 48 kg; women, 57.3 kg; and men, 66.2 kg<sup>383,384</sup>.

Table 3 presents the estimated daily intake (EDI) values of parabens for various populations through dust ingestion. Currently, employees in cosmetics stores exhibit the highest median estimated daily intake (EDI) values of  $\Sigma 6$  parabens ( $4.6 \text{ ng kg}^{-1} \text{ body weight/day}$ ). This finding indicates that potential health risks associated with dust ingestion warrant increased attention. The estimated daily intake (EDI) values of  $\Sigma 6$  parabens through dust ingestion decreased with increasing age. The median EDI for infants was  $0.83 \text{ ng kg}^{-1} \text{ body weight per day}$ , approximately ten times higher than that for adults ( $0.075\text{--}0.087 \text{ ng kg}^{-1} \text{ body weight per day}$ ).

The median estimated daily intake (EDI) values of  $\Sigma 6$  parabens ( $0.075\text{--}0.83 \text{ ng kg}^{-1} \text{ bw/day}$ ) observed in this study align with those reported for the Chinese ( $0.10\text{--}1.5 \text{ ng g}^{-1} \text{ bw/day}$ ) and Vietnamese populations ( $0.11\text{--}0.53 \text{ ng g}^{-1} \text{ bw/day}$ ). However, these values are substantially lower than those documented for American ( $0.52\text{--}6.6 \text{ ng g}^{-1} \text{ bw/day}$ ), Korean ( $1.11\text{--}5.42 \text{ ng g}^{-1} \text{ bw/day}$ ), and Japanese populations ( $1.18\text{--}5.38 \text{ ng g}^{-1} \text{ bw/day}$ )<sup>281,344,385</sup>. Furthermore, the median estimated daily intake (EDI) values of  $\Sigma 6$  parabens for female students ( $0.64 \text{ ng kg}^{-1} \text{ body weight/day}$ ) exceeded those for male students ( $0.56 \text{ ng kg}^{-1} \text{ body weight/day}$ ). This difference is attributed to higher paraben concentrations in dust from female dormitories and the generally lower body weight of female students. Overall, paraben exposure levels resulting from dust ingestion among the Chinese population remain low<sup>385</sup>. Table 2.3 presents the estimated daily intake (EDI,  $\text{ng kg}^{-1} \text{ body weight/day}$ ) of parabens resulting from the ingestion of indoor dust among different populations<sup>385</sup>.

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**Table 2.4: Estimated daily intake (EDI, ng per kg body weight per day) of parabens via ingestion of indoor dust among different populations<sup>385</sup>**

|                               |                 | MeP     | EtP    | Prp   | BuP    | BzP    | HeP    | Σ <sub>6</sub> Parabens |
|-------------------------------|-----------------|---------|--------|-------|--------|--------|--------|-------------------------|
| <b>Homes</b>                  |                 |         |        |       |        |        |        |                         |
| <b>Infants</b>                | Median          | 0.36    | 0.068  | 0.29  | 0.027  | 0.01   | 1.0e-4 | 0.83                    |
|                               | 95th percentile | 7.5     | 1.5    | 4.6   | 0.22   | 0.026  | 1.0e-4 | 14.5                    |
| <b>Toddlers</b>               | Median          | 0.29    | 0.054  | 0.23  | 0.021  | 0.008  | 8.0e-5 | 0.66                    |
|                               | 95th percentile | 6.0     | 1.2    | 3.7   | 0.17   | 0.020  | 8.0e-5 | 11.5                    |
| <b>Children</b>               | Median          | 0.17    | 0.032  | 0.14  | 0.013  | 4.8e-3 | 4.8e-5 | 0.39                    |
|                               | 95th percentile | 3.6     | 0.72   | 2.2   | 0.10   | 0.012  | 4.8e-5 | 7.4                     |
| <b>Teenagers</b>              | Median          | 0.089   | 0.017  | 0.072 | 6.6e-3 | 2.5e-3 | 2.5e-5 | 0.21                    |
|                               | 95th percentile | 1.9     | 0.38   | 1.2   | 0.054  | 6.5e-3 | 2.5e-5 | 3.9                     |
| <b>Male Adults</b>            | Median          | 0.032   | 6.1e-3 | 0.026 | 2.4e-3 | 9.1e-4 | 9.1e-6 | 0.075                   |
|                               | 95th percentile | 0.68    | 0.14   | 0.42  | 0.020  | 2.4e-3 | 9.1e-6 | 1.4                     |
| <b>Female Adults</b>          | Median          | 0.037   | 7.1e-3 | 0.030 |        | 2.8e-3 | 1.0e-5 | 0.087                   |
|                               | 95th percentile | 0.78    | 0.16   | 0.49  | 0.023  | 2.7e-3 | 1.0e-5 | 1.6                     |
| <b>University dormitories</b> |                 |         |        |       |        |        |        |                         |
| <b>Male students</b>          | Median          | 0.35    | 0.023  | 0.14  | 3.4e-3 | 1.4e-3 | 9.1e-6 | 0.56                    |
|                               | 95th percentile | 0.76    | 0.18   | 0.28  | 0.014  | 2.7e-3 | 9.1e6  | 1.3                     |
| <b>Female students</b>        | Median          | 0.40    | 0.026  | 0.16  | 3.9e-3 | 1.7e-3 | 1.0e-5 | 0,64                    |
|                               | 95th percentile | 0.88    | 0.20   | 0.32  | 0.017  | 3.1e-3 | 1.0e-5 | 1.9                     |
| <b>Cosmetics stores</b>       |                 |         |        |       |        |        |        |                         |
| <b>Female Adults</b>          | Median          | 4.6     | 0.67   | 2.6   | 0.10   | 0.021  | 1.0e-5 | 8.0                     |
|                               | 95th percentile | 9.9 4.5 | 4.5    | 6.3   | 0.19   | 0.042  | 1.0e-5 | 17.8                    |

### **2.30 Limitations of Previous Study and Research Needs**

Many studies have shown that heavy metals and parabens are ubiquitous in the environment and have high toxicity and endocrine disruption properties, respectively. Numerous studies have been conducted globally, especially in China, Vietnam, Japan, etc. However, in Africa, especially in developing countries like Nigeria, there is a scarcity of data on air contamination, and when available, it is limited to outdoor air environment contamination. In addition, in Nigeria, there is a scarcity of monitoring and risk assessment data on the co-occurrence of these chemical residues in indoor dust.

This research will assess the concentration and potential health risks of certain heavy metals and parabens present in indoor dust from specific locations in Ibadan, Oyo State, Nigeria. The levels of the parabens in the indoor dust will be quantified, and the Average Daily Dose of the studied heavy metals and parabens will be evaluated. Furthermore, the potential exposure risks of the inhabitants (adults and children) and the contamination source will be assessed using bivariate and multivariate statistical analysis (Correlation and Principal Component Analysis (PCA) study).

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## **Chapter Three**

### **Methodology**

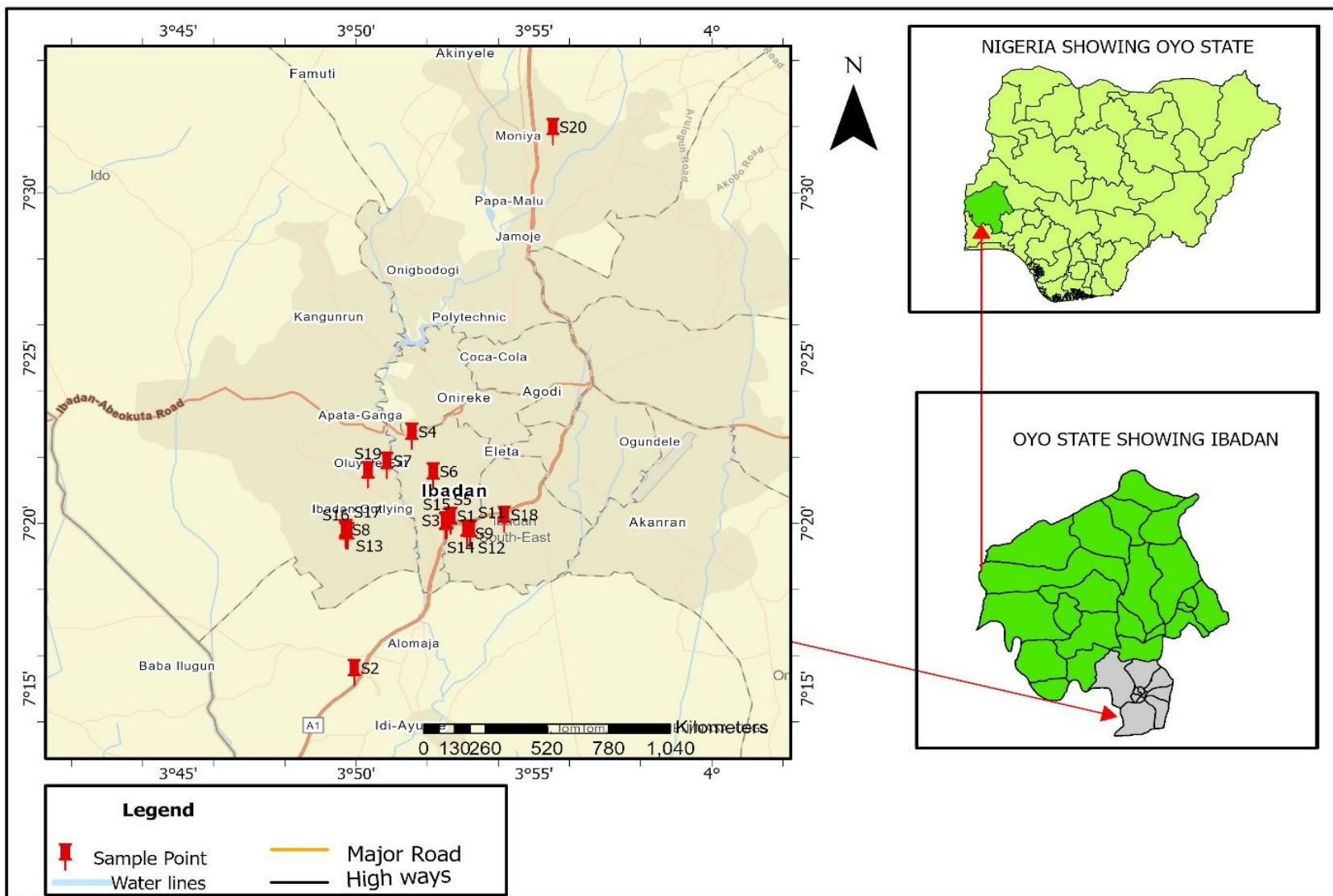
#### **3.1 Description of the Study Area**

This study was conducted using sampling points located within Ibadan city, one of Nigeria's most prominent and historically significant cities. It is also the capital and most populous city of Oyo State, located in the country's southwestern region. Ibadan lies approximately 128 km northeast of Lagos and serves as a key administrative, commercial, and academic hub. It is the city with the third-largest population in Nigeria, following Lagos and Kano, and the second most populous in Africa after Cairo, with a total population of 3,649,000 as of 2021<sup>1,2</sup>. Oyo State encompasses a total area of 28,454 km<sup>2</sup>. Ibadan, which covers 3,080 km<sup>2</sup>, is the largest city in Nigeria by land area and is situated between latitudes 7°15'N and 7°30'N and longitudes 3°45'E and 4°00'E. Additionally, it ranks among the largest cities in West Africa in terms of land size.

Ibadan experiences a tropical wet and dry climate, with a long rainy season and a shorter dry season. The dry season lasts from November to March, while the wet season runs from April to October. Average annual rainfall is 1,205 mm, ranging from 1,200 to 1,600 mm. Humidity averages 74.55% throughout the year, with a mean annual temperature of 28°C<sup>3</sup>.

Historically, Ibadan was founded in the early 19<sup>th</sup> century as a military outpost and later developed into a major hub of Yoruba politics and commerce. Presently, it functions as a strategic urban centre, hosting various academic institutions, several research institutes, government agencies, and major manufacturing companies. Some of the academic institutions include the University of Ibadan, Ibadan Polytechnic, Lead City, etc. Some manufacturing companies in Ibadan include





**Figure 3.1. Map Illustrating the Locations of the Sampling Sites**

**Source:** Author's Field work, 2025

Sumal Nig. Ltd, Agritech Nig. Ltd, 7-Up Bottling Company, Elixir Global, Steel Works Ltd, Polyfilm, etc. The United Nations Human Settlements Programme has identified the city of Ibadan as one of the fastest-growing urban centres in sub-Saharan Africa due to rapid industrialisation and urbanisation<sup>4,5</sup>. Consequently, it faces several environmental and public health challenges, including unregulated urban expansion, inadequate waste management, and insufficient water and sanitation services. Generally, these challenges result in an increasing level of environmental pollution, such as air pollution.

The coordinates of the sampling locations are illustrated and detailed in Figure 3.1 and Table 3.1, respectively.

### **3.2 Sample Collection and Preservation**

A total of 20 indoor dust samples ( $n = 6$ ), which are composite in nature, were randomly gathered from residential locations, including households (13), shops (3), and offices (4) within Ibadan between February and March 2024, using the method described by Bamigboye et al. with some modifications<sup>6</sup>. Dust particles from at least six different undisturbed surfaces in indoor environments, such as window nets, bookshelves, kitchen shelves, refrigerator tops, cemented floors, and tables from each sampling location, were gathered using a disposable plastic brush and dustpan. Additional samples of settled indoor dust were collected from offices and laboratories. Dust samples from different parts within each location were merged to create a composite sample in a re-sealable plastic bag that was clearly labelled. A new disposable plastic brush was used at each sampling site, and the dustpan was cleaned between locations to prevent cross-contamination. Dust particles from these locations at each sampling point were pooled, divided, and stored for elemental and parabens analyses in sealed plastic bags and pre-cleaned, dry amber-coloured bottles, respectively.

**Table 3.1. Coordinates for the Sampling Sites**

| <b>Sample</b> | <b>Description</b> | <b>Coordinates</b>   |
|---------------|--------------------|----------------------|
| <b>S 1</b>    | school             | 7°19'39"N, 3°52'39"E |
| <b>S 2</b>    | residential        | 7°15'3"N, 3°49'57"E  |
| <b>S 3</b>    | market             | 7°19'31"N, 3°52'33"E |
| <b>S 4</b>    | industrial         | 7°22'12"N, 3°51'34"E |
| <b>S 5</b>    | school             | 7°19'39"N, 3°52'40"E |
| <b>S 6</b>    | residential        | 7°21'0"N, 3°52'10"E  |
| <b>S 7</b>    | industrial         | 7°21'19"N, 3°50'52"E |
| <b>S 8</b>    | residential        | 7°19'14"N, 3°49'42"E |
| <b>S 9</b>    | residential        | 7°19' 16"N, 3°53'7"E |
| <b>S 10</b>   | residential        | -                    |
| <b>S 11</b>   | residential        | 7°19'16"N, 3°53'13"E |
| <b>S 12</b>   | residential        | 7°19'15"N, 3°53'12"E |
| <b>S 13</b>   | residential        | 7°19'11"N, 3°49'46"E |
| <b>S 14</b>   | market             | 7°19'29"N, 3°52'31"E |
| <b>S 15</b>   | market             | 7°19'30"N, 3°52'33"E |
| <b>S 16</b>   | residential        | 7°19'11"N, 3°49'43"E |
| <b>S 17</b>   | residential        | 7°19'17"N, 3°49'43"E |
| <b>S 18</b>   | residential        | 7°19'41"N, 3°54'10"E |
| <b>S 19</b>   | residential        | 7°21'2"N, 3°50'20"E  |
| <b>S 20</b>   | residential        | 7°31'25"N, 3°55'32"E |

**Source:** Author's Analysis, 2025

Samples for parabens analysis were kept away from sunlight at the sampling site to prevent degradation. All the samples were subsequently taken to the laboratory for examination.

### **3.3 Sample Pre-treatment**

#### **3.3.1 Sample Pre-treatment for Heavy Metals**

The dust samples for elemental study were initially air-dried at the Research Laboratory, Lead City University, Ibadan, Oyo State, Nigeria and were subsequently screened to eliminate any apparent contaminants such as hair, soil, and grit. Subsequently, samples were dried in an oven at 50°C for 24 hours. The dried material was then homogenised using a mortar and pestle and sieved through a mesh with openings smaller than 63 mm.

Exactly 0.5 g of the consolidated dust particles from each public place were acidified separately using 30 mL of aqua regia (3:1 [v/v] HCl and HNO<sub>3</sub>) in a 250 mL beaker. The sample-acid mixture was allowed to predigest for approximately one hour, then heated in a controlled hot plate within a fume cupboard for two hours at 120 °C. After digestion, the sample was allowed to cool down to room temperature, afterward filtered through a 0.45µm Millipore membrane filter into a 25 mL volumetric flask, where the volume was made up to 25 mL and stored for further analysis. Digestion was conducted on samples obtained from each sampling point. Blanks were prepared and digested using the identical procedure applied to the sample solutions.

#### **3.3.2 Sample Pre-treatment for Parabens**

The separate samples kept in the refrigerator to prevent degradation were used for paraben extraction. The same samples were kept initially away from sunlight at the sampling sites to avoid degradation due to sunlight. Extraction and recovery of analytes from the dust samples

were achieved using the liquid-solid ultrasound extraction method with HPLC-grade methanol via five (5) sequential extraction times described by Bamigboye et al.<sup>6</sup>. Specifically, 10 mL HPLC-grade methanol (99%) was poured into the 50 mL beaker. The extraction took place in an ultrasonic bath for 10 minutes at ambient temperature. After 5 minutes of standing, the mixture was placed in an ultrasonicator for sonication at ambient temperature. The sonication lasted for 5 minutes before the mixture was filtered. This extraction process was repeated four additional times, and during each repetition, an aliquot of the solution was gathered through decantation. Upon completion of the extraction cycle, the extract was filtered through a 0.22 µm PTFE syringe filter. 0.8 mL of the filtrate solution was spiked with 0.2 mL of 1ppm of the analytes (methyl, ethyl, propyl, butyl-paraben, bisphenol A and triclosan) before HPLC analysis<sup>1</sup>.

### **3.4 Instrumental Analysis**

#### **3.4.1 Heavy Metals Analysis**

Concentrations of the targeted heavy metals, specifically Cd, Cr, Cu, Mn, Ni, Pb, and Zn, in all digested dust samples and blanks were determined using atomic absorption spectrometry (AAS) (Model AA-7000, Shimadzu Corporation, Japan). The apparatus was adjusted using standard solutions of the heavy metals of interest and all calibration curves achieved a correlation coefficient of  $r^2 \geq 0.993$  (Table 3.2). All analysis was done in triplicate. The accuracy of analytical procedures for the elemental determination was checked by analysing certified reference materials (CRMs). A D081–540 soil CRM (ERA, A Waters Company, Milford, MA, USA) was used for the analysis of dust samples (Table 3.2). The validity of the experimental outcomes was assessed against certified results (Table 3.2). The measured values showed good

agreement with the certified values ( $p < 0.05$ ), and the recovery percentages of the instrument fell within the standard ranges.

**Table 3.2. Elemental Wavelength, Curve Correlation Coefficient ( $R^2$ ) and Validation of the Digestion Recovery and Elemental Analysis Method using Soil Certified Reference Materials**

| Certified reference materials | Elements | Measured<br>( $\mu\text{g g}^{-1}$ ) | Certified<br>( $\mu\text{g g}^{-1}$ ) | Recovery (%) |
|-------------------------------|----------|--------------------------------------|---------------------------------------|--------------|
| D081–540                      | Cd       | $144 \pm 5$                          | $143 \pm 6$                           | 101          |
|                               | Cr       | $86.6 \pm 2.1$                       | $86.8 \pm 6.1$                        | 99.8         |
|                               | Cu       | $267 \pm 15$                         | $268 \pm 10$                          | 99.6         |
|                               | Ni       | $234 \pm 22$                         | $236 \pm 5$                           | 99.2         |
|                               | Pb       | $97.8 \pm 7.2$                       | $98.0 \pm 5.1$                        | 99.8         |
|                               | Zn       | $132 \pm 8$                          | $130 \pm 12$                          | 104          |

Source: Author's Field work, 2025

### 3.4.2 Analysis of Parabens

Paraben quantification was conducted using a liquid chromatography-ultraviolet (LC-UV) system comprising an Agilent Series 1100 LC (Agilent Technologies, Germany) with a G1312B Bin pump SL degassing chamber and a column oven set at 20°C (G1330B, 1290 Thermostat). The system was equipped with a G1365D, 1260MWD VL multiwavelength UV/vis detector. Paraben concentrations in the sample solutions were assessed using an Agilent Liquid Chromatography system (Agilent series 1100LC), which includes a degassing chamber (G1312B Bin pump SL) and a column oven set at 20°C and a multiwavelength UV/Vis detector.

The target compound was separated using a C18 column with a particle size of 5 $\mu$  and dimensions of 250 x 4.6mm (inner diameter). Chromatographic conditions were as follows: isocratic elution with water and methanol (30:70, v/v) as the mobile phase, flow rate of 0.7 mL/min, and injection volume of 20  $\mu$ L; the column maintained at 20 °C, and the detector set to a wavelength of 254 nm. Similarly, the target analyte retention times were 6 min, 7 min, 9 min, and 12 min for MeP, EtP, PrP, and BuP, respectively. All injections were done using an autosampler, and analysis was done in triplicate. All the outcomes were presented based on dry mass.

### 3.5 Reagents and Chemicals

Analytical standards for methyl, ethyl, propyl, and butyl 4-hydroxybenzoate, bisphenol A, and triclosan (purity 99.0% or higher) were sourced from Sigma-Aldrich (St. Louis, MO, USA).

HPLC-grade methanol was also obtained from Sigma-Aldrich. Ultrapure water was generated using the Milli-Q Direct 8/16 System. Individual stock solutions were prepared in methanol and stored at 4 °C. For the elemental analysis, 70% HNO<sub>3</sub> and 38% HCl were sourced from Sigma-Aldrich (Buchs, Switzerland). Additionally, stock standard solutions of 1000 mg L<sup>-1</sup>, which are of spectroscopic grade, were acquired from Sigma-Aldrich (Buchs, Switzerland) to create a multi-elemental calibration standard for calibration purposes. To confirm the accuracy of the analytical methods, soil certified reference material (CRM), D081-540 (ERA, A Waters Company, Milford, MA, USA) was employed.

### **3.6 Analytical Quality Assurance / Quality Control**

All sampling bottles were rigorously cleaned and rinsed with highly purified water. Every chemical used was of analytical reagent grade. Ultra-pure water was consistently utilised throughout the experiments for the analysis of parabens. Procedural blanks were used to confirm that solvents and extraction materials did not introduce contamination or interference. Analytical accuracy was verified by analysing Certified Reference Materials for heavy metals and relevant standards for parabens<sup>7</sup>. Concentrations detected in procedural blanks were subtracted from environmental sample results. Methanol blanks and midpoint calibration standards were injected after each batch to monitor for instrumental discrepancies and analyte carryover. Quantification of analytes was performed using a calibration curve generated from standard solutions, which were prepared by analysing aqueous samples containing the target compounds across a concentration range of 100 to 100,000 ng L<sup>-1</sup>, thereby ensuring measurement accuracy<sup>6</sup>. The instrumental limit of detection (LOD), which is a signal that is 3 times greater than the standard deviation of the signal from a blank, was assessed at three times the signal-to-noise ratio calculated by dividing the standard deviation of the six-point calibration intercepts by the slope.



The limit of quantification (LOQ) was defined as the signal corresponding to ten times the standard deviation of the blank signal, calculated using the same ratio applied for the limit of detection (LOD).

### **3.7 Statistical Analysis**

Experiments were conducted in duplicates and presented as Mean  $\pm$  SD. A correlation study was done to investigate the relationships between the studied parameters. A One-way analysis of variance (ANOVA) was employed in identifying significant differences ( $p < 0.05$ ) among the examined parameters. Tukey's test was used for post-hoc analyses. In addition, multivariate analysis incorporating principal component analysis (PCA) and cluster analysis (CA) was conducted<sup>8,9</sup>. Principal component analysis with varimax normalisation was applied to reduce the dimensionality of the resulting data. Sampling adequacy was checked by computing the proportion of common variance between variables, and if the variables are related or not through the Kaiser-Meyer-Olkin (KMO) and Barlett's Sphericity assessment. The outcomes of these assessment were used to validate PCA results. Patterns in the concentrations of heavy metals and parabens were detected. Interactions between heavy metals and parabens were also detected. Furthermore, possible sources of contamination were identified. Statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS, version 26; IBM Corporation, Cornell, NY, USA).

### **3.8 Human Health Risk Assessment for Heavy Metals**

#### **3.8.1 Non-Carcinogenic Risk Assessment for Heavy Metals**

Health risk assessment involves evaluating potential negative health impacts resulting from human exposure to contaminants<sup>7</sup>. In this study, exposure levels of humans to heavy metals on a daily basis were evaluated through ingestion, inhalation, and dermal absorption pathways, using Average Daily Dose (ADD), expressed in milligrams per kilogram of body weight per day (mg kg<sup>-1</sup> bw day<sup>-1</sup>). The health risk assessment model recommended by the United States Environmental Protection Agency was employed to quantify the Average Daily Dose (ADD) (mg kg<sup>-1</sup> day<sup>-1</sup>) of heavy metals present in indoor dust, as calculated using Equations 3.1 to 3.3<sup>10,11,12</sup>. The human population was categorised into two segments: children from 0 to 15 years and adults from 15 years and above, respectively.

$$ADD_{Ing} = \frac{C \times Ing_{rate} \times EF \times ED}{BW \times AT} \times 10^{-6} \quad \text{Equation 3.1}$$

$$ADD_{Inh} = \frac{C \times Inh_{rate} \times EF \times ED}{PEF \times BW \times AT} \quad \text{Equation 3.2}$$

$$ADD_{Derm} = \frac{C \times SA \times AF \times ABS \times EF \times ED}{BW \times AT} \times 10^{-6} \quad \text{Equation 3.3}$$

Where  $ADD_{Ing}$ ,  $ADD_{Inh}$ , and  $ADD_{Derm}$  refer to the average daily dose for ingestion, inhalation, and dermal contact, respectively.  $C$  denotes the concentration of heavy metal in dust (mg per kg).  $EF$  is the exposure frequency (days per year), set at 350<sup>10,11,12,13,14</sup>;

ED denotes the Exposure Duration measured in years, is defined as 30 years for adults and 6 years for children<sup>10,11,12,13,14</sup>; BW denotes the Body Weight, with 72 for adults and 15 for children<sup>8,10,11,12,13,14</sup>;

AT denotes the Average Time (years), which is  $70 \times 365$ <sup>10,11,12,13,14</sup>;

Ing<sub>rate</sub> denotes the Ingestion rate (m<sup>3</sup> per day), which is 20 for adults and 30 for children<sup>10,11,12,13,14</sup>;

Inh<sub>rate</sub> denotes Inhalation Rate (m<sup>3</sup> day<sup>-1</sup>), which is 20 for adults and 7.6 for children<sup>10,11,12,13,14</sup>;

PEF denotes the Particle Emission Factor (m<sup>3</sup> kg<sup>-1</sup>), with 550 for adults and 300 for children<sup>10,11,12,13,14</sup>; AF denotes the dermal Adherence Factor (mg/cm<sup>2</sup>/h), with 0.07 for adults and 0.2 for children<sup>10,11,12,13,14</sup>;

SA denotes the Exposed skin area in cm<sup>2</sup>, with 5700 for adults and 2800 for children<sup>10,11,12,13,14</sup>;

ABS denotes the Dermal absorption factor and it is unitless, which is Copper (Cu): 0.1, Manganese (Mn): 0.001, Lead (Pb): 0.006, Zinc (Zn): 0.02, Chromium (Cr): 0.04, Nickel (Ni): 0.001, Cadmium (Cd): 0.1<sup>10,11,12,13,14</sup>;

RfD denotes the Reference Dose in mg kg<sup>-1</sup> day<sup>-1</sup>, with Ingestion RfD: Copper (Cu):  $3.7 \times 10^{-2}$ , Manganese (Mn):  $2.4 \times 10^{-2}$ , Lead (Pb):  $3.5 \times 10^{-3}$ , Zinc (Zn):  $3.0 \times 10^{-1}$ , Chromium (Cr):  $3.0 \times 10^{-3}$ , Nickel (Ni):  $2.0 \times 10^{-2}$ , Cadmium (Cd):  $1.0 \times 10^{-3}$ ;

Inhalation RfD: Copper (Cu):  $4 \times 10^{-2}$ , Manganese (Mn):  $5.0 \times 10^{-5}$ , Lead (Pb):  $3.5 \times 10^{-3}$ , Zinc (Zn):  $3.0 \times 10^{-2}$ , Chromium (Cr):  $3.0 \times 10^{-3}$ , Nickel (Ni):  $2.06 \times 10^{-2}$ , Cadmium (Cd):  $1.0 \times 10^{-5}$ ;

Dermal Contact RfD: Copper (Cu):  $1.2 \times 10^{-2}$ , Manganese (Mn):  $4.6 \times 10^{-2}$ , Lead (Pb):  $5.25 \times 10^{-5}$ , Zinc (Zn):  $6.0 \times 10^{-2}$ ,  $6.0 \times 10^{-5}$  (Cr),  $5.4 \times 10^{-3}$  (Ni),  $1.0 \times 10^{-5}$  (Cd)<sup>15,16,17,18,19,20,21,22,23,24,25,26,27,29</sup>;

SF refers to the slope factor, expressed in mg per kg per day, and is associated with ingestion exposure: 0.0085 (Pb), 1.7 (Ni), 6.3 (Cd), 0.5 (Cr); Inhalation: 0.042 (Pb), 0.84 (Ni), 6.1 (Cd), 42 (Cr); Dermal Contact: 1.5 (Pb), 42.5 (Ni), 20 (Cd), 20 (Cr)<sup>10,11,12,29,30</sup>.

### 3.8.2 Hazard Quotient for Heavy Metals

The assessment of non-carcinogenic health risk related to heavy metals found in indoor dust was conducted using the Hazard Quotient (HQ). The HQ serves as a tool for calculating the non-carcinogenic effects of heavy metals present in indoor dust. The HQ was estimated by multiplying the ADD for ingestion, inhalation and dermal contact by the Reference Dose (RfD) as indicated in Equation 3.4<sup>10,11,12,14,15</sup>.

$$HQ = \frac{ADD_{(Ing / Inh / Derm)}}{RfD} \quad \text{Equation 3.4}$$

Where HQ is the Hazard Quotient;

$ADD_{Ing, Inh, Derm}$  refer to the average daily dose for ingestion, inhalation, and dermal exposure, respectively. RfD denotes the Reference Dose.

### 3.8.3 Hazard Index for Heavy Metals

The Hazard Index (HI) quantifies the risk of non-carcinogenic effects associated with multiple exposure routes and chemical components. The total non-carcinogenic risk to humans is calculated by summing the hazard quotients (HQs) for ingestion, inhalation, and dermal contact, as described in Equation 3.5<sup>14</sup>. An HI value greater than one indicates a significant non-

carcinogenic risk to human health, whereas an HI value less than one suggests the absence of such risk.

$$HI = HQ_{Ing} + HQ_{Inh} + HQ_{Derm} \quad \text{Equation 3.5}$$

Where HI is the Hazard Index;

$HQ_{Ing / Inh / Derm}$  are the Hazard Quotient for ingestion, inhalation and dermal contact, respectively;

### 3.8.4 Carcinogenic Risk Assessment for Heavy Metals

The carcinogenic risk assesses the likelihood that an individual may develop cancer due to their lifetime exposure to carcinogens. Carcinogenic risk is classified as negligible when the CR value is less than  $1 \times 10^{-6}$ , acceptable or tolerable when it ranges from  $1 \times 10^{-6}$  to  $1 \times 10^{-4}$ , and unacceptable when the CR value exceeds  $1 \times 10^{-4}$  indicates there is a potential of 1 in 10,000 individuals to develop cancer as a result of lifetime exposure to carcinogenic threats<sup>15,31,32</sup>. The Average Daily Dose (ADD) and cancer Slope Factor (SF) from Equation 3.6 are combined to determine the Lifetime Cancer Risk (LCR). The LCR is then used to estimate carcinogenic risk in humans<sup>14</sup>.

$$LCR = ADD \times SF \quad \text{Equation 3.6}$$

The Total Lifetime Cancer Risk (TLCR) is calculated by summing the Lifetime Cancer Risk (LCR) values for ingestion, inhalation, and dermal exposure as shown in Equation 3.7 below<sup>14</sup>.

The United States Environmental Protection Agency (USEPA) establishes the acceptable range

for total lifetime cancer risk (TLCR) associated with cancer risk. TLCR values exceeding this acceptable range suggest a potential risk of carcinogenic effects, which may be probable.

$$\text{TLCR} = \text{LCR}_{\text{Ing}} + \text{LCR}_{\text{Inh}} + \text{LCR}_{\text{Derm}} \quad \text{Equation 3.7}$$

Where LCR is the Lifetime Cancer Risk;

ADD denotes the Average Daily Dose.

SF refers to the Slope Factor.

TLCR stands for Total Lifetime Cancer Risk.

$\text{LCR}_{\text{Ing}}$ ,  $\text{LCR}_{\text{Inh}}$ , and  $\text{LCR}_{\text{Derm}}$  is the Lifetime Cancer Risk for ingestion, inhalation and dermal contact, respectively.

### 3.9 Dust Pollution Assessment

Similarly, the evaluation of dust pollution caused by the heavy metals found in residential indoor dust samples was carried out using the following contamination indicators: contamination factor (level of contamination), geo-accumulation index, and pollution load index<sup>14,33</sup>.

#### 3.9.1 Contamination Factor

The Contamination Factor (CF) for each metal analyzed in this study was calculated using Equation 3.8 along with soil quality standards aimed at protecting environmental and human health impacts. Baseline values were determined based on the elemental composition of the Earth's crust<sup>14,34</sup>.

$$CF_n = \frac{C_{\text{sample}}}{C_{\text{background}}} \quad \text{Equation 3.8}$$

Where  $CF_n$  represents the Contamination Factor of each heavy metal;

$C_{\text{sample}}$  denotes the determined heavy metal concentrations

$C_{\text{background}}$  denotes the heavy metal background concentration. The crustal abundance values of the metals: Cu = 45, Mn = 900, Pb = 20, Zn = 95, Cr = 100, Ni = 68, and Cd = 0.3 were adopted as their background concentrations<sup>35,36,37</sup>.

The CF is divided into four categories:

CF less than 1 indicates low levels of contamination;

1 is less than or equal to CF and less than 3 signals moderate contamination;

CF ranging from 3 to less than 6 indicates considerable contamination;

CF greater than 6 indicates very high level of contamination.

### 3.9.2 Pollution Load Index

The concentration of pollutants in indoor dust was evaluated using the Pollution Load Index (PLI). This index is unitless and indicates the overall pollution impact of all heavy metals, summarised into a single contamination metric<sup>14, 34</sup>. The PLI was calculated by averaging the CF values of the metals as indicated in equation 3.9 below<sup>34</sup>.

$$PLI = (CF_1 \times CF_2 \times CF_3 \times \dots \times CF_n)^{\frac{1}{n}} \quad \text{Equation 3.9}$$

Where PLI stands for pollution load index. The variable  $n$  is the number of heavy metals assessed, and represents their contamination factor. A PLI of 1 or higher indicates pollution,

while a value below 1 suggests heavy metal concentrations are close to background levels. This provides a comparative method to assess the quality of the site<sup>14,34</sup>.

A PLI value of less than 1 indicates ideal conditions, meaning no pollution or high site quality.

A PLI of 1 serves as a benchmark when pollutants are detected, and

A PLI greater than 1 indicates a decline in site quality.

### 3.9.3 Index of Geo-accumulation

The Geo-accumulation Index (Igeo) values were determined using Muller's expression according to equation 3.10 below<sup>35,38</sup>.

$$I_{geo} = \log_2 \frac{C_n}{1.5 \times B_n} \quad \text{Equation 3.10}$$

Where Igeo is the Geoaccumulation index;  $C_n$  refers to the concentration of heavy metals in dust particles;  $B_n$  denotes the concentration in the background sample. A value of 1.5 is the constant for the background for lithogenic correction, which is used to consider any variations in baseline values caused by differences in rock types in the samples<sup>35,38</sup>.

### 3.10. Health Risk Assessment for Parabens

Research indicates that parabens are harmful to human health<sup>39</sup>. People can come into contact with parabens through ingestion, inhalation, and skin exposure.

#### 3.10.1 Non-Carcinogenic Risk Assessment for Parabens



To assess the risk to humans, the Average Daily Dose (ADD) was evaluated by using the mean concentrations of the parabens (methylparaben, ethylparaben, propylparaben and butylparaben) obtained from the indoor dust samples, daily intake rate, and the average body weight of humans<sup>6</sup>. The ADD was calculated using equation 3.11 and expressed in ng g<sup>-1</sup> of body weight/day (ng g<sup>-1</sup> bw/day)<sup>6</sup>.

$$\text{ADD}_{\text{Ing}} = \frac{C \times \text{FI} \times \text{IR} \times \text{EF} \times \text{ED}}{\text{BW} \times \text{AT}} \quad \text{Equation 3.11}$$

Where C represents the concentration of the parabens (ng g<sup>-1</sup>); FI signifies the fraction ingested, which is calculated to be ca. 80% (0.80)<sup>40</sup>. IR denotes the Intake Rate (0.06 g day<sup>-1</sup> as provided by U.S. EPA 2011)<sup>41</sup>. EF represents the Exposure Frequency (365 days for adults and 250 days for children)<sup>6</sup>. ED refers to Exposure Duration, which is defined as 30 years for adults and 5 years for children)<sup>6</sup>. Body Weight (BW) is defined as 80 kg for adults and 70 kg for children aged six years. Average Time (AT) is calculated as 30 times 365 days for adults and 5 times 365 days for children.)<sup>6</sup>.

### 3.10.2 Hazard Quotient for Parabens

The Hazard Quotient (HQ) will be calculated to evaluate the potential non-carcinogenic risk associated with indoor dust. Hazard Quotient will be calculated based on the concentration of the parabens that will be recorded for this study in the dust sample using the formula as shown in equation 3.12 below. The non-carcinogenic risk is classified as high when HQ is greater than 1, whereas it is considered low when HQ is less than 1.

$$\text{HQ} = \text{ADD} \quad \text{Equation 3.12}^1$$

RfD

Where HQ represents Hazard Quotient; ADD represents Average Daily Dose; RfD refer to the Oral Reference Dose value ( $\text{ng kg}^{-1} / \text{day}$ ), which is  $10000000 \text{ ng kg}^{-1} \text{ day}^{-1}$  each for MeP and EtP,  $100000 \text{ ng kg}^{-1} \text{ day}^{-1}$  each for PrP and BuP<sup>6,42</sup>.

### 3.10.3 Hazard Index for Parabens

The Hazard Index (HI) was utilised to evaluate the potential for non-carcinogenic health risks associated with indoor dust as shown in equation 3.13 below<sup>6</sup>.

$$\text{HI} = \sum \text{HQ} \quad \text{Equation 3.13}$$

Where HI is the Hazard Index and HQ is the Hazard Quotient.

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## Chapter Four

### Results and Discussions of Findings

#### 4.1 Elemental Concentrations of Dust Samples

Table 4.1 summarised the elemental levels in indoor dust samples obtained from twenty (20) randomly selected areas in Ibadan, Oyo State, Nigeria. Overall, the mean elemental concentrations of the analyzed heavy metals across the study areas (households, shops, laboratories, and offices) followed a decreasing trend of  $Mn > Zn > Cu > Pb > Cr > Ni > Cd$ . Throughout the sampling locations, the concentrations of the examined heavy metals ranged from 5.20 to 32.10, 0.51 to 10.30, 2.15 to 6.80,  $< LOD$  to 0.04, 0.01 up to 0.64, 0.09 up to 1.60, and 0.04 up to 4.36 expressed in milligrams per kilogram for manganese, copper, zinc, cadmium, chromium, nickel, and lead, respectively. In particular, the indoor dust sample obtained from the laboratory showed the highest elemental mean concentration of  $32.0 \text{ mg kg}^{-1}$  for Mn. Exposure to high levels of Mn, whether for short or prolonged periods, can cause significant impairment to the nervous system and result in lasting neurological damage<sup>1</sup>. However, Cd had the lowest mean concentration, falling below the detection limit at sites S3, S7, S8, and S20.

Although elemental concentrations from this present investigation were lower than those reported by Famuyiwa et al., nevertheless, 100, 95, 5, and 5% of the indoor samples had concentrations higher than those reported by Abdulraheem et al., for Cu, Mn, Zn, and Ni, respectively<sup>2,3</sup>. Likewise, the mean elemental concentrations of Cd, Cr, Ni, and Pb observed in this study were notably lower than previously reported values by Alotaibi et al. (Saudi Arabia) and Hammood and Sobhanardakani (Iran), respectively<sup>4,5</sup>. These results suggest that dust from the previous study was more loaded with the studied heavy metals. Although there are currently no established regulatory



**Table 4.1: Comparison of Concentrations of Heavy Metals with Standard and Other Studies**

| Sample              | Cu           | Mn           | Pb          | Zn          | Cr          | Ni          | Cd          |
|---------------------|--------------|--------------|-------------|-------------|-------------|-------------|-------------|
| S1                  | 1.52 ± 0.04  | 32.00 ± 0.10 | 0.18 ± 0.02 | 6.73 ± 0.06 | 0.18 ± 0.01 | 1.57 ± 0.06 | 0.01 ± 0.01 |
| S2                  | 0.57 ± 0.02  | 17.40 ± 0.10 | 0.12 ± 0.02 | 2.52 ± 0.01 | 0.09 ± 0.01 | 0.19 ± 0.01 | 0.04 ± 0.00 |
| S3                  | 0.93 ± 0.08  | 15.93 ± 0.15 | 0.10 ± 0.02 | 2.65 ± 0.01 | 0.45 ± 0.01 | 0.21 ± 0.01 | < LOD       |
| S4                  | 1.00 ± 0.09  | 15.20 ± 0.44 | 0.74 ± 1.08 | 2.73 ± 0.04 | 0.17 ± 0.01 | 0.33 ± 0.01 | 0.01 ± 0.01 |
| S5                  | 1.88 ± 0.05  | 18.53 ± 0.06 | 0.94 ± 1.46 | 3.06 ± 0.01 | 0.13 ± 0.01 | 0.26 ± 0.01 | 0.02 ± 0.01 |
| S6                  | 1.27 ± 0.30  | 18.70 ± 0.10 | 0.83 ± 1.32 | 2.73 ± 3.06 | 0.17 ± 0.01 | 0.21 ± 0.01 | 0.01 ± 0.01 |
| S7                  | 1.15 ± 0.05  | 31.57 ± 0.21 | 1.44 ± 2.33 | 2.81 ± 0.02 | 0.01 ± 0.01 | 0.10 ± 0.01 | < LOD       |
| S8                  | 0.87 ± 0.31  | 22.67 ± 0.06 | 1.05 ± 1.61 | 2.17 ± 3.03 | 0.07 ± 0.01 | 0.23 ± 0.01 | < LOD       |
| S9                  | 1.14 ± 0.07  | 22.50 ± 0.10 | 0.87 ± 1.33 | 2.81 ± 0.02 | 0.13 ± 0.01 | 0.25 ± 0.01 | 0.01 ± 0.01 |
| S10                 | 10.23 ± 0.06 | 16.10 ± 0.10 | 1.09 ± 1.82 | 3.20 ± 0.01 | 0.22 ± 0.01 | 0.61 ± 0.02 | 0.02 ± 0.01 |
| S11                 | 0.94 ± 0.25  | 5.23 ± 0.06  | 1.03 ± 1.58 | 2.31 ± 2.01 | 0.36 ± 0.01 | 0.16 ± 0.01 | 0.01 ± 0.01 |
| S12                 | 1.81 ± 0.02  | 15.33 ± 0.06 | 1.31 ± 2.09 | 2.77 ± 0.02 | 0.37 ± 0.01 | 0.21 ± 0.01 | 0.01 ± 0.01 |
| S13                 | 1.89 ± 0.02  | 23.13 ± 0.12 | 1.23 ± 2.03 | 2.73 ± 0.02 | 0.13 ± 0.01 | 0.23 ± 0.01 | 0.01 ± 0.01 |
| S14                 | 0.91 ± 0.02  | 17.03 ± 0.12 | 1.45 ± 2.33 | 2.52 ± 0.01 | 0.19 ± 0.01 | 0.26 ± 0.01 | 0.01 ± 0.01 |
| S15                 | 1.06 ± 0.07  | 14.77 ± 0.06 | 1.50 ± 2.41 | 2.56 ± 0.01 | 0.26 ± 0.01 | 0.25 ± 0.01 | 0.01 ± 0.01 |
| S16                 | 1.16 ± 0.01  | 10.67 ± 0.06 | 1.47 ± 2.40 | 2.76 ± 0.01 | 0.07 ± 0.00 | 0.28 ± 0.01 | 0.01 ± 0.01 |
| S17                 | 0.52 ± 0.01  | 14.27 ± 0.12 | 1.41 ± 2.23 | 2.18 ± 0.03 | 0.12 ± 0.01 | 0.30 ± 0.01 | 0.01 ± 0.01 |
| S18                 | 0.81 ± 0.03  | 12.73 ± 0.06 | 1.53 ± 2.45 | 2.44 ± 0.01 | 0.63 ± 0.01 | 0.21 ± 0.01 | 0.01 ± 0.01 |
| S19                 | 1.01 ± 0.19  | 10.03 ± 0.06 | 1.45 ± 2.32 | 2.46 ± 1.01 | 0.16 ± 0.01 | 0.26 ± 0.01 | 0.02 ± 0.01 |
| S20                 | 1.11 ± 0.10  | 9.03 ± 0.05  | 1.48 ± 2.39 | 2.78 ± 1.01 | 0.15 ± 0.01 | 0.26 ± 0.01 | < LOD       |
| Ilorin <sup>3</sup> | 0.47         | 6.45         | 5.74        | 3.99        | 2.13        | 1.09        | 0.60        |
| Ilaro <sup>2</sup>  | 59.4         | 328          | 51.8        | 378         | 35.2        | 9.71        | 461         |
| CSQG <sup>6</sup>   | 63           | -            | 140         | 200         | 64          | 50          | 10          |

\*LOD is Limit of Detection. CSQG = Canadian Soil Quality Guideline.

**Source:** Author's Analysis, 2025

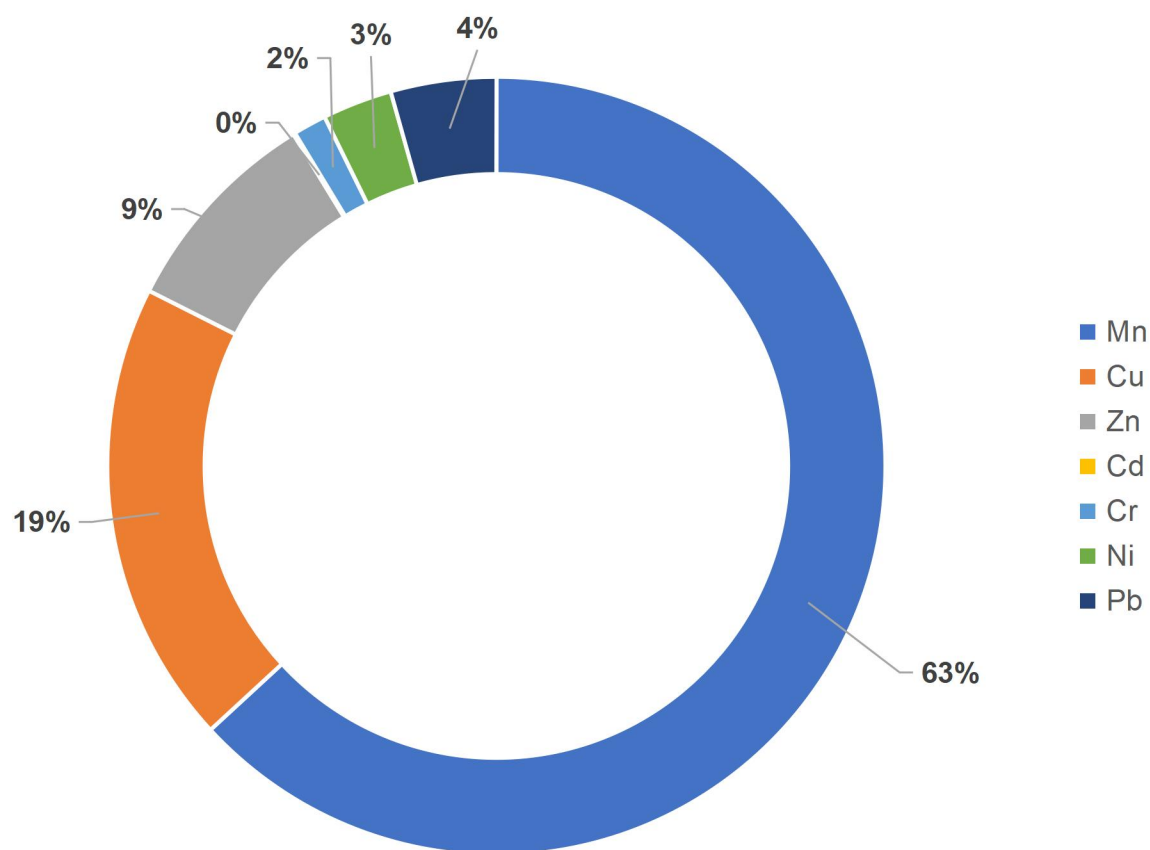
standards for metal concentrations in dust at the local, national, or international levels, this study adopted soil regulatory guidelines as reference values, an approach commonly used in several previous studies<sup>7,8,9,10,11</sup>. Consequently, all measured elemental concentrations were compared to the Canadian Soil Quality Guideline (CSQG) for residential and parkland land use, as established by the Canadian Council of Ministers of the Environment (CCME) and found to be below the regulatory limits set for metals in soil.

The elemental profile data from this study showed that Mn was the most prevalent, accounting for 63.0% of the total studied heavy metals in the indoor dust across all the sampling locations. (Figure 4.1). The high levels of Mn could be attributed to human activities like industrial discharges and the burning of fossil fuels<sup>12</sup>. Several reports have established the elevation of Mn levels due to anthropogenic activities such as the combustion of fossil fuels<sup>13,14,15</sup>.

#### **4.2 Parabens Concentrations of Indoor Dust Samples**

The concentrations of parabens found in 20 randomly obtained indoor dust samples for four target parabens are summarised in Table 4.2. Methylparaben (MeP), ethylparaben (EtP), propylparaben (PrP), and butylparaben (BuP) were detected across all the sample locations. The mean concentrations of the targeted parabens ranged from 0.24 to 7.10, 0.30 to 1.47, 0.29 to 2.06, and 0.28 to 2.38 mg kg<sup>-1</sup> for MeP, EtP, PrP, and BuP, respectively. Overall, this study's mean concentrations of the targeted parabens follow the trend MeP > EtP > BuP > PrP. In this study, MeP was the most prevalent paraben, accounting for 52% of total parabens (Figure 3.2). This is likely because the MeP analogue is widely used in consumer products<sup>16</sup>. Overall, the percentage contribution of parabens in this study decreased in the following order: MeP < EtP < BuP < PrP. While the high percentage contribution of MeP is consistent with earlier reports, the value is

lower than the 78.4% reported by Zhu et al. in China<sup>17</sup>. The highest concentrations in this study for MeP,



**Figure 4.1: Composition Profiles of Heavy Metals in Indoor Dust Particles**

**Source:** Author's Analysis, 2025

EtP, BuP, and PrP were reported for sites S3 (7096.04 ng g<sup>-1</sup>), S7 (1468.83 ng g<sup>-1</sup>), S16 (2382.38 ng g<sup>-1</sup>) and S16 (2062.91 ng g<sup>-1</sup>), respectively (Table 4.2). However, the lowest concentrations for MeP, EtP, BuP, and PrP were recorded for S2 (243.58 ng g<sup>-1</sup>), S19 (296.41 ng g<sup>-1</sup>), S11 (279.55 ng g<sup>-1</sup>), and S13 (291.86 ng g<sup>-1</sup>), respectively (Table 3.1). Data from this study support the previous report that suggests MeP as having the highest concentration in indoor dust from classrooms in the United States<sup>18,19</sup>. However, this result negates the previous study that PrP, out of the four parabens, has the highest mean concentration in indoor dust from staff offices in Iran<sup>20</sup>. The elevated average levels of MeP detected in the dust may stem from the incorporation of MeP in numerous consumer goods<sup>21,22</sup>.

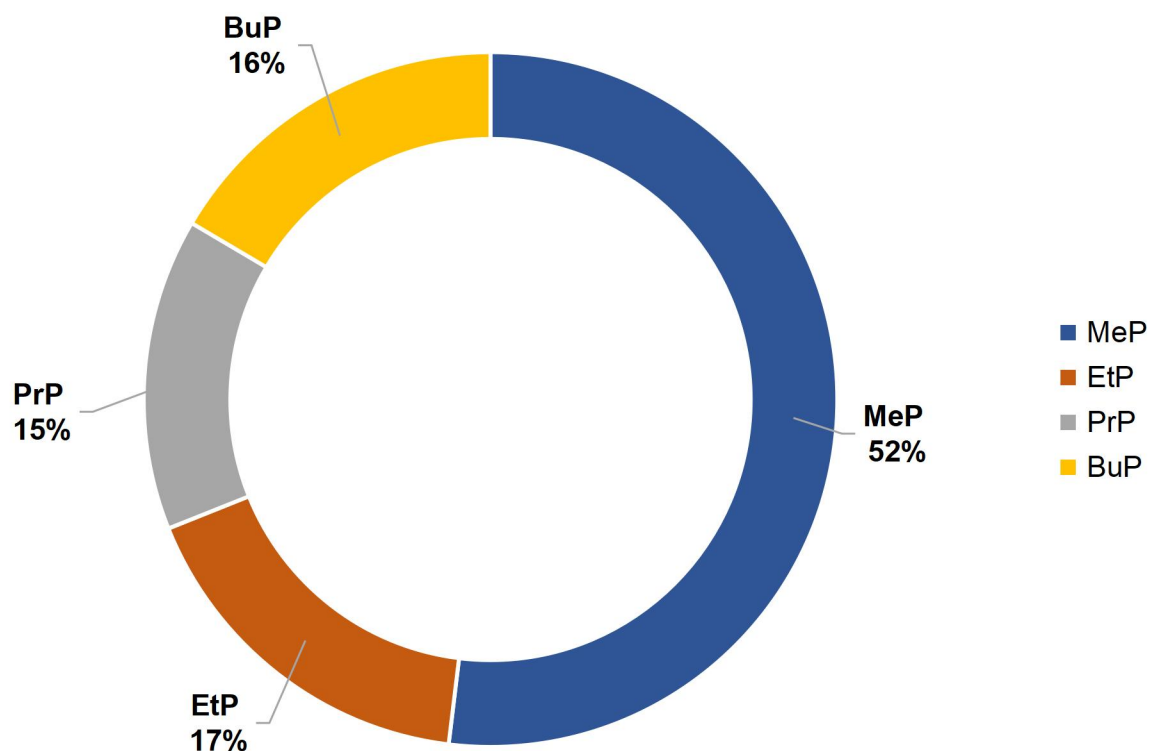
#### **4.3 Bivariate Statistical Analysis of Targeted Analytes in Indoor Dust Samples**

The correlation results for the targeted parameters are summarised in Table 4.3. Correlation data revealed several significant relationships among the studied analytes detected in the dust samples. The results showed significant correlations (positive and negative) among the targeted analytes. The highest negative correlation coefficient of -0.4 was observed for a three-way correlation between Pb, Zn and Ni. These notable, significant negative correlations indicate the influence of various sources. Particularly, a significant ( $p \leq 0.01$ ) correlation was observed between Zn and Mn ( $r = 0.6$ ), as well as between Ni and Zn ( $r = 0.9$ ), indicating that their concentrations in indoor dust may originate from common sources, respectively. Also, significant correlation coefficients of 0.6, 0.4 and 0.3 associated with a positive three-way correlation between Mn, Zn and Ni were recorded.

**Table 4.2: Concentrations of Parabens in Indoor Dust Samples (ng g<sup>-1</sup>)**

| Sample | MeP         | EtP        | PrP        | BuP        |
|--------|-------------|------------|------------|------------|
| S1     | 721 ± 54    | 684 ± 327  | 593 ± 259  | 821 ± 219  |
| S2     | 244 ± 1     | 319 ± 78   | 314 ± 32   | 355 ± 47   |
| S3     | 7096 ± 311  | 1399 ± 271 | 1189 ± 301 | 429 ± 15   |
| S4     | 2798 ± 246  | 858 ± 221  | 500 ± 127  | 643 ± 30   |
| S5     | 5623 ± 300  | 1063 ± 359 | 898 ± 152  | 1061 ± 313 |
| S6     | 1986 ± 46   | 715 ± 70   | 501 ± 133  | 806 ± 34   |
| S7     | 1173 ± 11   | 1469 ± 109 | 558 ± 20   | 687 ± 20   |
| S8     | 1173 ± 12   | 1434 ± 142 | 700 ± 114  | 687 ± 20   |
| S9     | 359 ± 84    | 963 ± 71   | 738 ± 57   | 564 ± 35   |
| S10    | 2405 ± 75   | 693 ± 113  | 426 ± 74   | 678 ± 31   |
| S11    | 5201 ± 336  | 871 ± 104  | 692 ± 42   | 280 ± 80   |
| S12    | 6541 ± 1464 | 651 ± 205  | 445 ± 101  | 468 ± 337  |
| S13    | 3428 ± 232  | 1015 ± 69  | 292 ± 3    | 634 ± 80   |
| S14    | 2204 ± 239  | 788 ± 9    | 456 ± 10   | 744 ± 36   |
| S15    | 1644 ± 30   | 913 ± 328  | 1300 ± 22  | 760 ± 665  |
| S16    | 2475 ± 176  | 1429 ± 86  | 2063 ± 51  | 2382 ± 198 |
| S17    | 762 ± 226   | 825 ± 238  | 1288 ± 549 | 1425 ± 780 |
| S18    | 1433 ± 373  | 648 ± 185  | 710 ± 104  | 1156 ± 325 |
| S19    | 1326 ± 56   | 296 ± 17   | 650 ± 182  | 699 ± 394  |
| S20    | 5536 ± 1171 | 712 ± 89   | 832 ± 375  | 1560 ± 384 |

**Source:** Author's Analysis, 2025



**Figure 4.2: Composition Profiles of Targeted Parabens in Indoor Dust Particle**

**Source:** Author's Analysis, 2025

Similarly, BuP showed a strong, significant ( $p \leq 0.01$ ) correlation with PrP ( $r = 0.7$ ). Butyl paraben and PrP are commonly found in cosmetic products such as makeup, moisturizers, hair care items, and shaving creams or gels<sup>23,24</sup>. Likewise, EtP showed a significant positive correlation with PrP ( $r = 0.5$ ), indicating similarities in the origins of the associated analytes and suggesting a shared source of contamination. On the other hand, there were also significant negative three and four-way synergies between (Cd, MeP and EtP) and (Mn, Cr, MeP and PrP). Conversely, these significant negative correlations suggest contributions from different sources.

#### **4.4 Multivariate Statistics Analysis**

##### **4.4.1 Principal Component Analysis (PCA)**

Principal component analysis (PCA) was conducted to examine the associations among the analytes and to predict their potential sources. The results of the PCA are presented in Table 4.4. Preliminary assessments, including a Kaiser-Meyer-Olkin (KMO) value of at least 0.6 and a significant Bartlett's sphericity test ( $p < 0.001$ ), confirmed the adequacy of the dataset for factor analysis<sup>25</sup>.

As presented in Table 4.4, the principal component analysis revealed five dominant principal components, collectively explaining 79.95% of the overall variance. The components were primarily influenced by Ni, Zn and Mn (PC1); EtP (PC2); PrP and BuP (PC3); Cr and MeP (PC4); and Cu and Pb (PC5), contributing 25.36%, 19.06%, 13.54%, 12.70%, and 9.29% of the total variance, respectively. Analytes grouped within the same component are typically linked to a common origin<sup>26</sup>. Figure 4.3B visually illustrates the relationship's direction and intensity between the analytes and the component. The strong loading of 0.97 and close association between Ni and Zn (Figure 4.3A) support the correlation analysis, and may indicate shared anthropogenic inputs, such as vehicle emissions.

**Table 4.3: Correlation Matrix for Analytes in Dust Samples**

|     | Mn            | Cu          | Zn           | Cd            | Cr           | Ni   | Pb  | MeP  | EtP          | PrP          | BuP |
|-----|---------------|-------------|--------------|---------------|--------------|------|-----|------|--------------|--------------|-----|
| Mn  | 1             |             |              |               |              |      |     |      |              |              |     |
| Cu  | 0.0           | 1           |              |               |              |      |     |      |              |              |     |
| Zn  | <b>0.6**</b>  | 0.2         | 1            |               |              |      |     |      |              |              |     |
| Cd  | -0.1          | 0.2         | 0.1          | 1             |              |      |     |      |              |              |     |
| Cr  | <b>-0.4**</b> | 0.0         | -0.1         | -0.1          | 1            |      |     |      |              |              |     |
| Ni  | <b>0.4**</b>  | <b>0.3*</b> | <b>0.9**</b> | 0.1           | -0.0         | 1    |     |      |              |              |     |
| Pb  | -0.1          | 0.0         | -0.1         | -0.1          | -0.0         | -0.1 | 1   |      |              |              |     |
| MeP | <b>-0.4**</b> | 0.0         | -0.1         | <b>-0.3*</b>  | <b>0.4**</b> | -0.2 | 0.0 | 1    |              |              |     |
| EtP | <b>0.3*</b>   | -0.1        | -0.1         | <b>-0.6**</b> | -0.2         | -0.2 | 0.1 | 0.2  | 1            |              |     |
| PrP | <b>-0.3*</b>  | -0.2        | -0.1         | -0.3*         | -0.0         | -0.1 | 0.1 | 0.1  | <b>0.5**</b> | 1            |     |
| BuP | -0.2          | -0.1        | 0.0          | -0.2          | -0.2         | 0.0  | 0.1 | -0.0 | 0.2          | <b>0.7**</b> | 1   |

\*, \*\* Correlations significant at  $p \leq 0.05$  and  $p \leq 0.01$  respectively

Source: Author's Analysis, 2025



Conversely, the relatively high positive and negative loading for EtP (0.88) and Cd (-0.83) in PC 2 imply unrelated sources. This is further corroborated by the large distance between EtP and Cd in Figure 4.3A. In PC 3, PrP was found to be strongly associated with BuP with high loading. The strong correlation between PrP and BuP is further supported by their dominance in PC3, with strong factor loading values of 0.88 and 0.91, respectively, demonstrating a likely shared source of these parabens in indoor dust. Cosmetic products are major sources of PrP and BuP, and have been implicated in numerous studies (Azeredo et al., 2023; Wang et al., 2021)<sup>23,24</sup>. Similarly, PC 4 was dominated by Cr and MeP. However, a moderately negative high loading of -0.57 (Figure 4.3 was observed for Mn, suggesting the influence of another source within the same PC. In contrast, PC 5 was primarily dominated by Pb, with a moderately high loading of 0.7, while Cu exhibited a quasi-independent pattern with a loading of 0.64 within the same component, suggesting the contribution of another source. This weaker association is depicted by the larger distance observed in Figure 4.3A and agrees with the correlation matrix result ( $r = 0$ ) in Table 4.3. Likewise, the large distance between EtP and Cd (Figure 4.3A), as well as the significantly negative high loading of Cd (-0.83) in PC 2 (Figure 4.3B and Table 4.4) are all in agreement with the correlation matrix results of -0.6\*\* between EtP and Cd.

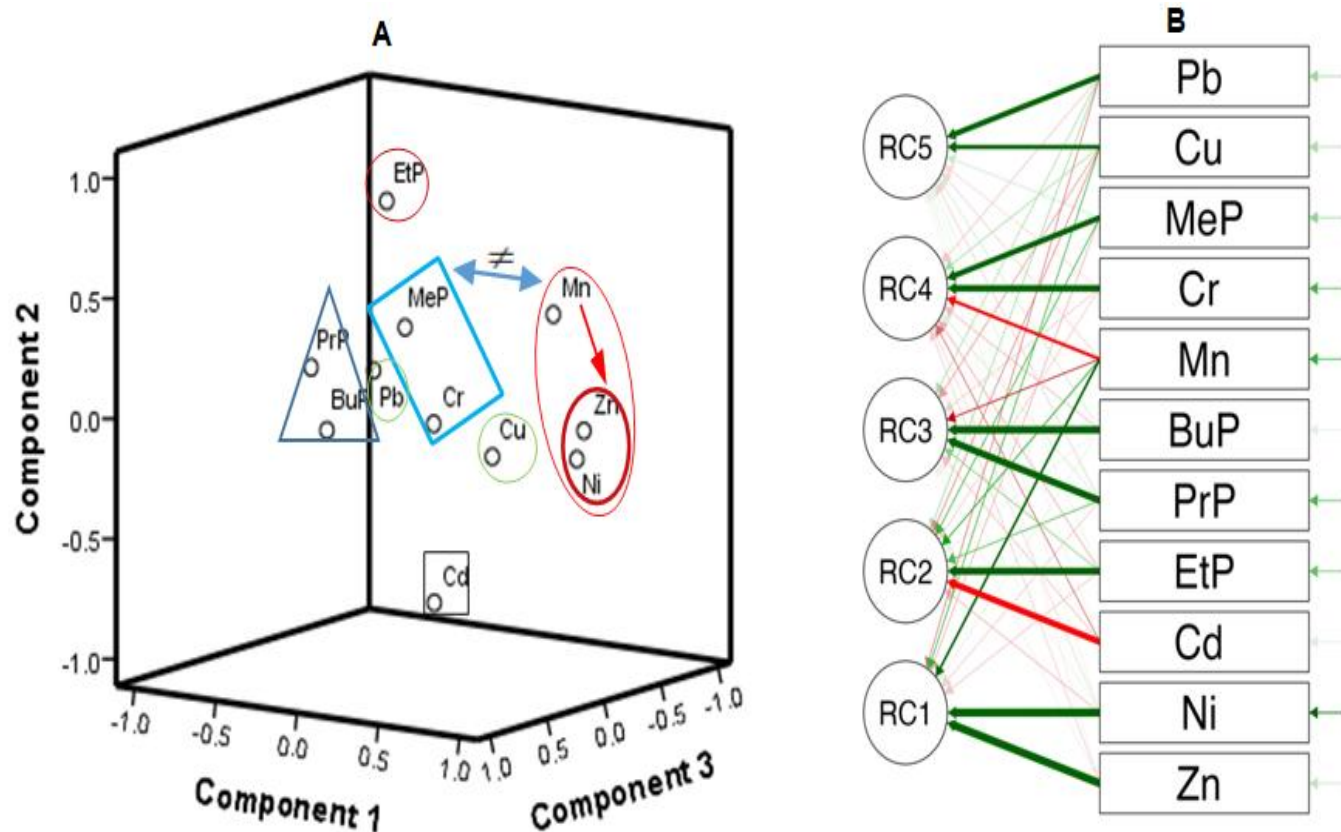
#### **4.4.2 Hierarchical Cluster Analysis (HCA)**

Additionally, hierarchical cluster analysis (HCA) was conducted on the concentrations of the targeted analytes in the indoor dust samples. The resulting dendrogram (Fig. 4.4) illustrates the associations among analytes, as indicated by the distances between clusters. Analytes examined in indoor dust samples were categorised into two primary clusters (A and B), along with a separate cluster C. The PCA result was further corroborated by the degree of association depicted in the

**Table 4.4. Rotated Component Matrix for Analytes in Dust Samples**

|                     | <b>Component</b> |              |             |             |             |
|---------------------|------------------|--------------|-------------|-------------|-------------|
|                     | 1                | 2            | 3           | 4           | 5           |
| <b>Mn</b>           | 0.52             | 0.38         | -0.40       | -0.57       | -0.07       |
| <b>Cu</b>           | 0.31             | -0.20        | -0.16       | 0.14        | 0.64        |
| <b>Zn</b>           | <b>0.97</b>      | -0.004       | -0.03       | -0.08       | -0.03       |
| <b>Cd</b>           | -0.003           | <b>-0.83</b> | -0.10       | -0.24       | 0.04        |
| <b>Cr</b>           | 0.01             | -0.08        | -0.08       | <b>0.84</b> | -0.06       |
| <b>Ni</b>           | <b>0.97</b>      | -0.11        | 0.03        | -0.06       | 0.04        |
| <b>Pb</b>           | -0.21            | 0.15         | 0.13        | -0.09       | <b>0.77</b> |
| <b>MeP</b>          | -0.12            | 0.32         | -0.01       | <b>0.76</b> | 0.08        |
| <b>EtP</b>          | -0.09            | <b>0.88</b>  | 0.19        | -0.13       | 0.04        |
| <b>PrP</b>          | -0.08            | 0.28         | <b>0.88</b> | 0.06        | -0.07       |
| <b>BuP</b>          | 0.04             | 0.04         | <b>0.91</b> | -0.11       | 0.07        |
| <b>Eigenvalues</b>  | 2.79             | 2.10         | 1.489       | 1.397       | 1.021       |
| <b>% Total</b>      | 25.36            | 19.06        | 13.54       | 12.70       | 9.29        |
| <b>variance</b>     |                  |              |             |             |             |
| <b>Cumulative %</b> | 25.36            | 44.42        | 57.96       | 70.66       | 79.95       |

Source: Author's Analysis, 2025

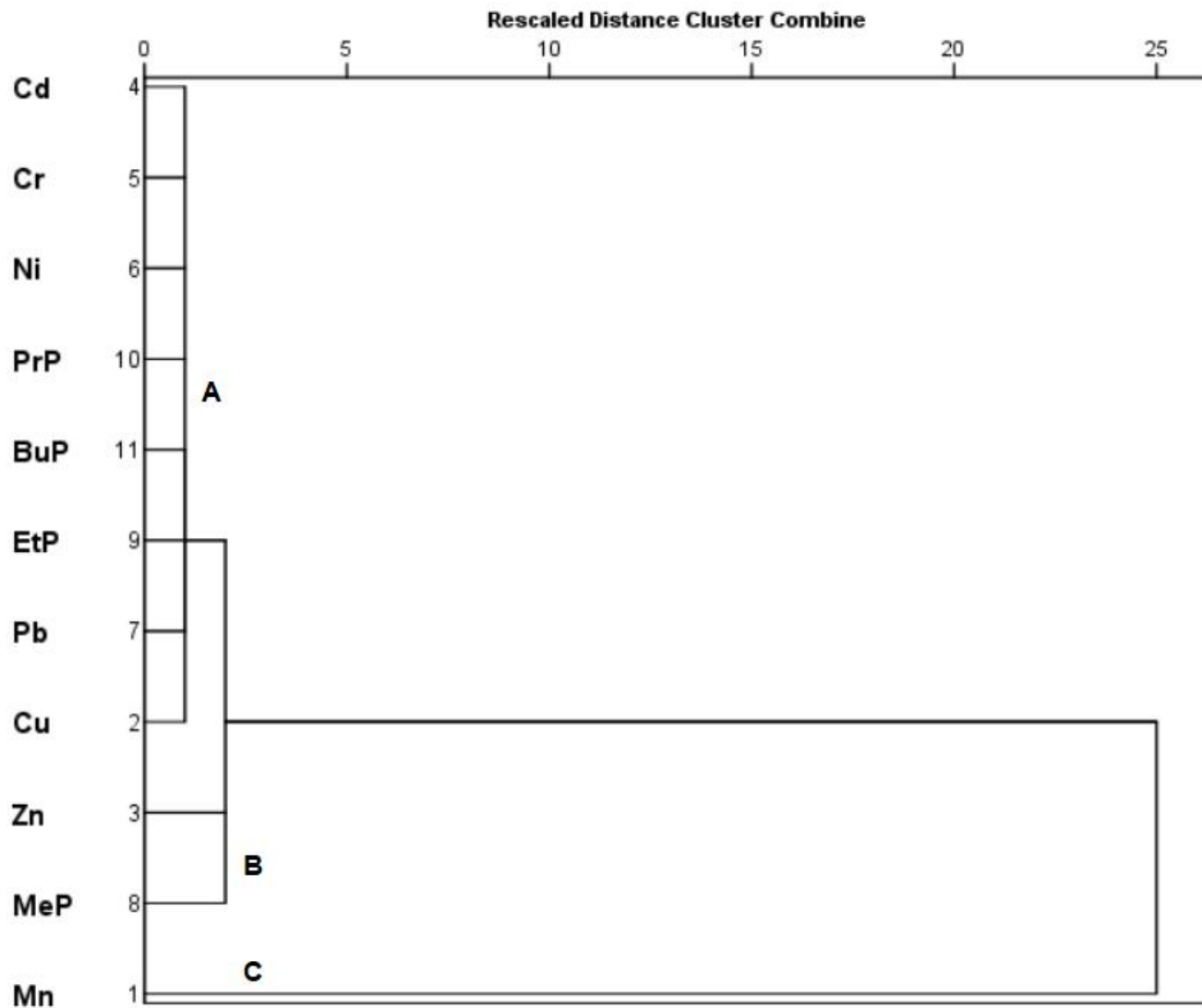


**Figure 4.3.** 3-D Principal Component Analysis (PCA) Loading Plot (A) and Path Diagram (B) for Heavy Metals and Parabens in Indoor Dust Samples.

Source: Author's Analysis, 2025

generated dendrogram<sup>27</sup>. The shorter the distance, the more significant the association.

Notably, clusters A and B comprise Cd, Cr, Ni, PrP, BuP, EtP, Pb, & Cu and Zn & MeP, respectively, while cluster C contains only Mn. Nonetheless, clusters A and B are connected at a fairly elevated level, suggesting a potential shared origin. The significant ( $p < 0.01$ ) associations between PrP & BuP ( $r = 0.7^{**}$ ) and EtP & PrP ( $r = 0.5^{**}$ ) in Table 5 are additionally supported by the closeness and small linkage distances detected in Figure 4.4. Similarly, the relatively large distance observed in Figure 4.4 between Pb and Cu further corroborates the quasi-independent behaviour exhibited by Cu (0.64) in PC 5 and hence the weak association between Pb and Cu. Equally, the stand-alone cluster C (Mn) was joined together with cluster B at a significant ( $p < 0.01$ ) and relatively high level, implying the influence of different anthropogenic sources such as vehicular emissions.



**Figure 4.4.** Dendrogram from Hierarchical Cluster Analysis Illustrating the Relationships among Eleven Analytes in Indoor Dust Samples (the Distances Indicating the Level of Correlation between Each Analyte).

**Source:** Author's Analysis, 2025

## 4.5 Exposure and Human Health Risk Assessment of Selected Heavy metals

### 4.5.1 Average Daily Dose for the Heavy Metals

The exposure to potentially toxic metals in indoor dust by humans was evaluated through the three primary pathways: ingestion, inhalation, and dermal contact. The exposure risk was computed using the Average Daily Dose (ADD)<sup>28</sup>. The study population was categorised into two age groups: children (aged 0–15 years) and adults (aged 15 years and above). The health risk assessment model developed by the United States Environmental Protection Agency (USEPA) was utilised to estimate the average daily dose (ADD,  $\text{mg kg}^{-1} \text{ day}^{-1}$ ) of potentially toxic metals in indoor dust<sup>28,29,30,31</sup>.

Table 4.5 shows the estimated ADD for the studied potentially toxic metals in dust samples for children and adults. Data from this study showed that ADD for children was greater than for adults for the ingestion and dermal pathways. However, the ADD for adults was higher than for children for the inhalation pathway. Overall, this result indicates that children are more exposed because the ingestion and dermal pathways are significant routes of exposure. Similarly, for both age groups,  $\text{ADD}_{\text{inhalation}}$  was greater than  $\text{ADD}_{\text{ingestion}}$  and  $\text{ADD}_{\text{dermal}}$ , while  $\text{ADD}_{\text{ingestion}}$  was greater than  $\text{ADD}_{\text{dermal}}$  for all the studied potentially toxic metals. Generally, the estimated ADD followed a decreasing trend of  $\text{ADD}_{\text{inhalation}} > \text{ADD}_{\text{ingestion}} > \text{ADD}_{\text{dermal}}$ . This indicates that inhalation emerged as the primary exposure pathway, followed by ingestion, while dermal contact was the least significant exposure pathway for both children and adults. This trend contradicts other studies where dermal contact was the primary exposure pathway, followed by ingestion and inhalation<sup>32</sup>.

**Table 4.5: Average Daily Dose for Heavy Metals in Children and Adults**

| Sample | HM | Children              |                       |                        | Adults                |                        |                        |
|--------|----|-----------------------|-----------------------|------------------------|-----------------------|------------------------|------------------------|
|        |    | ADD<br>Ingestion      | ADD<br>Inhalation     | ADD<br>Dermal          | ADD<br>Ingestion      | ADD<br>Inhalation      | ADD<br>Dermal          |
| S1     | Cu | $2.49 \times 10^{-6}$ | $2.11 \times 10^{-4}$ | $4.65 \times 10^{-7}$  | $3.46 \times 10^{-7}$ | $1.51 \times 10^{-3}$  | $3.45 \times 10^{-7}$  |
|        | Mn | $5.26 \times 10^{-5}$ | $4.44 \times 10^{-3}$ | $9.82 \times 10^{-8}$  | $7.31 \times 10^{-6}$ | $3.19 \times 10^{-2}$  | $7.29 \times 10^{-8}$  |
|        | Pb | $2.96 \times 10^{-7}$ | $2.50 \times 10^{-5}$ | $3.31 \times 10^{-9}$  | $4.11 \times 10^{-8}$ | $1.79 \times 10^{-4}$  | $2.46 \times 10^{-9}$  |
|        | Zn | $1.11 \times 10^{-5}$ | $9.34 \times 10^{-4}$ | $4.13 \times 10^{-7}$  | $1.54 \times 10^{-6}$ | $6.70 \times 10^{-3}$  | $3.07 \times 10^{-7}$  |
|        | Cr | $2.96 \times 10^{-7}$ | $2.50 \times 10^{-5}$ | $2.21 \times 10^{-8}$  | $4.11 \times 10^{-8}$ | $1.79 \times 10^{-4}$  | $1.64 \times 10^{-8}$  |
|        | Ni | $2.58 \times 10^{-6}$ | $2.18 \times 10^{-4}$ | $4.82 \times 10^{-9}$  | $3.58 \times 10^{-7}$ | $1.56 \times 10^{-3}$  | $3.58 \times 10^{-9}$  |
|        | Cd | $1.64 \times 10^{-8}$ | $1.39 \times 10^{-6}$ | $3.07 \times 10^{-9}$  | $2.28 \times 10^{-9}$ | $9.96 \times 10^{-6}$  | $2.28 \times 10^{-9}$  |
| S2     | Cu | $9.42 \times 10^{-7}$ | $7.96 \times 10^{-5}$ | $1.76 \times 10^{-7}$  | $1.31 \times 10^{-7}$ | $5.71 \times 10^{-4}$  | $1.31 \times 10^{-7}$  |
|        | Mn | $2.86 \times 10^{-5}$ | $2.42 \times 10^{-3}$ | $5.34 \times 10^{-8}$  | $3.97 \times 10^{-6}$ | $1.73 \times 10^{-2}$  | $3.96 \times 10^{-8}$  |
|        | Pb | $1.97 \times 10^{-7}$ | $1.67 \times 10^{-5}$ | $2.21 \times 10^{-9}$  | $2.74 \times 10^{-8}$ | $1.20 \times 10^{-4}$  | $1.64 \times 10^{-9}$  |
|        | Zn | $4.14 \times 10^{-6}$ | $3.50 \times 10^{-4}$ | $1.55 \times 10^{-7}$  | $5.75 \times 10^{-7}$ | $2.51 \times 10^{-3}$  | $1.15 \times 10^{-7}$  |
|        | Cr | $1.48 \times 10^{-7}$ | $1.25 \times 10^{-5}$ | $1.10 \times 10^{-8}$  | $2.05 \times 10^{-8}$ | $8.97 \times 10^{-5}$  | $8.20 \times 10^{-9}$  |
|        | Ni | $3.12 \times 10^{-7}$ | $2.64 \times 10^{-5}$ | $5.83 \times 10^{-10}$ | $4.34 \times 10^{-8}$ | $1.89 \times 10^{-4}$  | $4.33 \times 10^{-10}$ |
|        | Cd | $6.58 \times 10^{-8}$ | $5.55 \times 10^{-6}$ | $1.23 \times 10^{-8}$  | $9.13 \times 10^{-9}$ | $3.99 \times 10^{-5}$  | $9.11 \times 10^{-9}$  |
| S3     | Cu | $1.53 \times 10^{-6}$ | $1.30 \times 10^{-4}$ | $2.86 \times 10^{-7}$  | $2.13 \times 10^{-7}$ | $9.30 \times 10^{-4}$  | $2.13 \times 10^{-7}$  |
|        | Mn | $2.62 \times 10^{-5}$ | $2.21 \times 10^{-3}$ | $4.89 \times 10^{-8}$  | $3.64 \times 10^{-6}$ | $1.59 \times 10^{-2}$  | $3.63 \times 10^{-8}$  |
|        | Pb | $1.64 \times 10^{-7}$ | $1.39 \times 10^{-5}$ | $1.84 \times 10^{-9}$  | $2.28 \times 10^{-8}$ | $9.96 \times 10^{-5}$  | $1.37 \times 10^{-9}$  |
|        | Zn | $4.36 \times 10^{-6}$ | $3.68 \times 10^{-4}$ | $1.63 \times 10^{-7}$  | $6.05 \times 10^{-7}$ | $2.64 \times 10^{-3}$  | $1.21 \times 10^{-7}$  |
|        | Cr | $7.40 \times 10^{-7}$ | $6.25 \times 10^{-5}$ | $5.52 \times 10^{-8}$  | $1.03 \times 10^{-7}$ | $4.48 \times 10^{-4}$  | $4.10 \times 10^{-8}$  |
|        | Ni | $3.45 \times 10^{-7}$ | $2.92 \times 10^{-5}$ | $6.44 \times 10^{-10}$ | $4.79 \times 10^{-8}$ | $2.09 \times 10^{-4}$  | $4.78 \times 10^{-10}$ |
|        | Cd | -                     | -                     | -                      | -                     | -                      | -                      |
| S4     | Cu | $1.65 \times 10^{-6}$ | $1.39 \times 10^{-4}$ | $3.08 \times 10^{-7}$  | $2.29 \times 10^{-7}$ | $10.00 \times 10^{-4}$ | $2.28 \times 10^{-7}$  |
|        | Mn | $2.50 \times 10^{-5}$ | $2.11 \times 10^{-3}$ | $4.66 \times 10^{-8}$  | $3.47 \times 10^{-6}$ | $1.51 \times 10^{-2}$  | $3.46 \times 10^{-8}$  |
|        | Pb | $1.20 \times 10^{-6}$ | $1.01 \times 10^{-4}$ | $1.34 \times 10^{-8}$  | $1.67 \times 10^{-7}$ | $7.27 \times 10^{-4}$  | $9.98 \times 10^{-9}$  |
|        | Zn | $4.49 \times 10^{-6}$ | $3.79 \times 10^{-4}$ | $1.68 \times 10^{-7}$  | $6.23 \times 10^{-7}$ | $2.72 \times 10^{-3}$  | $1.24 \times 10^{-7}$  |
|        | Cr | $2.79 \times 10^{-7}$ | $2.36 \times 10^{-5}$ | $2.09 \times 10^{-8}$  | $3.88 \times 10^{-8}$ | $1.69 \times 10^{-4}$  | $1.55 \times 10^{-8}$  |
|        | Ni | $5.42 \times 10^{-7}$ | $4.58 \times 10^{-5}$ | $1.01 \times 10^{-9}$  | $7.53 \times 10^{-8}$ | $3.29 \times 10^{-4}$  | $7.52 \times 10^{-10}$ |
|        | Cd | $1.64 \times 10^{-8}$ | $1.39 \times 10^{-6}$ | $3.07 \times 10^{-9}$  | $2.28 \times 10^{-9}$ | $9.96 \times 10^{-6}$  | $2.28 \times 10^{-9}$  |
| S5     | Cu | $3.09 \times 10^{-6}$ | $2.61 \times 10^{-4}$ | $5.77 \times 10^{-7}$  | $4.29 \times 10^{-7}$ | $1.87 \times 10^{-3}$  | $4.28 \times 10^{-7}$  |
|        | Mn | $3.05 \times 10^{-5}$ | $2.57 \times 10^{-3}$ | $5.69 \times 10^{-8}$  | $4.23 \times 10^{-6}$ | $1.85 \times 10^{-2}$  | $4.22 \times 10^{-8}$  |
|        | Pb | $1.53 \times 10^{-6}$ | $1.29 \times 10^{-4}$ | $1.71 \times 10^{-8}$  | $2.12 \times 10^{-7}$ | $9.27 \times 10^{-4}$  | $1.27 \times 10^{-8}$  |
|        | Zn | $5.03 \times 10^{-6}$ | $4.25 \times 10^{-4}$ | $1.88 \times 10^{-7}$  | $6.99 \times 10^{-7}$ | $3.05 \times 10^{-3}$  | $1.39 \times 10^{-7}$  |
|        | Cr | $1.97 \times 10^{-7}$ | $1.67 \times 10^{-5}$ | $1.47 \times 10^{-8}$  | $2.74 \times 10^{-8}$ | $1.20 \times 10^{-4}$  | $1.09 \times 10^{-8}$  |
|        | Ni | $4.11 \times 10^{-7}$ | $3.47 \times 10^{-5}$ | $7.67 \times 10^{-10}$ | $5.71 \times 10^{-8}$ | $2.49 \times 10^{-4}$  | $5.69 \times 10^{-10}$ |
|        | Cd | $1.64 \times 10^{-8}$ | $1.39 \times 10^{-6}$ | $3.07 \times 10^{-9}$  | $2.28 \times 10^{-9}$ | $9.96 \times 10^{-6}$  | $2.28 \times 10^{-9}$  |

Source: Author's Analysis, 2025

**Table 4.5: Average Daily Dose for Heavy Metals in Children and Adults**

| Sample     | HM | Children              |                       |                        | Adults                |                       |                        |
|------------|----|-----------------------|-----------------------|------------------------|-----------------------|-----------------------|------------------------|
|            |    | ADD<br>Ingestion      | ADD<br>Inhalation     | ADD<br>Dermal          | ADD<br>Ingestion      | ADD<br>Inhalation     | ADD<br>Dermal          |
| <b>S6</b>  | Cu | $2.08 \times 10^{-6}$ | $1.76 \times 10^{-4}$ | $3.89 \times 10^{-7}$  | $2.89 \times 10^{-7}$ | $1.26 \times 10^{-3}$ | $2.88 \times 10^{-7}$  |
|            | Mn | $3.07 \times 10^{-5}$ | $2.60 \times 10^{-3}$ | $5.74 \times 10^{-8}$  | $4.27 \times 10^{-6}$ | $1.86 \times 10^{-2}$ | $4.26 \times 10^{-8}$  |
|            | Pb | $1.35 \times 10^{-6}$ | $1.14 \times 10^{-4}$ | $1.51 \times 10^{-8}$  | $1.87 \times 10^{-7}$ | $8.17 \times 10^{-4}$ | $1.12 \times 10^{-8}$  |
|            | Zn | $4.49 \times 10^{-6}$ | $3.79 \times 10^{-4}$ | $1.68 \times 10^{-7}$  | $6.23 \times 10^{-7}$ | $2.72 \times 10^{-3}$ | $1.24 \times 10^{-7}$  |
|            | Cr | $2.79 \times 10^{-7}$ | $2.36 \times 10^{-5}$ | $2.09 \times 10^{-8}$  | $3.88 \times 10^{-8}$ | $1.69 \times 10^{-4}$ | $1.55 \times 10^{-8}$  |
|            | Ni | $3.45 \times 10^{-7}$ | $2.92 \times 10^{-5}$ | $6.44 \times 10^{-10}$ | $4.79 \times 10^{-8}$ | $2.09 \times 10^{-4}$ | $4.78 \times 10^{-10}$ |
|            | Cd | $1.64 \times 10^{-8}$ | $1.39 \times 10^{-6}$ | $3.07 \times 10^{-9}$  | $2.28 \times 10^{-9}$ | $9.96 \times 10^{-6}$ | $2.28 \times 10^{-9}$  |
| <b>S7</b>  | Cu | $1.88 \times 10^{-6}$ | $1.59 \times 10^{-4}$ | $3.52 \times 10^{-7}$  | $2.62 \times 10^{-7}$ | $1.14 \times 10^{-3}$ | $2.61 \times 10^{-7}$  |
|            | Mn | $5.19 \times 10^{-5}$ | $4.38 \times 10^{-3}$ | $9.69 \times 10^{-8}$  | $7.21 \times 10^{-6}$ | $3.15 \times 10^{-2}$ | $7.19 \times 10^{-8}$  |
|            | Pb | $2.37 \times 10^{-6}$ | $2.00 \times 10^{-4}$ | $2.65 \times 10^{-8}$  | $3.29 \times 10^{-7}$ | $1.43 \times 10^{-3}$ | $1.97 \times 10^{-8}$  |
|            | Zn | $4.60 \times 10^{-6}$ | $3.89 \times 10^{-4}$ | $1.72 \times 10^{-7}$  | $6.39 \times 10^{-7}$ | $2.79 \times 10^{-3}$ | $1.28 \times 10^{-7}$  |
|            | Cr | $1.64 \times 10^{-8}$ | $1.39 \times 10^{-6}$ | $1.23 \times 10^{-9}$  | $2.28 \times 10^{-9}$ | $9.96 \times 10^{-6}$ | $9.11 \times 10^{-10}$ |
|            | Ni | $1.48 \times 10^{-7}$ | $1.25 \times 10^{-5}$ | $2.76 \times 10^{-10}$ | $2.05 \times 10^{-8}$ | $8.97 \times 10^{-5}$ | $2.05 \times 10^{-10}$ |
|            | Cd | -                     | -                     | -                      | -                     | -                     | -                      |
| <b>S8</b>  | Cu | $1.42 \times 10^{-6}$ | $1.20 \times 10^{-4}$ | $2.66 \times 10^{-7}$  | $1.98 \times 10^{-7}$ | $8.63 \times 10^{-4}$ | $1.97 \times 10^{-7}$  |
|            | Mn | $3.73 \times 10^{-5}$ | $3.15 \times 10^{-3}$ | $6.96 \times 10^{-8}$  | $5.18 \times 10^{-6}$ | $2.26 \times 10^{-2}$ | $5.16 \times 10^{-8}$  |
|            | Pb | $1.71 \times 10^{-6}$ | $1.44 \times 10^{-4}$ | $1.91 \times 10^{-8}$  | $2.37 \times 10^{-7}$ | $1.04 \times 10^{-3}$ | $1.42 \times 10^{-8}$  |
|            | Zn | $3.57 \times 10^{-6}$ | $3.01 \times 10^{-4}$ | $1.33 \times 10^{-7}$  | $4.95 \times 10^{-7}$ | $2.16 \times 10^{-3}$ | $9.88 \times 10^{-8}$  |
|            | Cr | $1.15 \times 10^{-7}$ | $9.72 \times 10^{-6}$ | $8.59 \times 10^{-9}$  | $1.60 \times 10^{-8}$ | $6.97 \times 10^{-5}$ | $6.38 \times 10^{-9}$  |
|            | Ni | $3.78 \times 10^{-7}$ | $3.19 \times 10^{-5}$ | $7.06 \times 10^{-10}$ | $5.25 \times 10^{-8}$ | $2.29 \times 10^{-4}$ | $5.24 \times 10^{-10}$ |
|            | Cd | -                     | -                     | -                      | -                     | -                     | -                      |
| <b>S9</b>  | Cu | $1.88 \times 10^{-6}$ | $1.59 \times 10^{-4}$ | $3.51 \times 10^{-7}$  | $2.61 \times 10^{-7}$ | $1.14 \times 10^{-3}$ | $2.60 \times 10^{-7}$  |
|            | Mn | $3.70 \times 10^{-5}$ | $3.12 \times 10^{-3}$ | $6.90 \times 10^{-8}$  | $5.14 \times 10^{-6}$ | $2.24 \times 10^{-2}$ | $5.12 \times 10^{-8}$  |
|            | Pb | $1.43 \times 10^{-6}$ | $1.21 \times 10^{-4}$ | $1.60 \times 10^{-8}$  | $1.99 \times 10^{-7}$ | $8.67 \times 10^{-4}$ | $1.19 \times 10^{-8}$  |
|            | Zn | $4.60 \times 10^{-6}$ | $3.89 \times 10^{-4}$ | $1.72 \times 10^{-7}$  | $6.39 \times 10^{-7}$ | $2.79 \times 10^{-3}$ | $1.28 \times 10^{-7}$  |
|            | Cr | $1.97 \times 10^{-7}$ | $1.67 \times 10^{-5}$ | $1.47 \times 10^{-8}$  | $2.74 \times 10^{-8}$ | $1.20 \times 10^{-4}$ | $1.09 \times 10^{-8}$  |
|            | Ni | $3.95 \times 10^{-7}$ | $3.33 \times 10^{-5}$ | $7.36 \times 10^{-10}$ | $5.48 \times 10^{-8}$ | $2.39 \times 10^{-4}$ | $5.47 \times 10^{-10}$ |
|            | Cd | $1.64 \times 10^{-8}$ | $1.39 \times 10^{-6}$ | $3.07 \times 10^{-9}$  | $2.28 \times 10^{-9}$ | $9.96 \times 10^{-6}$ | $2.28 \times 10^{-9}$  |
| <b>S10</b> | Cu | $1.68 \times 10^{-5}$ | $1.42 \times 10^{-3}$ | $3.14 \times 10^{-6}$  | $2.34 \times 10^{-6}$ | $1.02 \times 10^{-2}$ | $2.33 \times 10^{-6}$  |
|            | Mn | $2.65 \times 10^{-5}$ | $2.23 \times 10^{-3}$ | $4.94 \times 10^{-8}$  | $3.68 \times 10^{-6}$ | $1.60 \times 10^{-2}$ | $3.67 \times 10^{-8}$  |
|            | Pb | $1.79 \times 10^{-6}$ | $1.51 \times 10^{-4}$ | $2.01 \times 10^{-8}$  | $2.49 \times 10^{-7}$ | $1.09 \times 10^{-3}$ | $1.49 \times 10^{-8}$  |
|            | Zn | $4.60 \times 10^{-6}$ | $3.89 \times 10^{-4}$ | $1.72 \times 10^{-7}$  | $6.39 \times 10^{-7}$ | $2.79 \times 10^{-3}$ | $1.28 \times 10^{-7}$  |
|            | Cr | $3.62 \times 10^{-7}$ | $3.05 \times 10^{-5}$ | $2.70 \times 10^{-8}$  | $5.02 \times 10^{-8}$ | $2.19 \times 10^{-4}$ | $2.00 \times 10^{-8}$  |
|            | Ni | $1.00 \times 10^{-6}$ | $8.47 \times 10^{-5}$ | $1.87 \times 10^{-9}$  | $1.39 \times 10^{-7}$ | $6.08 \times 10^{-4}$ | $1.39 \times 10^{-9}$  |
|            | Cd | $3.29 \times 10^{-8}$ | $2.78 \times 10^{-6}$ | $6.14 \times 10^{-9}$  | $4.57 \times 10^{-9}$ | $1.99 \times 10^{-5}$ | $4.55 \times 10^{-9}$  |

**Source:** Author's Analysis, 2025



**Table 4.5: Average Daily Dose for Heavy Metals in Children and Adults**

| Sample | HM | Children              |                       |                        | Adults                |                       |                        |
|--------|----|-----------------------|-----------------------|------------------------|-----------------------|-----------------------|------------------------|
|        |    | ADD<br>Ingestion      | ADD<br>Inhalation     | ADD<br>Dermal          | ADD<br>Ingestion      | ADD<br>Inhalation     | ADD<br>Dermal          |
| S11    | Cu | $1.54 \times 10^{-6}$ | $1.30 \times 10^{-4}$ | $2.87 \times 10^{-7}$  | $2.14 \times 10^{-7}$ | $9.33 \times 10^{-4}$ | $2.13 \times 10^{-7}$  |
|        | Mn | $8.60 \times 10^{-6}$ | $7.26 \times 10^{-4}$ | $1.60 \times 10^{-8}$  | $1.19 \times 10^{-6}$ | $5.21 \times 10^{-3}$ | $1.19 \times 10^{-8}$  |
|        | Pb | $1.69 \times 10^{-6}$ | $1.43 \times 10^{-4}$ | $1.90 \times 10^{-8}$  | $2.35 \times 10^{-7}$ | $1.03 \times 10^{-3}$ | $1.41 \times 10^{-8}$  |
|        | Zn | $3.80 \times 10^{-6}$ | $3.21 \times 10^{-4}$ | $1.42 \times 10^{-7}$  | $5.27 \times 10^{-7}$ | $2.30 \times 10^{-3}$ | $1.05 \times 10^{-7}$  |
|        | Cr | $5.92 \times 10^{-7}$ | $5.00 \times 10^{-5}$ | $4.42 \times 10^{-8}$  | $8.22 \times 10^{-8}$ | $3.59 \times 10^{-4}$ | $3.28 \times 10^{-8}$  |
|        | Ni | $2.63 \times 10^{-7}$ | $2.22 \times 10^{-5}$ | $4.91 \times 10^{-10}$ | $3.65 \times 10^{-8}$ | $1.59 \times 10^{-4}$ | $3.64 \times 10^{-10}$ |
|        | Cd | $1.64 \times 10^{-8}$ | $1.39 \times 10^{-6}$ | $3.07 \times 10^{-9}$  | $2.28 \times 10^{-9}$ | $9.96 \times 10^{-6}$ | $2.28 \times 10^{-9}$  |
| S12    | Cu | $2.98 \times 10^{-6}$ | $2.51 \times 10^{-4}$ | $5.55 \times 10^{-7}$  | $4.13 \times 10^{-7}$ | $1.80 \times 10^{-3}$ | $4.12 \times 10^{-7}$  |
|        | Mn | $2.52 \times 10^{-5}$ | $2.13 \times 10^{-3}$ | $4.70 \times 10^{-8}$  | $3.50 \times 10^{-6}$ | $1.53 \times 10^{-2}$ | $3.49 \times 10^{-8}$  |
|        | Pb | $2.14 \times 10^{-6}$ | $1.80 \times 10^{-4}$ | $2.39 \times 10^{-8}$  | $2.97 \times 10^{-7}$ | $1.30 \times 10^{-3}$ | $1.78 \times 10^{-8}$  |
|        | Zn | $4.54 \times 10^{-6}$ | $3.83 \times 10^{-4}$ | $1.69 \times 10^{-7}$  | $6.30 \times 10^{-7}$ | $2.75 \times 10^{-3}$ | $1.26 \times 10^{-7}$  |
|        | Cr | $6.08 \times 10^{-7}$ | $5.14 \times 10^{-5}$ | $4.54 \times 10^{-8}$  | $8.45 \times 10^{-8}$ | $3.69 \times 10^{-4}$ | $3.37 \times 10^{-8}$  |
|        | Ni | $3.45 \times 10^{-7}$ | $2.92 \times 10^{-5}$ | $6.44 \times 10^{-10}$ | $4.79 \times 10^{-8}$ | $2.09 \times 10^{-4}$ | $4.78 \times 10^{-10}$ |
|        | Cd | $1.64 \times 10^{-8}$ | $1.39 \times 10^{-6}$ | $3.07 \times 10^{-9}$  | $2.28 \times 10^{-9}$ | $9.96 \times 10^{-6}$ | $2.28 \times 10^{-9}$  |
| S13    | Cu | $3.11 \times 10^{-6}$ | $2.63 \times 10^{-4}$ | $5.81 \times 10^{-7}$  | $4.32 \times 10^{-7}$ | $1.89 \times 10^{-3}$ | $4.31 \times 10^{-7}$  |
|        | Mn | $3.80 \times 10^{-5}$ | $3.21 \times 10^{-3}$ | $7.10 \times 10^{-8}$  | $5.28 \times 10^{-6}$ | $2.30 \times 10^{-2}$ | $5.27 \times 10^{-8}$  |
|        | Pb | $2.02 \times 10^{-6}$ | $1.71 \times 10^{-4}$ | $2.26 \times 10^{-8}$  | $2.81 \times 10^{-7}$ | $1.23 \times 10^{-3}$ | $1.68 \times 10^{-8}$  |
|        | Zn | $4.47 \times 10^{-6}$ | $3.78 \times 10^{-4}$ | $1.67 \times 10^{-7}$  | $6.21 \times 10^{-7}$ | $2.71 \times 10^{-3}$ | $1.24 \times 10^{-7}$  |
|        | Cr | $2.14 \times 10^{-7}$ | $1.80 \times 10^{-5}$ | $1.60 \times 10^{-8}$  | $2.97 \times 10^{-8}$ | $1.30 \times 10^{-4}$ | $1.18 \times 10^{-8}$  |
|        | Ni | $3.78 \times 10^{-7}$ | $3.19 \times 10^{-5}$ | $7.06 \times 10^{-10}$ | $5.25 \times 10^{-8}$ | $2.29 \times 10^{-4}$ | $5.24 \times 10^{-10}$ |
|        | Cd | $1.64 \times 10^{-8}$ | $1.39 \times 10^{-6}$ | $3.07 \times 10^{-9}$  | $2.28 \times 10^{-9}$ | $9.96 \times 10^{-6}$ | $2.28 \times 10^{-9}$  |
| S14    | Cu | $1.49 \times 10^{-6}$ | $1.26 \times 10^{-4}$ | $2.78 \times 10^{-7}$  | $2.07 \times 10^{-7}$ | $9.03 \times 10^{-4}$ | $2.06 \times 10^{-7}$  |
|        | Mn | $2.79 \times 10^{-5}$ | $2.36 \times 10^{-3}$ | $5.22 \times 10^{-8}$  | $3.88 \times 10^{-6}$ | $1.69 \times 10^{-2}$ | $3.87 \times 10^{-8}$  |
|        | Pb | $2.37 \times 10^{-6}$ | $2.00 \times 10^{-4}$ | $2.65 \times 10^{-8}$  | $3.29 \times 10^{-7}$ | $1.43 \times 10^{-3}$ | $1.97 \times 10^{-8}$  |
|        | Zn | $4.14 \times 10^{-6}$ | $3.50 \times 10^{-4}$ | $1.55 \times 10^{-7}$  | $5.75 \times 10^{-7}$ | $2.51 \times 10^{-3}$ | $1.15 \times 10^{-7}$  |
|        | Cr | $2.96 \times 10^{-7}$ | $2.50 \times 10^{-5}$ | $2.21 \times 10^{-8}$  | $4.11 \times 10^{-8}$ | $1.79 \times 10^{-4}$ | $1.64 \times 10^{-8}$  |
|        | Ni | $4.11 \times 10^{-7}$ | $3.47 \times 10^{-5}$ | $7.67 \times 10^{-10}$ | $5.71 \times 10^{-8}$ | $2.49 \times 10^{-4}$ | $5.69 \times 10^{-10}$ |
|        | Cd | $1.64 \times 10^{-8}$ | $1.39 \times 10^{-6}$ | $3.07 \times 10^{-9}$  | $2.28 \times 10^{-9}$ | $9.96 \times 10^{-6}$ | $2.28 \times 10^{-9}$  |
| S15    | Cu | $1.74 \times 10^{-6}$ | $1.47 \times 10^{-4}$ | $3.24 \times 10^{-7}$  | $2.41 \times 10^{-7}$ | $1.05 \times 10^{-3}$ | $2.41 \times 10^{-7}$  |
|        | Mn | $2.43 \times 10^{-5}$ | $2.05 \times 10^{-3}$ | $4.53 \times 10^{-8}$  | $3.37 \times 10^{-6}$ | $1.47 \times 10^{-2}$ | $3.36 \times 10^{-8}$  |
|        | Pb | $2.47 \times 10^{-6}$ | $2.08 \times 10^{-4}$ | $2.76 \times 10^{-8}$  | $3.42 \times 10^{-7}$ | $1.49 \times 10^{-3}$ | $2.05 \times 10^{-8}$  |
|        | Zn | $4.19 \times 10^{-6}$ | $3.54 \times 10^{-4}$ | $1.56 \times 10^{-7}$  | $5.82 \times 10^{-7}$ | $2.54 \times 10^{-3}$ | $1.16 \times 10^{-7}$  |
|        | Cr | $4.11 \times 10^{-7}$ | $3.47 \times 10^{-5}$ | $3.07 \times 10^{-8}$  | $5.71 \times 10^{-8}$ | $2.49 \times 10^{-4}$ | $2.28 \times 10^{-8}$  |
|        | Ni | $4.11 \times 10^{-7}$ | $3.47 \times 10^{-5}$ | $7.67 \times 10^{-10}$ | $5.71 \times 10^{-8}$ | $2.49 \times 10^{-4}$ | $5.69 \times 10^{-10}$ |
|        | Cd | $1.64 \times 10^{-8}$ | $1.39 \times 10^{-6}$ | $3.07 \times 10^{-9}$  | $2.28 \times 10^{-9}$ | $9.96 \times 10^{-6}$ | $2.28 \times 10^{-9}$  |

Source: Author's Analysis, 2025

**Table 4.5: Average Daily Dose for Heavy Metals in Children and Adults**

| Sample     | HM | Children              |                       |                        | Adults                |                       |                        |
|------------|----|-----------------------|-----------------------|------------------------|-----------------------|-----------------------|------------------------|
|            |    | ADD<br>Ingestion      | ADD<br>Inhalation     | ADD<br>Dermal          | ADD<br>Ingestion      | ADD<br>Inhalation     | ADD<br>Dermal          |
| <b>S16</b> | Cu | $1.91 \times 10^{-6}$ | $1.61 \times 10^{-4}$ | $3.57 \times 10^{-7}$  | $2.66 \times 10^{-7}$ | $1.16 \times 10^{-3}$ | $2.65 \times 10^{-7}$  |
|            | Mn | $1.75 \times 10^{-5}$ | $1.48 \times 10^{-3}$ | $3.27 \times 10^{-8}$  | $2.44 \times 10^{-6}$ | $1.06 \times 10^{-2}$ | $2.43 \times 10^{-8}$  |
|            | Pb | $2.42 \times 10^{-6}$ | $2.04 \times 10^{-4}$ | $2.71 \times 10^{-8}$  | $3.36 \times 10^{-7}$ | $1.46 \times 10^{-3}$ | $2.01 \times 10^{-8}$  |
|            | Zn | $4.52 \times 10^{-6}$ | $3.82 \times 10^{-4}$ | $1.69 \times 10^{-7}$  | $6.28 \times 10^{-7}$ | $2.74 \times 10^{-3}$ | $1.25 \times 10^{-7}$  |
|            | Cr | $1.15 \times 10^{-7}$ | $9.72 \times 10^{-6}$ | $8.59 \times 10^{-9}$  | $1.60 \times 10^{-8}$ | $6.97 \times 10^{-5}$ | $6.38 \times 10^{-9}$  |
|            | Ni | $4.44 \times 10^{-7}$ | $3.75 \times 10^{-5}$ | $8.28 \times 10^{-10}$ | $6.16 \times 10^{-8}$ | $2.69 \times 10^{-4}$ | $6.15 \times 10^{-10}$ |
|            | Cd | $1.64 \times 10^{-8}$ | $1.39 \times 10^{-6}$ | $3.07 \times 10^{-9}$  | $2.28 \times 10^{-9}$ | $9.96 \times 10^{-6}$ | $2.28 \times 10^{-9}$  |
| <b>S17</b> | Cu | $8.49 \times 10^{-7}$ | $7.17 \times 10^{-5}$ | $1.59 \times 10^{-7}$  | $1.18 \times 10^{-7}$ | $5.15 \times 10^{-4}$ | $1.18 \times 10^{-7}$  |
|            | Mn | $2.35 \times 10^{-5}$ | $1.98 \times 10^{-3}$ | $4.38 \times 10^{-8}$  | $3.26 \times 10^{-6}$ | $1.42 \times 10^{-2}$ | $3.25 \times 10^{-8}$  |
|            | Pb | $2.30 \times 10^{-6}$ | $1.94 \times 10^{-4}$ | $2.58 \times 10^{-8}$  | $3.20 \times 10^{-7}$ | $1.39 \times 10^{-3}$ | $1.91 \times 10^{-8}$  |
|            | Zn | $3.58 \times 10^{-6}$ | $3.03 \times 10^{-4}$ | $1.34 \times 10^{-7}$  | $4.98 \times 10^{-7}$ | $2.17 \times 10^{-3}$ | $9.93 \times 10^{-8}$  |
|            | Cr | $1.97 \times 10^{-7}$ | $1.67 \times 10^{-5}$ | $1.47 \times 10^{-8}$  | $2.74 \times 10^{-8}$ | $1.20 \times 10^{-4}$ | $1.09 \times 10^{-8}$  |
|            | Ni | $4.77 \times 10^{-7}$ | $4.03 \times 10^{-5}$ | $8.90 \times 10^{-10}$ | $6.62 \times 10^{-8}$ | $2.89 \times 10^{-4}$ | $6.60 \times 10^{-10}$ |
|            | Cd | $1.64 \times 10^{-8}$ | $1.39 \times 10^{-6}$ | $3.07 \times 10^{-9}$  | $2.28 \times 10^{-9}$ | $9.96 \times 10^{-6}$ | $2.28 \times 10^{-9}$  |
| <b>S18</b> | Cu | $1.33 \times 10^{-6}$ | $1.12 \times 10^{-4}$ | $2.49 \times 10^{-7}$  | $1.85 \times 10^{-7}$ | $8.07 \times 10^{-4}$ | $1.84 \times 10^{-7}$  |
|            | Mn | $2.09 \times 10^{-5}$ | $1.77 \times 10^{-3}$ | $3.91 \times 10^{-8}$  | $2.91 \times 10^{-6}$ | $1.27 \times 10^{-2}$ | $2.90 \times 10^{-8}$  |
|            | Pb | $2.50 \times 10^{-6}$ | $2.11 \times 10^{-4}$ | $2.80 \times 10^{-8}$  | $3.47 \times 10^{-7}$ | $1.51 \times 10^{-3}$ | $2.08 \times 10^{-8}$  |
|            | Zn | $4.01 \times 10^{-6}$ | $3.39 \times 10^{-4}$ | $1.50 \times 10^{-7}$  | $5.57 \times 10^{-7}$ | $2.43 \times 10^{-3}$ | $1.11 \times 10^{-7}$  |
|            | Cr | $1.04 \times 10^{-6}$ | $8.75 \times 10^{-5}$ | $7.73 \times 10^{-8}$  | $1.44 \times 10^{-7}$ | $6.28 \times 10^{-4}$ | $5.74 \times 10^{-8}$  |
|            | Ni | $3.45 \times 10^{-7}$ | $2.92 \times 10^{-5}$ | $6.44 \times 10^{-10}$ | $4.79 \times 10^{-8}$ | $2.09 \times 10^{-4}$ | $4.78 \times 10^{-10}$ |
|            | Cd | $1.64 \times 10^{-8}$ | $1.39 \times 10^{-6}$ | $3.07 \times 10^{-9}$  | $2.28 \times 10^{-9}$ | $9.96 \times 10^{-6}$ | $2.28 \times 10^{-9}$  |
| <b>S19</b> | Cu | $1.66 \times 10^{-6}$ | $1.40 \times 10^{-4}$ | $3.10 \times 10^{-7}$  | $2.31 \times 10^{-7}$ | $1.01 \times 10^{-3}$ | $2.30 \times 10^{-7}$  |
|            | Mn | $1.65 \times 10^{-5}$ | $1.39 \times 10^{-3}$ | $3.08 \times 10^{-8}$  | $2.29 \times 10^{-6}$ | $9.99 \times 10^{-3}$ | $2.28 \times 10^{-8}$  |
|            | Pb | $2.38 \times 10^{-6}$ | $2.01 \times 10^{-4}$ | $2.67 \times 10^{-8}$  | $3.31 \times 10^{-7}$ | $1.44 \times 10^{-3}$ | $1.98 \times 10^{-8}$  |
|            | Zn | $4.04 \times 10^{-6}$ | $3.41 \times 10^{-4}$ | $1.51 \times 10^{-7}$  | $5.62 \times 10^{-7}$ | $2.45 \times 10^{-3}$ | $1.12 \times 10^{-7}$  |
|            | Cr | $2.63 \times 10^{-7}$ | $2.22 \times 10^{-5}$ | $1.96 \times 10^{-8}$  | $3.65 \times 10^{-8}$ | $1.59 \times 10^{-4}$ | $1.46 \times 10^{-8}$  |
|            | Ni | $4.27 \times 10^{-7}$ | $3.61 \times 10^{-5}$ | $7.98 \times 10^{-10}$ | $5.94 \times 10^{-8}$ | $2.59 \times 10^{-4}$ | $5.92 \times 10^{-10}$ |
|            | Cd | $1.64 \times 10^{-8}$ | $1.39 \times 10^{-6}$ | $3.07 \times 10^{-9}$  | $2.28 \times 10^{-9}$ | $9.96 \times 10^{-6}$ | $2.28 \times 10^{-9}$  |
| <b>S20</b> | Cu | $1.83 \times 10^{-6}$ | $1.55 \times 10^{-4}$ | $3.42 \times 10^{-7}$  | $2.54 \times 10^{-7}$ | $1.11 \times 10^{-3}$ | $2.54 \times 10^{-7}$  |
|            | Mn | $1.48 \times 10^{-5}$ | $1.25 \times 10^{-3}$ | $2.77 \times 10^{-8}$  | $2.06 \times 10^{-6}$ | $9.00 \times 10^{-3}$ | $2.06 \times 10^{-8}$  |
|            | Pb | $2.43 \times 10^{-6}$ | $2.05 \times 10^{-4}$ | $2.72 \times 10^{-8}$  | $3.38 \times 10^{-7}$ | $1.47 \times 10^{-3}$ | $2.02 \times 10^{-8}$  |
|            | Zn | $4.57 \times 10^{-6}$ | $3.86 \times 10^{-4}$ | $1.71 \times 10^{-7}$  | $6.35 \times 10^{-7}$ | $2.77 \times 10^{-3}$ | $1.27 \times 10^{-7}$  |
|            | Cr | $2.47 \times 10^{-7}$ | $2.08 \times 10^{-5}$ | $1.84 \times 10^{-8}$  | $3.42 \times 10^{-8}$ | $1.49 \times 10^{-4}$ | $1.37 \times 10^{-8}$  |
|            | Ni | $4.27 \times 10^{-7}$ | $3.61 \times 10^{-5}$ | $7.98 \times 10^{-10}$ | $5.94 \times 10^{-8}$ | $2.59 \times 10^{-4}$ | $5.92 \times 10^{-10}$ |
|            | Cd | -                     | -                     | -                      | -                     | -                     | -                      |

Source: Author's Analysis, 2025

In terms of potentially toxic metals in indoor dust, Mn had the highest estimated ADD, while Cd had the lowest values for both children and adults. Also, the trend followed the decreasing order for both children and adults: Mn > Cu > Zn > Ni > Pb > Cr > Cd. This pattern is in contrast to Cr > Ni > Pb > Al > As > Zn > Mn > Cu reported by Famuyiwa and Entwistle<sup>33</sup>.

#### **4.5.2 Non-Carcinogenic Risk Assessment for the Heavy Metals**

Equally, Table 4.6 summarised the assessment of Hazard Quotient (HQ) and Hazard Index (HI) for Potentially Toxic Metals in Indoor Dust. All the calculated HQ values for ingestion, inhalation and dermal contact for the studied potentially toxic metals in this study were less than 1, except for HQ and HI values for Mn. Although data from this study showed that there was a non-carcinogenic health risk due to Mn via the inhalation pathway, this result indicates that the ingestion and dermal contact exposure pathways are not significant exposure routes in this study. The HQ values obtained for ingestion, inhalation and dermal contact for Cu, Zn, Cr and Ni are in line with those reported by Kenechukwu et al<sup>34</sup>. The HI results calculated for children and adults for the selected potentially toxic metals, across all sampled sites, via ingestion, inhalation and dermal contact exposure pathways were less than 1 except for manganese which is  $8.88 \times 10^1$  for children and  $6.38 \times 10^2$  for adults, while the HI obtained for adults is greater compared to that obtained for children. This indicates that children and, in particular, adults, over an extended period, may accumulate manganese in their body system due to exposure to dust via inhalation. The source of manganese could be a result of vehicle emissions, industrial activities such as mining, welding, cleaning products, and construction materials such as tiles. When inhaled, manganese can cause gradual lung inflammation and respiratory issues such as coughing, bronchitis, pneumonitis, and reduced lung function<sup>35</sup>.

**Table 4.6: Hazard Quotients (HQing, HQinh, HQderm) and Hazard Indices (HIing, HIinh, HIderm) for Heavy Metals Exposure in Children and Adults**

| Sample | HM | Children              |                                      |                       |                                      | Adult                 |                                      |                       |                                      |
|--------|----|-----------------------|--------------------------------------|-----------------------|--------------------------------------|-----------------------|--------------------------------------|-----------------------|--------------------------------------|
|        |    | HQing                 | HQinh                                | HQderm                | HI children                          | HQing                 | HQinh                                | HQderm                | HI Adult                             |
| S1     | Cu | $6.74 \times 10^{-5}$ | $5.69 \times 10^{-3}$                | $1.26 \times 10^{-5}$ | $5.77 \times 10^{-3}$                | $9.36 \times 10^{-6}$ | $4.08 \times 10^{-2}$                | $9.34 \times 10^{-6}$ | $4.09 \times 10^{-2}$                |
|        | Mn | $2.19 \times 10^{-3}$ | <b><math>8.88 \times 10^1</math></b> | $2.13 \times 10^{-6}$ | <b><math>8.88 \times 10^1</math></b> | $3.04 \times 10^{-4}$ | <b><math>6.38 \times 10^2</math></b> | $1.58 \times 10^{-6}$ | <b><math>6.38 \times 10^2</math></b> |
|        | Pb | $8.45 \times 10^{-5}$ | $7.14 \times 10^{-3}$                | $6.31 \times 10^{-5}$ | $7.29 \times 10^{-3}$                | $1.17 \times 10^{-5}$ | $5.12 \times 10^{-2}$                | $4.68 \times 10^{-5}$ | $5.13 \times 10^{-2}$                |
|        | Zn | $3.69 \times 10^{-5}$ | $3.11 \times 10^{-2}$                | $6.88 \times 10^{-6}$ | $3.12 \times 10^{-2}$                | $5.12 \times 10^{-6}$ | $2.23 \times 10^{-1}$                | $5.11 \times 10^{-6}$ | $2.24 \times 10^{-1}$                |
|        | Cr | $9.86 \times 10^{-5}$ | $8.33 \times 10^{-3}$                | $3.68 \times 10^{-4}$ | $8.80 \times 10^{-3}$                | $1.37 \times 10^{-5}$ | $5.98 \times 10^{-2}$                | $2.73 \times 10^{-4}$ | $6.01 \times 10^{-2}$                |
|        | Ni | $1.29 \times 10^{-4}$ | $1.06 \times 10^{-2}$                | $8.92 \times 10^{-7}$ | $1.07 \times 10^{-2}$                | $1.79 \times 10^{-5}$ | $7.59 \times 10^{-2}$                | $6.62 \times 10^{-7}$ | $7.59 \times 10^{-2}$                |
|        | Cd | $1.64 \times 10^{-5}$ | $1.39 \times 10^{-1}$                | $3.07 \times 10^{-4}$ | $1.39 \times 10^{-1}$                | $2.28 \times 10^{-6}$ | $9.96 \times 10^{-1}$                | $2.28 \times 10^{-4}$ | $9.96 \times 10^{-1}$                |
| S2     | Cu | $2.55 \times 10^{-5}$ | $2.15 \times 10^{-3}$                | $4.75 \times 10^{-6}$ | $2.18 \times 10^{-3}$                | $3.54 \times 10^{-6}$ | $1.54 \times 10^{-2}$                | $3.53 \times 10^{-6}$ | $1.54 \times 10^{-2}$                |
|        | Mn | $1.19 \times 10^{-3}$ | <b><math>4.83 \times 10^1</math></b> | $1.16 \times 10^{-6}$ | <b><math>4.83 \times 10^1</math></b> | $1.66 \times 10^{-4}$ | <b><math>3.47 \times 10^2</math></b> | $8.61 \times 10^{-7}$ | <b><math>3.47 \times 10^2</math></b> |
|        | Pb | $5.64 \times 10^{-5}$ | $4.76 \times 10^{-3}$                | $4.21 \times 10^{-5}$ | $4.86 \times 10^{-3}$                | $7.83 \times 10^{-6}$ | $3.42 \times 10^{-2}$                | $3.12 \times 10^{-5}$ | $3.42 \times 10^{-2}$                |
|        | Zn | $1.38 \times 10^{-5}$ | $1.17 \times 10^{-2}$                | $2.58 \times 10^{-6}$ | $1.17 \times 10^{-2}$                | $1.92 \times 10^{-6}$ | $8.37 \times 10^{-2}$                | $1.91 \times 10^{-6}$ | $8.37 \times 10^{-2}$                |
|        | Cr | $4.93 \times 10^{-5}$ | $4.16 \times 10^{-3}$                | $3.98 \times 10^{-7}$ | $4.21 \times 10^{-3}$                | $6.85 \times 10^{-6}$ | $2.99 \times 10^{-2}$                | $1.37 \times 10^{-4}$ | $3.00 \times 10^{-2}$                |
|        | Ni | $1.56 \times 10^{-5}$ | $1.28 \times 10^{-3}$                | $1.08 \times 10^{-7}$ | $1.30 \times 10^{-3}$                | $2.17 \times 10^{-6}$ | $9.19 \times 10^{-3}$                | $8.01 \times 10^{-8}$ | $9.19 \times 10^{-3}$                |
|        | Cd | $6.58 \times 10^{-5}$ | $5.55 \times 10^{-1}$                | $1.23 \times 10^{-3}$ | $5.57 \times 10^{-1}$                | $9.13 \times 10^{-6}$ | <b><math>3.99 \times 10^0</math></b> | $9.11 \times 10^{-4}$ | <b><math>3.99 \times 10^0</math></b> |
| S3     | Cu | $4.15 \times 10^{-5}$ | $3.50 \times 10^{-3}$                | $7.74 \times 10^{-6}$ | $3.55 \times 10^{-3}$                | $5.76 \times 10^{-6}$ | $2.51 \times 10^{-2}$                | $5.74 \times 10^{-6}$ | $2.51 \times 10^{-2}$                |
|        | Mn | $1.09 \times 10^{-3}$ | <b><math>4.42 \times 10^1</math></b> | $1.06 \times 10^{-6}$ | <b><math>4.42 \times 10^1</math></b> | $1.52 \times 10^{-4}$ | <b><math>3.17 \times 10^2</math></b> | $7.89 \times 10^{-7}$ | <b><math>3.17 \times 10^2</math></b> |
|        | Pb | $4.70 \times 10^{-5}$ | $3.97 \times 10^{-3}$                | $3.51 \times 10^{-5}$ | $4.05 \times 10^{-3}$                | $6.52 \times 10^{-6}$ | $2.85 \times 10^{-2}$                | $2.60 \times 10^{-5}$ | $2.85 \times 10^{-2}$                |
|        | Zn | $1.45 \times 10^{-5}$ | $1.23 \times 10^{-2}$                | $2.71 \times 10^{-6}$ | $1.23 \times 10^{-2}$                | $2.02 \times 10^{-6}$ | $8.80 \times 10^{-2}$                | $2.01 \times 10^{-6}$ | $8.80 \times 10^{-2}$                |
|        | Cr | $2.47 \times 10^{-4}$ | $2.08 \times 10^{-2}$                | $5.64 \times 10^{-7}$ | $2.11 \times 10^{-2}$                | $3.42 \times 10^{-5}$ | $1.49 \times 10^{-1}$                | $6.83 \times 10^{-4}$ | $1.50 \times 10^{-1}$                |
|        | Ni | $1.73 \times 10^{-5}$ | $1.42 \times 10^{-3}$                | $1.19 \times 10^{-7}$ | $1.43 \times 10^{-3}$                | $2.40 \times 10^{-6}$ | $1.02 \times 10^{-2}$                | $8.86 \times 10^{-8}$ | $1.02 \times 10^{-2}$                |
|        | Cd | -                     | -                                    | -                     | -                                    | -                     | -                                    | -                     | -                                    |
| S4     | Cu | $4.46 \times 10^{-5}$ | $3.76 \times 10^{-3}$                | $8.32 \times 10^{-6}$ | $3.82 \times 10^{-3}$                | $6.19 \times 10^{-6}$ | $2.70 \times 10^{-2}$                | $6.18 \times 10^{-6}$ | $2.70 \times 10^{-2}$                |
|        | Mn | $1.04 \times 10^{-3}$ | <b><math>4.22 \times 10^1</math></b> | $1.01 \times 10^{-6}$ | <b><math>4.22 \times 10^1</math></b> | $1.45 \times 10^{-4}$ | <b><math>3.03 \times 10^2</math></b> | $7.53 \times 10^{-7}$ | <b><math>3.03 \times 10^2</math></b> |
|        | Pb | $3.43 \times 10^{-4}$ | $2.90 \times 10^{-2}$                | $2.56 \times 10^{-4}$ | $2.96 \times 10^{-2}$                | $4.76 \times 10^{-5}$ | $2.08 \times 10^{-1}$                | $1.90 \times 10^{-4}$ | $2.08 \times 10^{-1}$                |
|        | Zn | $1.50 \times 10^{-5}$ | $1.26 \times 10^{-2}$                | $2.79 \times 10^{-6}$ | $1.26 \times 10^{-2}$                | $2.08 \times 10^{-6}$ | $9.07 \times 10^{-2}$                | $2.07 \times 10^{-6}$ | $9.07 \times 10^{-2}$                |
|        | Cr | $9.32 \times 10^{-5}$ | $7.87 \times 10^{-3}$                | $3.32 \times 10^{-8}$ | $7.96 \times 10^{-3}$                | $1.29 \times 10^{-5}$ | $5.65 \times 10^{-2}$                | $2.58 \times 10^{-4}$ | $5.67 \times 10^{-2}$                |
|        | Ni | $2.71 \times 10^{-5}$ | $2.22 \times 10^{-3}$                | $1.88 \times 10^{-7}$ | $2.25 \times 10^{-3}$                | $3.77 \times 10^{-6}$ | $1.60 \times 10^{-2}$                | $1.39 \times 10^{-7}$ | $1.60 \times 10^{-2}$                |
|        | Cd | $1.64 \times 10^{-5}$ | $1.39 \times 10^{-1}$                | $3.07 \times 10^{-4}$ | $1.39 \times 10^{-1}$                | $2.28 \times 10^{-6}$ | $9.96 \times 10^{-1}$                | $2.28 \times 10^{-4}$ | $9.96 \times 10^{-1}$                |

Source: Author's Analysis, 2025

**Table 4.6: Hazard Quotients (HQing, HQinh, HQderm) and Hazard Indices (HIing, HIinh, HIderm) for Heavy Metals Exposure in Children and Adults Cont'd**

| Sample | HM | Children              |                                      |                       |                                      | Adult                 |                                      |                       |                                      |
|--------|----|-----------------------|--------------------------------------|-----------------------|--------------------------------------|-----------------------|--------------------------------------|-----------------------|--------------------------------------|
|        |    | HQing                 | HQinh                                | HQderm                | HI children                          | HQing                 | HQinh                                | HQderm                | HI Adult                             |
| S5     | Cu | $8.35 \times 10^{-5}$ | $7.05 \times 10^{-3}$                | $1.56 \times 10^{-5}$ | $7.15 \times 10^{-3}$                | $1.16 \times 10^{-5}$ | $5.06 \times 10^{-2}$                | $1.16 \times 10^{-5}$ | $5.06 \times 10^{-2}$                |
|        | Mn | $1.27 \times 10^{-3}$ | <b><math>5.14 \times 10^1</math></b> | $1.24 \times 10^{-6}$ | <b><math>5.14 \times 10^1</math></b> | $1.76 \times 10^{-4}$ | <b><math>3.69 \times 10^2</math></b> | $9.17 \times 10^{-7}$ | <b><math>3.69 \times 10^2</math></b> |
|        | Pb | $4.37 \times 10^{-4}$ | $3.69 \times 10^{-2}$                | $3.26 \times 10^{-4}$ | $3.76 \times 10^{-2}$                | $6.07 \times 10^{-5}$ | $2.65 \times 10^{-1}$                | $2.42 \times 10^{-4}$ | $2.65 \times 10^{-1}$                |
|        | Zn | $1.68 \times 10^{-5}$ | $1.42 \times 10^{-2}$                | $3.13 \times 10^{-6}$ | $1.42 \times 10^{-2}$                | $2.33 \times 10^{-6}$ | $1.02 \times 10^{-1}$                | $2.32 \times 10^{-6}$ | $1.02 \times 10^{-1}$                |
|        | Cr | $6.58 \times 10^{-5}$ | $5.55 \times 10^{-3}$                | $2.32 \times 10^{-7}$ | $5.62 \times 10^{-3}$                | $9.13 \times 10^{-6}$ | $3.99 \times 10^{-2}$                | $1.82 \times 10^{-4}$ | $4.00 \times 10^{-2}$                |
|        | Ni | $2.05 \times 10^{-5}$ | $1.68 \times 10^{-3}$                | $1.42 \times 10^{-7}$ | $1.71 \times 10^{-3}$                | $2.85 \times 10^{-6}$ | $1.21 \times 10^{-2}$                | $1.05 \times 10^{-7}$ | $1.21 \times 10^{-2}$                |
|        | Cd | $1.64 \times 10^{-5}$ | $1.39 \times 10^{-1}$                | $3.07 \times 10^{-4}$ | $1.39 \times 10^{-1}$                | $2.28 \times 10^{-6}$ | $9.96 \times 10^{-1}$                | $2.28 \times 10^{-4}$ | $9.96 \times 10^{-1}$                |
| S6     | Cu | $5.63 \times 10^{-5}$ | $4.75 \times 10^{-3}$                | $1.05 \times 10^{-5}$ | $4.82 \times 10^{-3}$                | $7.82 \times 10^{-6}$ | $3.41 \times 10^{-2}$                | $7.80 \times 10^{-6}$ | $3.41 \times 10^{-2}$                |
|        | Mn | $1.28 \times 10^{-3}$ | <b><math>5.19 \times 10^1</math></b> | $1.25 \times 10^{-6}$ | <b><math>5.19 \times 10^1</math></b> | $1.78 \times 10^{-4}$ | <b><math>3.73 \times 10^2</math></b> | $9.26 \times 10^{-7}$ | <b><math>3.73 \times 10^2</math></b> |
|        | Pb | $3.85 \times 10^{-4}$ | $3.25 \times 10^{-2}$                | $2.88 \times 10^{-4}$ | $3.32 \times 10^{-2}$                | $5.35 \times 10^{-5}$ | $2.33 \times 10^{-1}$                | $2.13 \times 10^{-4}$ | $2.34 \times 10^{-1}$                |
|        | Zn | $1.50 \times 10^{-5}$ | $1.26 \times 10^{-2}$                | $2.79 \times 10^{-6}$ | $1.26 \times 10^{-2}$                | $2.08 \times 10^{-6}$ | $9.07 \times 10^{-2}$                | $2.07 \times 10^{-6}$ | $9.07 \times 10^{-2}$                |
|        | Cr | $9.32 \times 10^{-5}$ | $7.87 \times 10^{-3}$                | $3.98 \times 10^{-7}$ | $7.96 \times 10^{-3}$                | $1.29 \times 10^{-5}$ | $5.65 \times 10^{-2}$                | $2.58 \times 10^{-4}$ | $5.67 \times 10^{-2}$                |
|        | Ni | $1.73 \times 10^{-5}$ | $1.42 \times 10^{-3}$                | $1.19 \times 10^{-7}$ | $1.43 \times 10^{-3}$                | $2.40 \times 10^{-6}$ | $1.02 \times 10^{-2}$                | $8.86 \times 10^{-8}$ | $1.02 \times 10^{-2}$                |
|        | Cd | $1.64 \times 10^{-5}$ | $1.39 \times 10^{-1}$                | $3.07 \times 10^{-4}$ | $1.39 \times 10^{-1}$                | $2.28 \times 10^{-6}$ | $9.96 \times 10^{-1}$                | $2.28 \times 10^{-4}$ | $9.96 \times 10^{-1}$                |
| S7     | Cu | $5.09 \times 10^{-5}$ | $4.30 \times 10^{-3}$                | $9.51 \times 10^{-6}$ | $4.36 \times 10^{-3}$                | $7.08 \times 10^{-6}$ | $3.09 \times 10^{-2}$                | $7.06 \times 10^{-6}$ | $3.09 \times 10^{-2}$                |
|        | Mn | $2.16 \times 10^{-3}$ | <b><math>8.76 \times 10^1</math></b> | $2.11 \times 10^{-6}$ | <b><math>8.76 \times 10^1</math></b> | $3.00 \times 10^{-4}$ | <b><math>6.29 \times 10^2</math></b> | $1.56 \times 10^{-6}$ | <b><math>6.29 \times 10^2</math></b> |
|        | Pb | $6.76 \times 10^{-4}$ | $5.71 \times 10^{-2}$                | $5.05 \times 10^{-4}$ | $5.83 \times 10^{-2}$                | $9.39 \times 10^{-5}$ | $4.10 \times 10^{-1}$                | $3.75 \times 10^{-4}$ | $4.10 \times 10^{-1}$                |
|        | Zn | $1.53 \times 10^{-5}$ | $1.30 \times 10^{-2}$                | $2.86 \times 10^{-6}$ | $1.30 \times 10^{-2}$                | $2.13 \times 10^{-6}$ | $9.30 \times 10^{-2}$                | $2.13 \times 10^{-6}$ | $9.30 \times 10^{-2}$                |
|        | Cr | $5.48 \times 10^{-6}$ | $4.63 \times 10^{-4}$                | $7.30 \times 10^{-7}$ | $4.69 \times 10^{-4}$                | $7.61 \times 10^{-7}$ | $3.32 \times 10^{-3}$                | $1.52 \times 10^{-5}$ | $3.34 \times 10^{-3}$                |
|        | Ni | $7.40 \times 10^{-6}$ | $6.06 \times 10^{-4}$                | $5.11 \times 10^{-8}$ | $6.14 \times 10^{-4}$                | $1.03 \times 10^{-6}$ | $4.35 \times 10^{-3}$                | $3.80 \times 10^{-8}$ | $4.35 \times 10^{-3}$                |
|        | Cd | -                     | -                                    | -                     | -                                    | -                     | -                                    | -                     | -                                    |
| S8     | Cu | $3.85 \times 10^{-5}$ | $3.25 \times 10^{-3}$                | $7.19 \times 10^{-6}$ | $3.30 \times 10^{-3}$                | $5.35 \times 10^{-6}$ | $2.33 \times 10^{-2}$                | $5.33 \times 10^{-6}$ | $2.33 \times 10^{-2}$                |
|        | Mn | $1.55 \times 10^{-3}$ | <b><math>6.25 \times 10^1</math></b> | $1.51 \times 10^{-6}$ | <b><math>6.29 \times 10^1</math></b> | $2.16 \times 10^{-4}$ | <b><math>4.52 \times 10^2</math></b> | $1.12 \times 10^{-6}$ | <b><math>4.52 \times 10^2</math></b> |
|        | Pb | $4.88 \times 10^{-4}$ | $4.12 \times 10^{-2}$                | $3.65 \times 10^{-4}$ | $4.21 \times 10^{-2}$                | $6.78 \times 10^{-5}$ | $2.96 \times 10^{-1}$                | $2.71 \times 10^{-4}$ | $2.96 \times 10^{-1}$                |
|        | Zn | $1.19 \times 10^{-5}$ | $1.00 \times 10^{-2}$                | $2.22 \times 10^{-6}$ | $1.01 \times 10^{-2}$                | $1.65 \times 10^{-6}$ | $7.21 \times 10^{-2}$                | $1.65 \times 10^{-6}$ | $7.21 \times 10^{-2}$                |
|        | Cr | $3.84 \times 10^{-5}$ | $3.24 \times 10^{-3}$                | $1.19 \times 10^{-6}$ | $3.28 \times 10^{-3}$                | $5.33 \times 10^{-6}$ | $2.32 \times 10^{-2}$                | $1.06 \times 10^{-4}$ | $2.34 \times 10^{-2}$                |
|        | Ni | $1.89 \times 10^{-5}$ | $1.55 \times 10^{-3}$                | $1.31 \times 10^{-7}$ | $1.57 \times 10^{-3}$                | $2.63 \times 10^{-6}$ | $1.11 \times 10^{-2}$                | $9.70 \times 10^{-8}$ | $1.11 \times 10^{-2}$                |
|        | Cd | -                     | -                                    | -                     | -                                    | -                     | -                                    | -                     | -                                    |

Source: Author's Analysis, 2025

**Table 4.6: Hazard Quotients (HQing, HQinh, HQderm) and Hazard Indices (HIing, HIinh, HIderm) for Heavy Metals Exposure in Children and Adults Cont'd**

| Sample | HM | Children              |                                      |                       |                                      | Adult                 |                                      |                       |                                      |
|--------|----|-----------------------|--------------------------------------|-----------------------|--------------------------------------|-----------------------|--------------------------------------|-----------------------|--------------------------------------|
|        |    | HQing                 | HQinh                                | HQderm                | HI children                          | HQing                 | HQinh                                | HQderm                | HI Adult                             |
| S9     | Cu | $5.08 \times 10^{-5}$ | $4.29 \times 10^{-3}$                | $9.48 \times 10^{-6}$ | $4.35 \times 10^{-3}$                | $7.06 \times 10^{-6}$ | $3.08 \times 10^{-2}$                | $7.04 \times 10^{-6}$ | $3.08 \times 10^{-2}$                |
|        | Mn | $1.54 \times 10^{-3}$ | <b><math>6.25 \times 10^1</math></b> | $1.50 \times 10^{-6}$ | <b><math>6.25 \times 10^1</math></b> | $2.14 \times 10^{-4}$ | <b><math>4.48 \times 10^2</math></b> | $1.11 \times 10^{-6}$ | <b><math>4.48 \times 10^2</math></b> |
|        | Pb | $4.09 \times 10^{-4}$ | $3.45 \times 10^{-2}$                | $3.05 \times 10^{-4}$ | $3.52 \times 10^{-2}$                | $5.68 \times 10^{-5}$ | $2.48 \times 10^{-1}$                | $2.26 \times 10^{-4}$ | $2.48 \times 10^{-1}$                |
|        | Zn | $1.53 \times 10^{-5}$ | $1.30 \times 10^{-2}$                | $2.86 \times 10^{-6}$ | $1.30 \times 10^{-2}$                | $2.13 \times 10^{-6}$ | $9.30 \times 10^{-2}$                | $2.13 \times 10^{-6}$ | $9.30 \times 10^{-2}$                |
|        | Cr | $6.58 \times 10^{-5}$ | $5.55 \times 10^{-3}$                | $1.23 \times 10^{-6}$ | $5.62 \times 10^{-3}$                | $9.13 \times 10^{-6}$ | $3.99 \times 10^{-2}$                | $1.82 \times 10^{-4}$ | $4.00 \times 10^{-2}$                |
|        | Ni | $1.97 \times 10^{-5}$ | $1.62 \times 10^{-3}$                | $1.36 \times 10^{-7}$ | $1.64 \times 10^{-3}$                | $2.74 \times 10^{-6}$ | $1.16 \times 10^{-2}$                | $1.01 \times 10^{-7}$ | $1.16 \times 10^{-2}$                |
| S10    | Cd | $1.64 \times 10^{-5}$ | $1.39 \times 10^{-1}$                | $3.07 \times 10^{-4}$ | $1.39 \times 10^{-1}$                | $2.28 \times 10^{-6}$ | $9.96 \times 10^{-1}$                | $2.28 \times 10^{-4}$ | $9.96 \times 10^{-1}$                |
|        | Cu | $4.55 \times 10^{-4}$ | $3.84 \times 10^{-2}$                | $8.49 \times 10^{-5}$ | $3.89 \times 10^{-2}$                | $6.31 \times 10^{-5}$ | $2.76 \times 10^{-1}$                | $6.30 \times 10^{-5}$ | $2.76 \times 10^{-1}$                |
|        | Mn | $1.10 \times 10^{-3}$ | <b><math>4.47 \times 10^1</math></b> | $1.07 \times 10^{-6}$ | <b><math>4.47 \times 10^1</math></b> | $1.53 \times 10^{-4}$ | <b><math>3.21 \times 10^2</math></b> | $7.97 \times 10^{-7}$ | <b><math>3.21 \times 10^2</math></b> |
|        | Pb | $5.12 \times 10^{-4}$ | $4.32 \times 10^{-2}$                | $3.82 \times 10^{-4}$ | $4.41 \times 10^{-2}$                | $7.11 \times 10^{-5}$ | $3.10 \times 10^{-1}$                | $2.84 \times 10^{-4}$ | $3.11 \times 10^{-1}$                |
|        | Zn | $1.53 \times 10^{-5}$ | $1.30 \times 10^{-2}$                | $2.86 \times 10^{-6}$ | $1.30 \times 10^{-2}$                | $2.13 \times 10^{-6}$ | $9.30 \times 10^{-2}$                | $2.13 \times 10^{-6}$ | $9.30 \times 10^{-2}$                |
|        | Cr | $1.21 \times 10^{-4}$ | $1.02 \times 10^{-2}$                | $4.31 \times 10^{-7}$ | $1.03 \times 10^{-2}$                | $1.67 \times 10^{-5}$ | $7.31 \times 10^{-2}$                | $3.34 \times 10^{-4}$ | $7.34 \times 10^{-2}$                |
| S11    | Ni | $5.01 \times 10^{-5}$ | $4.11 \times 10^{-3}$                | $3.47 \times 10^{-7}$ | $4.16 \times 10^{-3}$                | $6.96 \times 10^{-6}$ | $2.95 \times 10^{-2}$                | $2.57 \times 10^{-7}$ | $2.95 \times 10^{-2}$                |
|        | Cd | $3.29 \times 10^{-5}$ | $2.78 \times 10^{-1}$                | $6.14 \times 10^{-4}$ | $2.78 \times 10^{-1}$                | $4.57 \times 10^{-6}$ | <b><math>1.99 \times 10^0</math></b> | $4.55 \times 10^{-4}$ | <b><math>1.99 \times 10^0</math></b> |
|        | Cu | $4.16 \times 10^{-5}$ | $3.51 \times 10^{-3}$                | $7.77 \times 10^{-6}$ | $3.56 \times 10^{-3}$                | $5.78 \times 10^{-6}$ | $2.52 \times 10^{-2}$                | $5.77 \times 10^{-6}$ | $2.52 \times 10^{-2}$                |
|        | Mn | $3.58 \times 10^{-4}$ | <b><math>1.45 \times 10^1</math></b> | $3.49 \times 10^{-7}$ | <b><math>1.45 \times 10^1</math></b> | $4.98 \times 10^{-5}$ | <b><math>1.04 \times 10^2</math></b> | $2.59 \times 10^{-7}$ | <b><math>1.04 \times 10^2</math></b> |
|        | Pb | $4.84 \times 10^{-4}$ | $4.09 \times 10^{-2}$                | $3.61 \times 10^{-4}$ | $4.17 \times 10^{-2}$                | $6.72 \times 10^{-5}$ | $2.93 \times 10^{-1}$                | $2.68 \times 10^{-4}$ | $2.94 \times 10^{-1}$                |
|        | Zn | $1.27 \times 10^{-5}$ | $1.07 \times 10^{-2}$                | $2.36 \times 10^{-6}$ | $1.07 \times 10^{-2}$                | $1.76 \times 10^{-6}$ | $7.67 \times 10^{-2}$                | $1.75 \times 10^{-6}$ | $7.67 \times 10^{-2}$                |
| S12    | Cr | $1.97 \times 10^{-4}$ | $1.67 \times 10^{-2}$                | $5.97 \times 10^{-7}$ | $1.69 \times 10^{-2}$                | $2.74 \times 10^{-5}$ | $1.20 \times 10^{-1}$                | $5.47 \times 10^{-4}$ | $1.20 \times 10^{-1}$                |
|        | Ni | $1.32 \times 10^{-5}$ | $1.08 \times 10^{-3}$                | $9.09 \times 10^{-8}$ | $1.09 \times 10^{-3}$                | $1.83 \times 10^{-6}$ | $7.74 \times 10^{-3}$                | $6.75 \times 10^{-8}$ | $7.74 \times 10^{-3}$                |
|        | Cd | $1.64 \times 10^{-5}$ | $1.39 \times 10^{-1}$                | $3.07 \times 10^{-4}$ | $1.39 \times 10^{-1}$                | $2.28 \times 10^{-6}$ | $9.96 \times 10^{-1}$                | $2.28 \times 10^{-4}$ | $9.96 \times 10^{-1}$                |
|        | Cu | $8.04 \times 10^{-5}$ | $6.79 \times 10^{-3}$                | $1.50 \times 10^{-5}$ | $6.89 \times 10^{-3}$                | $1.12 \times 10^{-5}$ | $4.87 \times 10^{-2}$                | $1.11 \times 10^{-5}$ | $4.88 \times 10^{-2}$                |
|        | Mn | $1.05 \times 10^{-3}$ | <b><math>4.26 \times 10^1</math></b> | $1.02 \times 10^{-6}$ | <b><math>4.26 \times 10^1</math></b> | $1.46 \times 10^{-4}$ | <b><math>3.05 \times 10^2</math></b> | $7.59 \times 10^{-7}$ | <b><math>3.05 \times 10^2</math></b> |
|        | Pb | $6.11 \times 10^{-4}$ | $5.16 \times 10^{-2}$                | $4.56 \times 10^{-4}$ | $5.26 \times 10^{-2}$                | $8.48 \times 10^{-5}$ | $3.70 \times 10^{-1}$                | $3.38 \times 10^{-4}$ | $3.70 \times 10^{-1}$                |
|        | Zn | $1.51 \times 10^{-5}$ | $1.28 \times 10^{-2}$                | $2.82 \times 10^{-6}$ | $1.28 \times 10^{-2}$                | $2.10 \times 10^{-6}$ | $9.17 \times 10^{-2}$                | $2.10 \times 10^{-6}$ | $9.17 \times 10^{-2}$                |
|        | Cr | $2.03 \times 10^{-4}$ | $1.71 \times 10^{-2}$                | $8.29 \times 10^{-7}$ | $1.73 \times 10^{-2}$                | $2.82 \times 10^{-5}$ | $1.23 \times 10^{-1}$                | $5.62 \times 10^{-4}$ | $1.23 \times 10^{-1}$                |
|        | Ni | $1.73 \times 10^{-5}$ | $1.42 \times 10^{-3}$                | $1.19 \times 10^{-7}$ | $1.43 \times 10^{-3}$                | $2.40 \times 10^{-6}$ | $1.02 \times 10^{-2}$                | $8.86 \times 10^{-8}$ | $1.02 \times 10^{-2}$                |
|        | Cd | $1.64 \times 10^{-5}$ | $1.39 \times 10^{-1}$                | $3.07 \times 10^{-4}$ | $1.39 \times 10^{-1}$                | $2.28 \times 10^{-6}$ | $9.96 \times 10^{-1}$                | $2.28 \times 10^{-4}$ | $9.96 \times 10^{-1}$                |

Source: Author's Analysis, 2025

**Table 4.6: Hazard Quotients (HQing, HQinh, HQderm) and Hazard Indices (HIing, HIinh, HIderm) for Heavy Metals Exposure in Children and Adults Cont'd**

| Sample | HM | Children              |                                      |                       |                                      | Adult                 |                                      |                       |                                      |
|--------|----|-----------------------|--------------------------------------|-----------------------|--------------------------------------|-----------------------|--------------------------------------|-----------------------|--------------------------------------|
|        |    | HQing                 | HQinh                                | HQderm                | HI children                          | HQing                 | HQinh                                | HQderm                | HI Adult                             |
| S13    | Cu | $8.41 \times 10^{-5}$ | $7.10 \times 10^{-3}$                | $1.57 \times 10^{-5}$ | $7.20 \times 10^{-3}$                | $1.17 \times 10^{-5}$ | $5.10 \times 10^{-2}$                | $1.17 \times 10^{-5}$ | $5.10 \times 10^{-2}$                |
|        | Mn | $1.58 \times 10^{-3}$ | <b><math>6.42 \times 10^1</math></b> | $1.54 \times 10^{-6}$ | <b><math>6.42 \times 10^1</math></b> | $2.20 \times 10^{-4}$ | <b><math>4.61 \times 10^2</math></b> | $1.15 \times 10^{-6}$ | <b><math>4.61 \times 10^2</math></b> |
|        | Pb | $5.78 \times 10^{-4}$ | $4.88 \times 10^{-2}$                | $4.31 \times 10^{-4}$ | $4.98 \times 10^{-2}$                | $8.02 \times 10^{-5}$ | $3.50 \times 10^{-1}$                | $3.20 \times 10^{-4}$ | $3.51 \times 10^{-1}$                |
|        | Zn | $1.49 \times 10^{-5}$ | $1.26 \times 10^{-2}$                | $2.78 \times 10^{-6}$ | $1.26 \times 10^{-2}$                | $2.07 \times 10^{-6}$ | $9.03 \times 10^{-2}$                | $2.06 \times 10^{-6}$ | $9.03 \times 10^{-2}$                |
|        | Cr | $7.12 \times 10^{-5}$ | $6.02 \times 10^{-3}$                | $2.32 \times 10^{-7}$ | $6.09 \times 10^{-3}$                | $9.89 \times 10^{-6}$ | $4.32 \times 10^{-2}$                | $1.97 \times 10^{-4}$ | $4.34 \times 10^{-2}$                |
|        | Ni | $1.89 \times 10^{-5}$ | $1.55 \times 10^{-3}$                | $1.31 \times 10^{-5}$ | $1.58 \times 10^{-3}$                | $2.63 \times 10^{-6}$ | $1.11 \times 10^{-2}$                | $9.70 \times 10^{-8}$ | $1.11 \times 10^{-2}$                |
| S14    | Cd | $1.64 \times 10^{-5}$ | $1.39 \times 10^{-1}$                | $3.07 \times 10^{-4}$ | $1.39 \times 10^{-1}$                | $2.28 \times 10^{-6}$ | $9.96 \times 10^{-1}$                | $2.28 \times 10^{-4}$ | $9.96 \times 10^{-1}$                |
|        | Cu | $4.03 \times 10^{-5}$ | $3.40 \times 10^{-3}$                | $7.52 \times 10^{-6}$ | $3.45 \times 10^{-3}$                | $5.59 \times 10^{-6}$ | $2.44 \times 10^{-2}$                | $5.58 \times 10^{-6}$ | $2.44 \times 10^{-2}$                |
|        | Mn | $1.16 \times 10^{-3}$ | <b><math>4.72 \times 10^1</math></b> | $1.13 \times 10^{-6}$ | <b><math>4.72 \times 10^1</math></b> | $1.62 \times 10^{-4}$ | <b><math>3.39 \times 10^2</math></b> | $8.42 \times 10^{-7}$ | <b><math>3.39 \times 10^2</math></b> |
|        | Pb | $6.76 \times 10^{-4}$ | $5.71 \times 10^{-2}$                | $5.05 \times 10^{-4}$ | $5.83 \times 10^{-2}$                | $9.39 \times 10^{-5}$ | $4.10 \times 10^{-1}$                | $3.75 \times 10^{-4}$ | $4.10 \times 10^{-1}$                |
|        | Zn | $1.38 \times 10^{-5}$ | $1.17 \times 10^{-2}$                | $2.58 \times 10^{-6}$ | $1.17 \times 10^{-2}$                | $1.92 \times 10^{-6}$ | $8.37 \times 10^{-2}$                | $1.91 \times 10^{-6}$ | $8.37 \times 10^{-2}$                |
|        | Cr | $9.86 \times 10^{-5}$ | $8.33 \times 10^{-3}$                | $3.98 \times 10^{-7}$ | $8.43 \times 10^{-3}$                | $1.37 \times 10^{-5}$ | $5.98 \times 10^{-2}$                | $2.73 \times 10^{-4}$ | $6.01 \times 10^{-2}$                |
| S15    | Ni | $2.05 \times 10^{-5}$ | $1.68 \times 10^{-3}$                | $1.31 \times 10^{-7}$ | $1.71 \times 10^{-3}$                | $2.85 \times 10^{-6}$ | $1.21 \times 10^{-2}$                | $1.05 \times 10^{-7}$ | $1.21 \times 10^{-2}$                |
|        | Cd | $1.64 \times 10^{-5}$ | $1.39 \times 10^{-1}$                | $3.07 \times 10^{-4}$ | $1.39 \times 10^{-1}$                | $2.28 \times 10^{-6}$ | $9.96 \times 10^{-1}$                | $2.28 \times 10^{-4}$ | $9.96 \times 10^{-1}$                |
|        | Cu | $4.69 \times 10^{-5}$ | $3.96 \times 10^{-3}$                | $8.76 \times 10^{-6}$ | $4.02 \times 10^{-3}$                | $6.52 \times 10^{-6}$ | $2.85 \times 10^{-2}$                | $6.50 \times 10^{-6}$ | $2.85 \times 10^{-2}$                |
|        | Mn | $1.01 \times 10^{-3}$ | <b><math>4.10 \times 10^1</math></b> | $9.85 \times 10^{-7}$ | <b><math>4.10 \times 10^1</math></b> | $1.41 \times 10^{-4}$ | <b><math>2.94 \times 10^2</math></b> | $7.31 \times 10^{-7}$ | <b><math>2.94 \times 10^2</math></b> |
|        | Pb | $7.05 \times 10^{-4}$ | $5.95 \times 10^{-2}$                | $5.26 \times 10^{-4}$ | $6.07 \times 10^{-2}$                | $9.78 \times 10^{-5}$ | $4.27 \times 10^{-1}$                | $3.90 \times 10^{-4}$ | $4.27 \times 10^{-1}$                |
|        | Zn | $1.40 \times 10^{-5}$ | $1.18 \times 10^{-2}$                | $2.61 \times 10^{-6}$ | $1.18 \times 10^{-2}$                | $1.94 \times 10^{-6}$ | $8.47 \times 10^{-2}$                | $1.94 \times 10^{-6}$ | $8.47 \times 10^{-2}$                |
| S16    | Cr | $1.37 \times 10^{-4}$ | $1.16 \times 10^{-2}$                | $2.09 \times 10^{-6}$ | $1.17 \times 10^{-2}$                | $1.90 \times 10^{-5}$ | $8.30 \times 10^{-2}$                | $3.80 \times 10^{-4}$ | $8.34 \times 10^{-2}$                |
|        | Ni | $2.05 \times 10^{-5}$ | $1.68 \times 10^{-3}$                | $1.42 \times 10^{-7}$ | $1.71 \times 10^{-3}$                | $2.85 \times 10^{-6}$ | $1.21 \times 10^{-2}$                | $1.05 \times 10^{-7}$ | $1.21 \times 10^{-2}$                |
|        | Cd | $1.64 \times 10^{-5}$ | $1.39 \times 10^{-1}$                | $3.07 \times 10^{-4}$ | $1.39 \times 10^{-1}$                | $2.28 \times 10^{-6}$ | $9.96 \times 10^{-1}$                | $2.28 \times 10^{-4}$ | $9.96 \times 10^{-1}$                |
|        | Cu | $5.17 \times 10^{-5}$ | $4.36 \times 10^{-3}$                | $9.65 \times 10^{-6}$ | $4.43 \times 10^{-3}$                | $7.18 \times 10^{-6}$ | $3.13 \times 10^{-2}$                | $7.16 \times 10^{-6}$ | $3.13 \times 10^{-2}$                |
|        | Mn | $7.31 \times 10^{-4}$ | <b><math>2.96 \times 10^1</math></b> | $7.12 \times 10^{-7}$ | <b><math>2.96 \times 10^1</math></b> | $1.02 \times 10^{-4}$ | <b><math>2.13 \times 10^2</math></b> | $5.28 \times 10^{-7}$ | <b><math>2.13 \times 10^2</math></b> |
|        | Pb | $6.90 \times 10^{-4}$ | $5.83 \times 10^{-2}$                | $5.16 \times 10^{-4}$ | $5.95 \times 10^{-2}$                | $9.59 \times 10^{-5}$ | $4.18 \times 10^{-1}$                | $3.83 \times 10^{-4}$ | $4.19 \times 10^{-1}$                |
|        | Zn | $1.51 \times 10^{-5}$ | $1.27 \times 10^{-2}$                | $2.81 \times 10^{-6}$ | $1.27 \times 10^{-2}$                | $2.09 \times 10^{-6}$ | $9.13 \times 10^{-2}$                | $2.09 \times 10^{-6}$ | $9.13 \times 10^{-2}$                |
|        | Cr | $3.84 \times 10^{-5}$ | $3.24 \times 10^{-3}$                | $5.31 \times 10^{-7}$ | $3.28 \times 10^{-3}$                | $5.33 \times 10^{-6}$ | $2.32 \times 10^{-2}$                | $1.06 \times 10^{-4}$ | $2.34 \times 10^{-2}$                |
|        | Ni | $2.22 \times 10^{-5}$ | $1.82 \times 10^{-3}$                | $1.42 \times 10^{-7}$ | $1.84 \times 10^{-3}$                | $3.08 \times 10^{-6}$ | $1.31 \times 10^{-2}$                | $1.14 \times 10^{-7}$ | $1.31 \times 10^{-2}$                |
|        | Cd | $1.64 \times 10^{-5}$ | $1.39 \times 10^{-1}$                | $3.07 \times 10^{-4}$ | $1.39 \times 10^{-1}$                | $2.28 \times 10^{-6}$ | $9.96 \times 10^{-1}$                | $2.28 \times 10^{-4}$ | $9.96 \times 10^{-1}$                |

Source: Author's Analysis, 2025

**Table 4.6: Hazard Quotients (HQing, HQinh, HQderm) and Hazard Indices (HIing, HIinh, HIderm) for Heavy Metals Exposure in Children and Adults Cont'd**

| Sample | HM | Children              |                                      |                       |                                      | Adult                 |                                      |                       |                                      |
|--------|----|-----------------------|--------------------------------------|-----------------------|--------------------------------------|-----------------------|--------------------------------------|-----------------------|--------------------------------------|
|        |    | HQing                 | HQinh                                | HQderm                | HI children                          | HQing                 | HQinh                                | HQderm                | HI Adult                             |
| S17    | Cu | $2.30 \times 10^{-5}$ | $1.94 \times 10^{-3}$                | $4.28 \times 10^{-6}$ | $1.97 \times 10^{-3}$                | $3.19 \times 10^{-6}$ | $1.39 \times 10^{-2}$                | $3.18 \times 10^{-6}$ | $1.39 \times 10^{-2}$                |
|        | Mn | $9.77 \times 10^{-4}$ | <b><math>3.96 \times 10^1</math></b> | $9.52 \times 10^{-7}$ | <b><math>3.96 \times 10^1</math></b> | $1.36 \times 10^{-4}$ | <b><math>2.84 \times 10^2</math></b> | $7.06 \times 10^{-7}$ | <b><math>2.84 \times 10^2</math></b> |
|        | Pb | $6.58 \times 10^{-4}$ | $5.55 \times 10^{-2}$                | $4.91 \times 10^{-4}$ | $5.67 \times 10^{-2}$                | $9.13 \times 10^{-5}$ | $3.99 \times 10^{-1}$                | $3.64 \times 10^{-4}$ | $3.99 \times 10^{-1}$                |
|        | Zn | $1.19 \times 10^{-5}$ | $1.01 \times 10^{-2}$                | $2.23 \times 10^{-6}$ | $1.01 \times 10^{-2}$                | $1.66 \times 10^{-6}$ | $7.24 \times 10^{-2}$                | $1.65 \times 10^{-6}$ | $7.24 \times 10^{-2}$                |
|        | Cr | $6.58 \times 10^{-5}$ | $5.55 \times 10^{-3}$                | $4.98 \times 10^{-7}$ | $5.62 \times 10^{-3}$                | $9.13 \times 10^{-6}$ | $3.99 \times 10^{-2}$                | $1.82 \times 10^{-4}$ | $4.00 \times 10^{-2}$                |
|        | Ni | $2.38 \times 10^{-5}$ | $1.95 \times 10^{-3}$                | $1.53 \times 10^{-7}$ | $1.98 \times 10^{-3}$                | $3.31 \times 10^{-6}$ | $1.40 \times 10^{-2}$                | $1.22 \times 10^{-7}$ | $1.40 \times 10^{-2}$                |
| S18    | Cd | $1.64 \times 10^{-5}$ | $1.39 \times 10^{-1}$                | $3.07 \times 10^{-4}$ | $1.39 \times 10^{-1}$                | $2.28 \times 10^{-6}$ | $9.96 \times 10^{-1}$                | $2.28 \times 10^{-4}$ | $9.96 \times 10^{-1}$                |
|        | Cu | $3.60 \times 10^{-5}$ | $3.04 \times 10^{-3}$                | $6.72 \times 10^{-6}$ | $3.08 \times 10^{-3}$                | $5.00 \times 10^{-6}$ | $2.18 \times 10^{-2}$                | $4.99 \times 10^{-6}$ | $2.18 \times 10^{-2}$                |
|        | Mn | $8.72 \times 10^{-4}$ | <b><math>3.53 \times 10^1</math></b> | $8.49 \times 10^{-7}$ | <b><math>3.53 \times 10^1</math></b> | $1.21 \times 10^{-4}$ | <b><math>2.54 \times 10^2</math></b> | $6.30 \times 10^{-7}$ | <b><math>2.54 \times 10^2</math></b> |
|        | Pb | $7.14 \times 10^{-4}$ | $6.03 \times 10^{-2}$                | $5.33 \times 10^{-4}$ | $6.15 \times 10^{-2}$                | $9.92 \times 10^{-5}$ | $4.33 \times 10^{-1}$                | $3.96 \times 10^{-4}$ | $4.33 \times 10^{-1}$                |
|        | Zn | $1.34 \times 10^{-5}$ | $1.13 \times 10^{-2}$                | $2.50 \times 10^{-6}$ | $1.13 \times 10^{-2}$                | $1.86 \times 10^{-6}$ | $8.10 \times 10^{-2}$                | $1.85 \times 10^{-6}$ | $8.10 \times 10^{-2}$                |
|        | Cr | $3.45 \times 10^{-4}$ | $2.92 \times 10^{-2}$                | $1.33 \times 10^{-5}$ | $2.95 \times 10^{-2}$                | $4.79 \times 10^{-5}$ | $2.09 \times 10^{-1}$                | $9.57 \times 10^{-4}$ | $2.10 \times 10^{-1}$                |
| S19    | Ni | $1.73 \times 10^{-5}$ | $1.42 \times 10^{-3}$                | $1.65 \times 10^{-7}$ | $1.43 \times 10^{-3}$                | $2.40 \times 10^{-6}$ | $1.02 \times 10^{-2}$                | $8.86 \times 10^{-8}$ | $1.02 \times 10^{-2}$                |
|        | Cd | $1.64 \times 10^{-5}$ | $1.39 \times 10^{-1}$                | $3.07 \times 10^{-4}$ | $1.39 \times 10^{-1}$                | $2.28 \times 10^{-6}$ | $9.96 \times 10^{-1}$                | $2.28 \times 10^{-4}$ | $9.96 \times 10^{-1}$                |
|        | Cu | $4.49 \times 10^{-5}$ | $3.79 \times 10^{-3}$                | $8.38 \times 10^{-6}$ | $3.84 \times 10^{-3}$                | $6.23 \times 10^{-6}$ | $2.72 \times 10^{-2}$                | $6.22 \times 10^{-6}$ | $2.72 \times 10^{-2}$                |
|        | Mn | $6.87 \times 10^{-4}$ | <b><math>2.78 \times 10^1</math></b> | $6.69 \times 10^{-7}$ | <b><math>2.78 \times 10^1</math></b> | $9.54 \times 10^{-5}$ | <b><math>2.00 \times 10^2</math></b> | $4.97 \times 10^{-7}$ | <b><math>2.00 \times 10^2</math></b> |
|        | Pb | $6.81 \times 10^{-4}$ | $5.75 \times 10^{-2}$                | $5.08 \times 10^{-4}$ | $5.87 \times 10^{-2}$                | $9.46 \times 10^{-5}$ | $4.13 \times 10^{-1}$                | $3.77 \times 10^{-4}$ | $4.13 \times 10^{-1}$                |
|        | Zn | $1.35 \times 10^{-5}$ | $1.14 \times 10^{-2}$                | $2.52 \times 10^{-6}$ | $1.14 \times 10^{-2}$                | $1.87 \times 10^{-6}$ | $8.17 \times 10^{-2}$                | $1.87 \times 10^{-6}$ | $8.17 \times 10^{-2}$                |
| S20    | Cr | $8.77 \times 10^{-5}$ | $7.40 \times 10^{-3}$                | #NUM!                 | $7.49 \times 10^{-3}$                | $1.22 \times 10^{-5}$ | $5.31 \times 10^{-2}$                | $2.43 \times 10^{-4}$ | $5.34 \times 10^{-2}$                |
|        | Ni | $2.14 \times 10^{-5}$ | $1.75 \times 10^{-3}$                | $1.19 \times 10^{-7}$ | $1.77 \times 10^{-3}$                | $2.97 \times 10^{-6}$ | $1.26 \times 10^{-2}$                | $1.10 \times 10^{-7}$ | $1.26 \times 10^{-2}$                |
|        | Cd | $1.64 \times 10^{-5}$ | $1.39 \times 10^{-1}$                | $3.07 \times 10^{-4}$ | $1.39 \times 10^{-1}$                | $2.28 \times 10^{-6}$ | $9.96 \times 10^{-1}$                | $2.28 \times 10^{-4}$ | $9.96 \times 10^{-1}$                |
|        | Cu | $4.95 \times 10^{-5}$ | $4.18 \times 10^{-3}$                | $9.23 \times 10^{-6}$ | $4.24 \times 10^{-3}$                | $6.87 \times 10^{-6}$ | $3.00 \times 10^{-2}$                | $6.85 \times 10^{-6}$ | $3.00 \times 10^{-2}$                |
|        | Mn | $6.18 \times 10^{-4}$ | <b><math>2.51 \times 10^1</math></b> | $6.02 \times 10^{-7}$ | <b><math>2.51 \times 10^1</math></b> | $8.59 \times 10^{-5}$ | <b><math>1.80 \times 10^2</math></b> | $4.47 \times 10^{-7}$ | <b><math>1.80 \times 10^2</math></b> |
|        | Pb | $6.95 \times 10^{-4}$ | $5.87 \times 10^{-2}$                | $5.19 \times 10^{-4}$ | $5.99 \times 10^{-2}$                | $9.65 \times 10^{-5}$ | $4.21 \times 10^{-1}$                | $3.85 \times 10^{-4}$ | $4.22 \times 10^{-1}$                |
|        | Zn | $1.52 \times 10^{-5}$ | $1.29 \times 10^{-2}$                | $2.84 \times 10^{-6}$ | $1.29 \times 10^{-2}$                | $2.12 \times 10^{-6}$ | $9.23 \times 10^{-2}$                | $2.11 \times 10^{-6}$ | $9.23 \times 10^{-2}$                |
|        | Cr | $8.22 \times 10^{-5}$ | $6.94 \times 10^{-3}$                | #NUM!                 | $7.02 \times 10^{-3}$                | $1.14 \times 10^{-5}$ | $4.98 \times 10^{-2}$                | $2.28 \times 10^{-4}$ | $5.01 \times 10^{-2}$                |
|        | Ni | $2.14 \times 10^{-5}$ | $1.75 \times 10^{-3}$                | $1.48 \times 10^{-7}$ | $1.77 \times 10^{-3}$                | $2.97 \times 10^{-6}$ | $1.26 \times 10^{-2}$                | $1.10 \times 10^{-7}$ | $1.26 \times 10^{-2}$                |
|        | Cd | -                     | -                                    | -                     | -                                    | -                     | -                                    | -                     | -                                    |

Source: Author's Analysis, 2025



### 4.5.3 Carcinogenic Risk Assessment for Heavy Metals

Based on the available slope factor, the carcinogenic risk assessment was computed for Pb, Cr, Ni and Cd in indoor dust in this study (Table 4.7). Generally, for both age groups, Cr had the highest value, while Cd exhibited the lowest value. The cancer risk associated with the ingestion pathway contributed to 0.89% and 0.02% of the overall cancer risk for children and adults, respectively. However, cancer risk via the inhalation pathway accounted for 96.34% and 99.66% of the total cancer risk for children and adults, respectively. Similarly, the risk of cancer through the ingestion route represented just 2.77% and 0.32% of the overall cancer risk for both children and adults, respectively. In this study, the CR<sub>ing</sub>, CR<sub>inh</sub> and CR<sub>derm</sub> in adults were observed to be 7.20, 0.14 and 1.35 times that of children. In this study, the indoor lifetime risk for Pb and Cd for both children and adults were not significant except for Cd for sites S2 and S10 which showed significant cancer risk with values of  $2.43 \times 10^{-4}$  and  $1.22 \times 10^{-4}$  respectively. Conversely, Cr and Ni showed unacceptable or significant cancer risk for adult while the indoor lifetime risk for Cr and S1 for Ni were significant for children, with CR ranging above  $1 \times 10^{-4}$  and  $1 \times 10^{-6}$ .

**Table 4.7: TLCR for Heavy Metals for Children and Adults**

| Sample | TLCRchildren          |                                         |                                         |                       | TLCRadult             |                                         |                                         |                                         |
|--------|-----------------------|-----------------------------------------|-----------------------------------------|-----------------------|-----------------------|-----------------------------------------|-----------------------------------------|-----------------------------------------|
|        | Pb                    | Cr                                      | Ni                                      | Cd                    | Pb                    | Cr                                      | Ni                                      | Cd                                      |
| S1     | $1.06 \times 10^{-6}$ | <b><math>1.05 \times 10^{-3}</math></b> | <b><math>2.08 \times 10^{-4}</math></b> | $8.63 \times 10^{-6}$ | $7.54 \times 10^{-6}$ | <b><math>7.53 \times 10^{-3}</math></b> | <b><math>1.33 \times 10^{-3}</math></b> | $6.08 \times 10^{-5}$                   |
| S2     | $7.05 \times 10^{-7}$ | <b><math>5.25 \times 10^{-4}</math></b> | $2.52 \times 10^{-5}$                   | $3.45 \times 10^{-5}$ | $5.02 \times 10^{-6}$ | <b><math>3.77 \times 10^{-3}</math></b> | <b><math>1.61 \times 10^{-4}</math></b> | <b><math>2.43 \times 10^{-4}</math></b> |
| S3     | $5.87 \times 10^{-7}$ | <b><math>2.63 \times 10^{-3}</math></b> | $2.78 \times 10^{-5}$                   | -                     | $4.19 \times 10^{-6}$ | <b><math>1.88 \times 10^{-2}</math></b> | <b><math>1.78 \times 10^{-4}</math></b> | -                                       |
| S4     | $4.29 \times 10^{-6}$ | <b><math>9.92 \times 10^{-4}</math></b> | $4.37 \times 10^{-5}$                   | $8.63 \times 10^{-6}$ | $3.06 \times 10^{-5}$ | <b><math>7.11 \times 10^{-3}</math></b> | <b><math>2.79 \times 10^{-4}</math></b> | $6.08 \times 10^{-5}$                   |
| S5     | $5.46 \times 10^{-6}$ | <b><math>7.00 \times 10^{-4}</math></b> | $3.31 \times 10^{-5}$                   | $8.63 \times 10^{-6}$ | $3.89 \times 10^{-5}$ | <b><math>5.02 \times 10^{-3}</math></b> | <b><math>2.12 \times 10^{-4}</math></b> | $6.08 \times 10^{-5}$                   |
| S6     | $4.81 \times 10^{-6}$ | <b><math>9.92 \times 10^{-4}</math></b> | $2.78 \times 10^{-5}$                   | $8.63 \times 10^{-6}$ | $3.43 \times 10^{-5}$ | <b><math>7.11 \times 10^{-3}</math></b> | <b><math>1.78 \times 10^{-4}</math></b> | $6.08 \times 10^{-5}$                   |
| S7     | $8.46 \times 10^{-6}$ | $5.83 \times 10^{-5}$                   | $1.19 \times 10^{-5}$                   | -                     | $6.03 \times 10^{-5}$ | <b><math>4.18 \times 10^{-4}</math></b> | $7.62 \times 10^{-5}$                   | -                                       |
| S8     | $6.11 \times 10^{-6}$ | <b><math>4.08 \times 10^{-4}</math></b> | $3.05 \times 10^{-5}$                   | -                     | $4.35 \times 10^{-5}$ | <b><math>2.93 \times 10^{-3}</math></b> | <b><math>1.95 \times 10^{-4}</math></b> | -                                       |
| S9     | $5.11 \times 10^{-6}$ | <b><math>7.00 \times 10^{-4}</math></b> | $3.18 \times 10^{-5}$                   | $8.63 \times 10^{-6}$ | $3.64 \times 10^{-5}$ | <b><math>5.02 \times 10^{-3}</math></b> | <b><math>2.03 \times 10^{-4}</math></b> | $6.08 \times 10^{-5}$                   |
| S10    | $6.40 \times 10^{-6}$ | <b><math>1.28 \times 10^{-3}</math></b> | $8.08 \times 10^{-5}$                   | $1.73 \times 10^{-5}$ | $4.56 \times 10^{-5}$ | <b><math>9.21 \times 10^{-3}</math></b> | <b><math>5.17 \times 10^{-4}</math></b> | <b><math>1.22 \times 10^{-4}</math></b> |
| S11    | $6.05 \times 10^{-6}$ | <b><math>2.10 \times 10^{-3}</math></b> | $2.12 \times 10^{-5}$                   | $8.63 \times 10^{-6}$ | $4.31 \times 10^{-5}$ | <b><math>1.51 \times 10^{-2}</math></b> | <b><math>1.36 \times 10^{-4}</math></b> | $6.08 \times 10^{-5}$                   |
| S12    | $7.63 \times 10^{-6}$ | <b><math>2.16 \times 10^{-3}</math></b> | $2.78 \times 10^{-5}$                   | $8.63 \times 10^{-6}$ | $5.44 \times 10^{-5}$ | <b><math>1.55 \times 10^{-2}</math></b> | <b><math>1.78 \times 10^{-4}</math></b> | $6.08 \times 10^{-5}$                   |
| S13    | $7.22 \times 10^{-6}$ | <b><math>7.58 \times 10^{-4}</math></b> | $3.05 \times 10^{-5}$                   | $8.63 \times 10^{-6}$ | $5.15 \times 10^{-5}$ | <b><math>5.44 \times 10^{-3}</math></b> | <b><math>1.95 \times 10^{-4}</math></b> | $6.08 \times 10^{-5}$                   |
| S14    | $8.46 \times 10^{-6}$ | <b><math>1.05 \times 10^{-3}</math></b> | $3.31 \times 10^{-5}$                   | $8.63 \times 10^{-6}$ | $6.03 \times 10^{-5}$ | <b><math>7.53 \times 10^{-3}</math></b> | <b><math>2.12 \times 10^{-4}</math></b> | $6.08 \times 10^{-5}$                   |
| S15    | $8.81 \times 10^{-6}$ | <b><math>1.46 \times 10^{-3}</math></b> | $3.31 \times 10^{-5}$                   | $8.63 \times 10^{-6}$ | $6.28 \times 10^{-5}$ | <b><math>1.05 \times 10^{-2}</math></b> | <b><math>2.12 \times 10^{-4}</math></b> | $6.08 \times 10^{-5}$                   |
| S16    | $8.63 \times 10^{-6}$ | <b><math>4.08 \times 10^{-4}</math></b> | $3.58 \times 10^{-5}$                   | $8.63 \times 10^{-6}$ | $6.15 \times 10^{-5}$ | <b><math>2.93 \times 10^{-3}</math></b> | <b><math>2.29 \times 10^{-4}</math></b> | $6.08 \times 10^{-5}$                   |
| S17    | $8.22 \times 10^{-6}$ | <b><math>7.00 \times 10^{-4}</math></b> | $3.84 \times 10^{-5}$                   | $8.63 \times 10^{-6}$ | $5.86 \times 10^{-5}$ | <b><math>5.02 \times 10^{-3}</math></b> | <b><math>2.46 \times 10^{-4}</math></b> | $6.08 \times 10^{-5}$                   |
| S18    | $8.93 \times 10^{-6}$ | <b><math>3.68 \times 10^{-3}</math></b> | $2.78 \times 10^{-5}$                   | $8.63 \times 10^{-6}$ | $6.36 \times 10^{-5}$ | <b><math>2.64 \times 10^{-2}</math></b> | <b><math>1.78 \times 10^{-4}</math></b> | $6.08 \times 10^{-5}$                   |
| S19    | $8.51 \times 10^{-6}$ | <b><math>9.33 \times 10^{-4}</math></b> | $3.44 \times 10^{-5}$                   | $8.63 \times 10^{-6}$ | $6.07 \times 10^{-5}$ | <b><math>6.70 \times 10^{-3}</math></b> | <b><math>2.20 \times 10^{-4}</math></b> | $6.08 \times 10^{-5}$                   |
| S20    | $8.69 \times 10^{-6}$ | <b><math>8.75 \times 10^{-4}</math></b> | $3.44 \times 10^{-5}$                   | -                     | $6.20 \times 10^{-5}$ | <b><math>6.28 \times 10^{-3}</math></b> | <b><math>2.20 \times 10^{-4}</math></b> | -                                       |

TCR values  $>1.0 \times 10^{-4}$  are shown in Bold figures

Source: Author's Analysis, 2025

## 4.6 Health Risk Assessment of Parabens in Indoor Dust Samples

Inhalation, ingestion and dermal contact are three exposure pathways through which humans can be exposed to parabens. Potential human health risks from exposure to parabens in indoor dust were evaluated using the Average Daily Dose (ADD) and Hazard Quotient (HQ), based on the USEPA's ingestion and dermal exposure assessment model. Generally, Individuals may encounter parabens via unintentional direct contact with tainted indoor dust, hand-to-mouth behaviours, and indirect exposure to dust that clings to food or household items that are later consumed. Inhalation and dermal absorption of contaminated indoor dust is also possible via resuspension of dust by human activities such as walking, cleaning, and vacuuming<sup>18,19,20</sup>.

### 4.6.1 Average Daily Dose for Parabens

Average Daily Dose (ADD) was evaluated for children and adults as shown in Tables 4.8 and 4.9. The ADD results obtained for children and adults were within the threshold limit 0 – 10 mg kg<sup>-1</sup> body weight set for parabens<sup>21</sup>. The ADD for adults were seen to be 1.28 times greater than that of children for Methylparabens (MeP) in sample locations S3, S4, S5, S10, S11, S12, S13, S14, S16 and S20 and for Butlyparaben (BuP) in sample location S16. For children, MeP, EtP, PrP, and BuP ADD ranged from 0.1144 to 3.3328, 0.1392 to 0.6899, 0.1371 to 0.9689, and 0.1313 to 1.1189, respectively. Likewise, for adults, the ADD range of 0.1461 to 4.2576, 0.1778 to 0.8813, 0.1751 to 1.2377, and 0.1677 to 1.4294 for MeP, EtP, PrP, and BuP, respectively, was observed.

**Table 4.8: Average Daily Dose for Parabens in Indoor Dust for Children**

| ADDchildren |        |        |        |        |
|-------------|--------|--------|--------|--------|
| Sample      | MeP    | EtP    | PrP    | BuP    |
| S1          | 0.3385 | 0.3213 | 0.2787 | 0.3856 |
| S2          | 0.1144 | 0.1500 | 0.1475 | 0.1666 |
| S3          | 3.3328 | 0.6570 | 0.5586 | 0.2013 |
| S4          | 1.3142 | 0.4031 | 0.2350 | 0.3020 |
| S5          | 2.6409 | 0.4992 | 0.4219 | 0.4981 |
| S6          | 0.9328 | 0.3360 | 0.2354 | 0.3785 |
| S7          | 0.5509 | 0.6899 | 0.2621 | 0.3229 |
| S8          | 0.5507 | 0.6735 | 0.3288 | 0.3229 |
| S9          | 0.1688 | 0.4522 | 0.3467 | 0.2648 |
| S10         | 1.1294 | 0.3252 | 0.2002 | 0.3187 |
| S11         | 2.4427 | 0.4089 | 0.3248 | 0.1313 |
| S12         | 3.0721 | 0.3056 | 0.2088 | 0.2200 |
| S13         | 1.6100 | 0.4766 | 0.1371 | 0.2976 |
| S14         | 1.0350 | 0.3701 | 0.2143 | 0.3494 |
| S15         | 0.7719 | 0.4286 | 0.6104 | 0.5369 |
| S16         | 1.1626 | 0.6710 | 0.9689 | 1.1189 |
| S17         | 0.3580 | 0.3875 | 0.6051 | 0.6693 |
| S18         | 0.6731 | 0.3044 | 0.3336 | 0.5429 |
| S19         | 0.6228 | 0.1392 | 0.3054 | 0.3283 |
| S20         | 2.6002 | 0.3345 | 0.3906 | 0.7326 |

**Source:** Author's Analysis, 2025

**Table 4.9: Average Daily Dose for Parabens in Indoor Dust for Adult**

| <b>ADDadult</b> |            |            |            |            |
|-----------------|------------|------------|------------|------------|
| <b>Sample</b>   | <b>MeP</b> | <b>EtP</b> | <b>PrP</b> | <b>BuP</b> |
| <b>S1</b>       | 0.4324     | 0.4105     | 0.3561     | 0.4926     |
| <b>S2</b>       | 0.1461     | 0.1916     | 0.1884     | 0.2129     |
| <b>S3</b>       | 4.2576     | 0.8393     | 0.7136     | 0.2572     |
| <b>S4</b>       | 1.6789     | 0.5150     | 0.3002     | 0.3858     |
| <b>S5</b>       | 3.3737     | 0.6377     | 0.5389     | 0.6364     |
| <b>S6</b>       | 1.1916     | 0.4292     | 0.3007     | 0.4835     |
| <b>S7</b>       | 0.7038     | 0.8813     | 0.3348     | 0.4124     |
| <b>S8</b>       | 0.7035     | 0.8604     | 0.4201     | 0.4124     |
| <b>S9</b>       | 0.2157     | 0.5777     | 0.4428     | 0.3383     |
| <b>S10</b>      | 1.4428     | 0.4155     | 0.2558     | 0.4071     |
| <b>S11</b>      | 3.1206     | 0.5223     | 0.4150     | 0.1677     |
| <b>S12</b>      | 3.9246     | 0.3904     | 0.2668     | 0.2811     |
| <b>S13</b>      | 2.0567     | 0.6088     | 0.1751     | 0.3802     |
| <b>S14</b>      | 1.3223     | 0.4729     | 0.2738     | 0.4464     |
| <b>S15</b>      | 0.9861     | 0.5476     | 0.7797     | 0.6859     |
| <b>S16</b>      | 1.4852     | 0.8572     | 1.2377     | 1.4294     |
| <b>S17</b>      | 0.4574     | 0.4950     | 0.7730     | 0.8551     |
| <b>S18</b>      | 0.8598     | 0.3889     | 0.4261     | 0.6936     |
| <b>S19</b>      | 0.7956     | 0.1778     | 0.3901     | 0.4194     |
| <b>S20</b>      | 3.3217     | 0.4273     | 0.4989     | 0.9358     |

**Source:** Author's Analysis, 2025

#### 4.6.2 Hazard Quotient and Hazard Index for Parabens

Tables 4.10 and 4.11 summarize the Hazard Quotient and Hazard Index for parabens in the indoor dust samples for children and adults, respectively. In this study, all four parabens detected for children and adults have HQ and HI values  $< 1$  (Low Risk). This indicates that there is a low non-carcinogenic risk of parabens in indoor dust for children and adults. For children, the HQ value for MeP range from  $1.14 \times 10^{-8}$  to  $3.33 \times 10^{-7}$  with the highest from S3, EtP range from  $1.39 \times 10^{-8}$  to  $6.90 \times 10^{-8}$  with the highest from S7, PrP range from  $1.37 \times 10^{-6}$  to  $9.69 \times 10^{-6}$  with the highest from S16, BuP range from  $1.31 \times 10^{-6}$  to  $1.12 \times 10^{-5}$  with the highest from S16. For adults, the HQ value for MeP range from  $1.46 \times 10^{-8}$  to  $4.26 \times 10^{-7}$  with the highest from S3, EtP range from  $1.78 \times 10^{-8}$  to  $8.81 \times 10^{-8}$  with the highest from S7, PrP range from  $1.75 \times 10^{-6}$  to  $1.24 \times 10^{-5}$  with the highest from S16, BuP range from  $1.68 \times 10^{-6}$  to  $1.43 \times 10^{-5}$  with the highest from S16. Adult has the highest mean HI values,  $2.69 \times 10^{-5}$ , compared to those of children,  $2.11 \times 10^{-5}$ . This indicates that adults are more likely to be exposed to possible contamination of parabens. However, the non-carcinogenic risk for adults and children is considered low, as indicated by the HI values for each group are below 1. These results obtained for children and adults negate the results of previous studies<sup>18</sup>.

**Table 4.10: Hazard Quotient and Hazard Index for Parabens for Children**

| Sample     | MeP                   | EtP                   | PrP                   | BuP                   | HI                    |
|------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
|            | <b>HQ</b>             |                       |                       |                       |                       |
| <b>S1</b>  | $3.39 \times 10^{-8}$ | $3.21 \times 10^{-8}$ | $2.79 \times 10^{-6}$ | $3.86 \times 10^{-6}$ | $6.71 \times 10^{-6}$ |
| <b>S2</b>  | $1.14 \times 10^{-8}$ | $1.50 \times 10^{-8}$ | $1.47 \times 10^{-6}$ | $1.67 \times 10^{-6}$ | $3.17 \times 10^{-6}$ |
| <b>S3</b>  | $3.33 \times 10^{-7}$ | $6.57 \times 10^{-8}$ | $5.59 \times 10^{-6}$ | $2.01 \times 10^{-6}$ | $8.00 \times 10^{-6}$ |
| <b>S4</b>  | $1.31 \times 10^{-7}$ | $4.03 \times 10^{-8}$ | $2.35 \times 10^{-6}$ | $3.02 \times 10^{-6}$ | $5.54 \times 10^{-6}$ |
| <b>S5</b>  | $2.64 \times 10^{-7}$ | $4.99 \times 10^{-8}$ | $4.22 \times 10^{-6}$ | $4.98 \times 10^{-6}$ | $9.51 \times 10^{-6}$ |
| <b>S6</b>  | $9.33 \times 10^{-8}$ | $3.36 \times 10^{-8}$ | $2.35 \times 10^{-6}$ | $3.78 \times 10^{-6}$ | $6.27 \times 10^{-6}$ |
| <b>S7</b>  | $5.51 \times 10^{-8}$ | $6.90 \times 10^{-8}$ | $2.62 \times 10^{-6}$ | $3.23 \times 10^{-6}$ | $5.97 \times 10^{-6}$ |
| <b>S8</b>  | $5.51 \times 10^{-8}$ | $6.74 \times 10^{-8}$ | $3.29 \times 10^{-6}$ | $3.23 \times 10^{-6}$ | $6.64 \times 10^{-6}$ |
| <b>S9</b>  | $1.69 \times 10^{-8}$ | $4.52 \times 10^{-8}$ | $3.47 \times 10^{-6}$ | $2.65 \times 10^{-6}$ | $6.18 \times 10^{-6}$ |
| <b>S10</b> | $1.13 \times 10^{-7}$ | $3.25 \times 10^{-8}$ | $2.00 \times 10^{-6}$ | $3.19 \times 10^{-6}$ | $5.33 \times 10^{-6}$ |
| <b>S11</b> | $2.44 \times 10^{-7}$ | $4.09 \times 10^{-8}$ | $3.25 \times 10^{-6}$ | $1.31 \times 10^{-6}$ | $4.85 \times 10^{-6}$ |
| <b>S12</b> | $3.07 \times 10^{-7}$ | $3.06 \times 10^{-8}$ | $2.09 \times 10^{-6}$ | $2.20 \times 10^{-6}$ | $4.63 \times 10^{-6}$ |
| <b>S13</b> | $1.61 \times 10^{-7}$ | $4.77 \times 10^{-8}$ | $1.37 \times 10^{-6}$ | $2.98 \times 10^{-6}$ | $4.56 \times 10^{-6}$ |
| <b>S14</b> | $1.04 \times 10^{-7}$ | $3.70 \times 10^{-8}$ | $2.14 \times 10^{-6}$ | $3.49 \times 10^{-6}$ | $5.78 \times 10^{-6}$ |
| <b>S15</b> | $7.72 \times 10^{-8}$ | $4.29 \times 10^{-8}$ | $6.10 \times 10^{-6}$ | $5.37 \times 10^{-6}$ | $1.16 \times 10^{-5}$ |
| <b>S16</b> | $1.16 \times 10^{-7}$ | $6.71 \times 10^{-8}$ | $9.69 \times 10^{-6}$ | $1.12 \times 10^{-5}$ | $2.11 \times 10^{-5}$ |
| <b>S17</b> | $3.58 \times 10^{-8}$ | $3.88 \times 10^{-8}$ | $6.05 \times 10^{-6}$ | $6.69 \times 10^{-6}$ | $1.28 \times 10^{-5}$ |
| <b>S18</b> | $6.73 \times 10^{-8}$ | $3.04 \times 10^{-8}$ | $3.34 \times 10^{-6}$ | $5.43 \times 10^{-6}$ | $8.86 \times 10^{-6}$ |
| <b>S19</b> | $6.23 \times 10^{-8}$ | $1.39 \times 10^{-8}$ | $3.05 \times 10^{-6}$ | $3.28 \times 10^{-6}$ | $6.41 \times 10^{-6}$ |
| <b>S20</b> | $2.60 \times 10^{-7}$ | $3.34 \times 10^{-8}$ | $3.91 \times 10^{-6}$ | $7.33 \times 10^{-6}$ | $1.15 \times 10^{-5}$ |

HI < 1 – Low Risk and HI > 1 – High Risk<sup>18</sup>.

**Source:** Author's Analysis, 2025

**Table 4.11: Hazard Quotient and Hazard Index for Parabens for Adults**

| Sample     | MeP                   | EtP                   | PrP                   | BuP                   | HI                    |
|------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
|            | <b>HQ</b>             |                       |                       |                       |                       |
| <b>S1</b>  | $4.32 \times 10^{-8}$ | $4.10 \times 10^{-8}$ | $3.56 \times 10^{-6}$ | $4.93 \times 10^{-6}$ | $8.57 \times 10^{-6}$ |
| <b>S2</b>  | $1.46 \times 10^{-8}$ | $1.92 \times 10^{-8}$ | $1.88 \times 10^{-6}$ | $2.13 \times 10^{-6}$ | $4.05 \times 10^{-6}$ |
| <b>S3</b>  | $4.26 \times 10^{-7}$ | $8.39 \times 10^{-8}$ | $7.14 \times 10^{-6}$ | $2.57 \times 10^{-6}$ | $1.02 \times 10^{-5}$ |
| <b>S4</b>  | $1.68 \times 10^{-7}$ | $5.15 \times 10^{-8}$ | $3.00 \times 10^{-6}$ | $3.86 \times 10^{-6}$ | $7.08 \times 10^{-6}$ |
| <b>S5</b>  | $3.37 \times 10^{-7}$ | $6.38 \times 10^{-8}$ | $5.39 \times 10^{-6}$ | $6.36 \times 10^{-6}$ | $1.22 \times 10^{-5}$ |
| <b>S6</b>  | $1.19 \times 10^{-7}$ | $4.29 \times 10^{-8}$ | $3.01 \times 10^{-6}$ | $4.83 \times 10^{-6}$ | $8.00 \times 10^{-6}$ |
| <b>S7</b>  | $7.04 \times 10^{-8}$ | $8.81 \times 10^{-8}$ | $3.35 \times 10^{-6}$ | $4.12 \times 10^{-6}$ | $7.63 \times 10^{-6}$ |
| <b>S8</b>  | $7.04 \times 10^{-8}$ | $8.60 \times 10^{-8}$ | $4.20 \times 10^{-6}$ | $4.12 \times 10^{-6}$ | $8.48 \times 10^{-6}$ |
| <b>S9</b>  | $2.16 \times 10^{-8}$ | $5.78 \times 10^{-8}$ | $4.43 \times 10^{-6}$ | $3.38 \times 10^{-6}$ | $7.89 \times 10^{-6}$ |
| <b>S10</b> | $1.44 \times 10^{-7}$ | $4.15 \times 10^{-8}$ | $2.56 \times 10^{-6}$ | $4.07 \times 10^{-6}$ | $6.81 \times 10^{-6}$ |
| <b>S11</b> | $3.12 \times 10^{-7}$ | $5.22 \times 10^{-8}$ | $4.15 \times 10^{-6}$ | $1.68 \times 10^{-6}$ | $6.19 \times 10^{-6}$ |
| <b>S12</b> | $3.92 \times 10^{-7}$ | $3.90 \times 10^{-8}$ | $2.67 \times 10^{-6}$ | $2.81 \times 10^{-6}$ | $5.91 \times 10^{-6}$ |
| <b>S13</b> | $2.06 \times 10^{-7}$ | $6.09 \times 10^{-8}$ | $1.75 \times 10^{-6}$ | $3.80 \times 10^{-6}$ | $5.82 \times 10^{-6}$ |
| <b>S14</b> | $1.32 \times 10^{-7}$ | $4.73 \times 10^{-8}$ | $2.74 \times 10^{-6}$ | $4.46 \times 10^{-6}$ | $7.38 \times 10^{-6}$ |
| <b>S15</b> | $9.86 \times 10^{-8}$ | $5.48 \times 10^{-8}$ | $7.80 \times 10^{-6}$ | $6.86 \times 10^{-6}$ | $1.48 \times 10^{-5}$ |
| <b>S16</b> | $1.49 \times 10^{-7}$ | $8.57 \times 10^{-8}$ | $1.24 \times 10^{-5}$ | $1.43 \times 10^{-5}$ | $2.69 \times 10^{-5}$ |
| <b>S17</b> | $4.57 \times 10^{-8}$ | $4.95 \times 10^{-8}$ | $7.73 \times 10^{-6}$ | $8.55 \times 10^{-6}$ | $1.64 \times 10^{-5}$ |
| <b>S18</b> | $8.60 \times 10^{-8}$ | $3.89 \times 10^{-8}$ | $4.26 \times 10^{-6}$ | $6.94 \times 10^{-6}$ | $1.13 \times 10^{-5}$ |
| <b>S19</b> | $7.96 \times 10^{-8}$ | $1.78 \times 10^{-8}$ | $3.90 \times 10^{-6}$ | $4.19 \times 10^{-6}$ | $8.19 \times 10^{-6}$ |
| <b>S20</b> | $3.32 \times 10^{-7}$ | $4.27 \times 10^{-8}$ | $4.99 \times 10^{-6}$ | $9.36 \times 10^{-6}$ | $1.47 \times 10^{-5}$ |

HI < 1 – Low Risk and HI > 1 – High Risk<sup>18</sup>.

**Source:** Author's Analysis, 2025



**Table 4.12: Comparison of Median Concentrations of Paraben in Indoor Dust with Previous Studies (ng g<sup>-1</sup>)**

| <b>Country</b> | <b>Sampled Sites</b> | <b>Sample matrix</b> | <b>MeP</b> | <b>EtP</b> | <b>PrP</b> | <b>BuP</b> | <b>References</b> |
|----------------|----------------------|----------------------|------------|------------|------------|------------|-------------------|
| Spain          | Homes                | Indoor Dust          | 451        | 135        | 266        | 106        | <sup>36</sup>     |
| Canada         | Homes                | Indoor Dust          | 1080       | 25         | 463        | 59         | <sup>37</sup>     |
| USA            | Homes                | Indoor Dust          | 1920       | 180        | 965        | 80         | <sup>38</sup>     |
| Korea          | Homes                | Indoor Dust          | 1310       | 46         | 800        | 40         | <sup>39</sup>     |
| Japan          | Homes                | Indoor Dust          | 1470       | 127        | 228        | 45         | <sup>39</sup>     |
| Vietnam        | Laboratories         | Indoor Dust          | 121        | 28.2       | 37.5       | 20.8       | <sup>40</sup>     |
| China          | Homes                | Indoor Dust          | 252        | 43.4       | 44.5       | 0.103      | <sup>41</sup>     |
| Nigeria        | Laboratories         | Indoor Dust          | 916        | 2945       | 4461       | 5213       | <sup>18</sup>     |
| Nigeria        | Residential          | Indoor Dust          | 2094.92    | 841.68     | 670.88     | 693.18     | This Study        |

## **4.7 Dust Pollution Assessment**

The contamination factor, the pollution load index, and the geo-accumulation index, also known as the single factor pollution index (PI), were utilised to assess the degree of metal contamination present in indoor dust.

### **4.7.1 Contamination Factor (CF)**

The contamination status or pollution intensity was assessed utilizing Forstner and Wittmann's recommendations<sup>34, 43</sup>. The information presented was derived from the determined Contamination Factor (CF) values indicated in Table 4.13. In the surveyed locations, the mean concentration indicates that all the heavy metals under this study have a low contamination status of  $CF < 1$  which indicates low contamination to all the sampled sites.

### **4.7.2 Pollution Load Index (PLI)**

The Pollution Load Index (PLI), as proposed by Tomlinson et al.<sup>44</sup>, was below one at all sampled locations, as shown in Table 4.13. The PLI values ranged from 0.010 to 0.027. This suggests that the indoor dust was free from pollution or contamination by heavy metals. Furthermore, it signifies that the site is of high quality or that there is no pollution present.

### **4.7.3 Index of Geo-accumulation (Igeo)**

The Geo-accumulation Index (Igeo) was applied to assess heavy metal contamination on indoor dust samples. The various Igeo values for the indoor dust samples are presented in Table 4.14. According to the contamination classification established by Muller, the Igeo values for all the heavy metals examined in the indoor dust samples are negative, indicating that Cu, Mn, Pb, Zn, Cr, Ni, and Cd are categorised as practically unpolluted ( $I_{geo} < 1$ )<sup>45</sup>.

**Table 4.13: Assessment of Contamination Factor and Pollution Load Index for Heavy Metals in Indoor Dust**

| Sample | Cu    | Mn    | Pb    | Zn    | Cr    | Ni    | Cd    | Pollution Load Index |
|--------|-------|-------|-------|-------|-------|-------|-------|----------------------|
| S1     | 0.034 | 0.036 | 0.009 | 0.071 | 0.002 | 0.023 | 0.044 | 0.020                |
| S2     | 0.013 | 0.019 | 0.006 | 0.027 | 0.001 | 0.003 | 0.133 | 0.010                |
| S3     | 0.021 | 0.018 | 0.005 | 0.028 | 0.005 | 0.003 | -     | 0.019                |
| S4     | 0.022 | 0.017 | 0.037 | 0.029 | 0.002 | 0.005 | 0.044 | 0.015                |
| S5     | 0.042 | 0.021 | 0.047 | 0.032 | 0.001 | 0.004 | 0.056 | 0.017                |
| S6     | 0.028 | 0.021 | 0.041 | 0.029 | 0.002 | 0.003 | 0.044 | 0.015                |
| S7     | 0.025 | 0.035 | 0.072 | 0.030 | 0.000 | 0.001 | -     | 0.017                |
| S8     | 0.019 | 0.025 | 0.052 | 0.023 | 0.001 | 0.003 | -     | 0.020                |
| S9     | 0.025 | 0.025 | 0.043 | 0.030 | 0.001 | 0.004 | 0.044 | 0.015                |
| S10    | 0.227 | 0.018 | 0.055 | 0.034 | 0.002 | 0.009 | 0.067 | 0.027                |
| S11    | 0.021 | 0.006 | 0.051 | 0.024 | 0.004 | 0.002 | 0.044 | 0.013                |
| S12    | 0.040 | 0.017 | 0.065 | 0.029 | 0.004 | 0.003 | 0.033 | 0.018                |
| S13    | 0.042 | 0.026 | 0.062 | 0.029 | 0.001 | 0.003 | 0.044 | 0.017                |
| S14    | 0.020 | 0.019 | 0.072 | 0.027 | 0.002 | 0.004 | 0.044 | 0.016                |
| S15    | 0.023 | 0.016 | 0.075 | 0.027 | 0.003 | 0.004 | 0.033 | 0.016                |
| S16    | 0.026 | 0.012 | 0.074 | 0.029 | 0.001 | 0.004 | 0.044 | 0.014                |
| S17    | 0.011 | 0.016 | 0.070 | 0.023 | 0.001 | 0.004 | 0.044 | 0.013                |
| S18    | 0.018 | 0.014 | 0.076 | 0.026 | 0.006 | 0.003 | 0.033 | 0.016                |
| S19    | 0.022 | 0.011 | 0.073 | 0.026 | 0.002 | 0.004 | 0.056 | 0.015                |
| S20    | 0.025 | 0.010 | 0.074 | 0.029 | 0.002 | 0.004 | -     | 0.023                |

CF < 1: low contamination;  $1 \leq \text{CF} < 3$ : moderate contamination;  $3 \leq \text{CF} < 6$ : considerable contamination; CF > 6: very high contamination<sup>43</sup>. PLI < 1 indicates perfection, i.e., no pollution or good site quality; PLI = 1 is considered a reference line when levels of pollutants are present and PLI > 1 is considered a worsening of site quality<sup>44</sup>.

**Source:** Author's Analysis, 2025

**Table 4.14: Igeo of Heavy Metals**

| Sample     | Cu     | Mn     | Pb     | Zn     | Cr      | Ni      | Cd     |
|------------|--------|--------|--------|--------|---------|---------|--------|
| <b>S1</b>  | -5.476 | -5.399 | -7.354 | -4.403 | -9.676  | -6.025  | -5.077 |
| <b>S2</b>  | -6.879 | -6.278 | -7.926 | -5.821 | -10.757 | -9.094  | -3.492 |
| <b>S3</b>  | -6.176 | -6.405 | -8.182 | -5.751 | -8.381  | -8.901  | -      |
| <b>S4</b>  | -6.072 | -6.473 | -5.348 | -5.706 | -9.757  | -8.272  | -5.077 |
| <b>S5</b>  | -5.166 | -6.187 | -5.001 | -5.540 | -10.210 | -8.634  | -4.755 |
| <b>S6</b>  | -5.736 | -6.174 | -5.182 | -5.704 | -9.757  | -8.924  | -5.077 |
| <b>S7</b>  | -5.879 | -5.418 | -4.377 | -5.666 | -13.458 | -10.043 | -      |
| <b>S8</b>  | -6.283 | -5.896 | -4.841 | -6.035 | -10.998 | -8.772  | -      |
| <b>S9</b>  | -5.884 | -5.907 | -5.113 | -5.666 | -10.210 | -8.692  | -5.077 |
| <b>S10</b> | -2.722 | -6.390 | -4.778 | -5.477 | -9.392  | -7.378  | -4.492 |
| <b>S11</b> | -6.171 | -8.011 | -4.869 | -5.947 | -8.716  | -9.287  | -5.077 |
| <b>S12</b> | -5.221 | -6.460 | -4.521 | -5.687 | -8.663  | -8.901  | -5.492 |
| <b>S13</b> | -5.156 | -5.867 | -4.604 | -5.708 | -10.172 | -8.772  | -5.077 |
| <b>S14</b> | -6.218 | -6.308 | -4.374 | -5.819 | -9.650  | -8.634  | -5.077 |
| <b>S15</b> | -5.997 | -6.514 | -4.322 | -5.801 | -9.191  | -8.653  | -5.492 |
| <b>S16</b> | -5.859 | -6.984 | -4.351 | -5.692 | -11.065 | -8.526  | -5.077 |
| <b>S17</b> | -7.030 | -6.564 | -4.415 | -6.030 | -10.248 | -8.426  | -5.077 |
| <b>S18</b> | -6.381 | -6.728 | -4.297 | -5.868 | -7.888  | -8.901  | -5.492 |
| <b>S19</b> | -6.062 | -7.072 | -4.371 | -5.856 | -9.843  | -8.597  | -4.755 |
| <b>S20</b> | -5.922 | -7.224 | -4.341 | -5.681 | -9.934  | -8.597  | -      |

Igeo < 1 is unpolluted; Igeo > 1 is polluted<sup>45</sup>.

**Source:** Author's Analysis, 2025

## Endnotes

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## Chapter Five

### Conclusion

#### 5.1 Summary of Findings

Overall, indoor dust samples were obtained from twenty residential sites in Ibadan. The concentrations of heavy metals and parabens in the analyzed samples decreased in the following order:  $Mn > Zn > Cu > Pb > Cr > Ni > Cd$  for heavy metals, and  $MeP > EtP > BuP > PrP$  for parabens. Likewise, indoor dust samples contained varying levels of heavy metals (Cu, Mn, Pb, Zn, Cr, Ni, Cd) and parabens (MeP, EtP, PrP, BuP). Even though the quantified elemental levels fall beneath the allowable thresholds established by the Canadian Soil Quality Guideline (CSQG) for metals in soil, Mn was the most dominant, making up about 63% of the total heavy metals found in the indoor dust across all sampled locations. The dominance of Mn may be attributable to human activities such as fossil fuel combustion from both vehicular and industrial emissions. In contrast, Cd was the least dominant, constituting 0.1% of the total heavy metals in the indoor dust across all sampled sites. Similarly, MeP was the most abundant paraben, representing 52.0% of the total parabens detected across the sampled sites, followed by EtP (17.0%), BuP (16.0%), and PrP (15.0%).

Correspondingly, correlation analysis revealed both positive and negative significant relationships among the analytes in indoor dust, with strong associations observed between Zn–Mn ( $r = 0.6$ ), Ni–Zn ( $r = 0.9$ ), BuP–PrP ( $r = 0.7$ ), and EtP–PrP ( $r = 0.5$ ), suggesting common sources of contamination. In contrast, significant negative correlations, including multi-way interactions such as Pb–Zn–Ni and Cd–MeP–EtP, indicated the influence of different sources. Likewise, principal component analysis identified five dominant components that explained

79.95% of the total variance, with Ni–Zn–Mn (PC1), EtP (PC2), PrP–BuP (PC3), Cr–MeP (PC4), and Cu–Pb (PC5) emerging as the main contributors. The grouping of analytes within the same components suggests common sources, such as vehicle emissions for Ni and Zn, or cosmetics for PrP and BuP, while distinct loadings, such as EtP and Cd in PC2, indicate contributions from different sources.

Furthermore, risk assessment showed that Mn posed significant non-carcinogenic risks through inhalation, with adults more vulnerable than children. Similarly, Cr and Ni were linked to notable target carcinogenic risks, higher in adults than in children. Conversely, parabens' hazard quotient and hazard index values were below one, indicating low health risks for both age groups. A notable negative correlation was observed between Cd and EtP, suggesting distinct sources. Overall, dust pollution by heavy metals was classified as low contamination, but the co-occurrence of toxic metals and parabens underscores the need for monitoring and preventive measures to protect human health.

## **5.2 Conclusion**

In conclusion, the findings of this present investigation indicate that indoor dust in the examined locations within Ibadan acts as a sink for both heavy metals and parabens, with Mn and MeP emerging as the predominant contaminants. While the concentrations of heavy metals were generally below the Canadian Soil Quality Guideline thresholds, the strong presence of Mn and the co-occurrence of other metals such as Pb, Cr, and Ni highlight potential anthropogenic influences, particularly from vehicular and industrial activities. Similarly, the predominance of MeP and the significant associations between parabens, especially PrP and BuP, suggest cosmetics and personal care products as major contributors.

Correlation and principal component analyses revealed both shared and distinct sources of contamination, emphasizing the complexity of indoor dust composition. Risk assessment further indicated that Mn pose considerable non-carcinogenic while Cr and Ni pose carcinogenic risks, particularly through inhalation, with adults more at risk than children. Although parabens showed low health risk indices, their co-existence with toxic metals raises concerns about long-term exposure effects.

Overall, this study underscores the importance of continuous monitoring of indoor dust pollutants in urban Nigerian environments and highlights the importance of implementing preventive health interventions and enforcing regulatory actions to reduce exposure to hazardous contaminants.

### **5.3 Recommendations**

Drawing from the results of this present investigation, the following recommendations are suggested:

1. Routine monitoring programs for indoor dust to track the levels and sources of heavy metals and parabens in Nigerian residential environments.
2. Increase public awareness on the potential health risks of indoor dust contamination, particularly regarding household sources such as cosmetics, cleaning agents, and building materials.
3. Implement strategies to minimize indoor pollution, including improved ventilation, regular cleaning practices, and regulation of consumer products (e.g., cosmetics containing parabens, paints, and materials that release heavy metals).

4. Develop and enforce national control of alternatives to parabens in personal care products.
5. Expand studies to include other emerging contaminants in indoor dust, larger sample sizes, and diverse geographical locations in Nigeria to provide a more comprehensive risk assessment framework.
6. Prioritize interventions for vulnerable groups who demonstrated higher non-carcinogenic and carcinogenic risks by promoting exposure reduction practices.

#### **5.4 Contribution to Knowledge**

1. Results from this research provided data on the co-occurrence of heavy metals and parabens in indoor dust from residential environments in Ibadan, filling a critical gap in national monitoring and exposure data.
2. It also provided insight into the understanding of the interactions of metals and parabens in indoor dust pollution pathways.
3. Moreover, the study provided baseline data for developing dust quality standards, exposure control strategies, and regulatory interventions in Nigeria.

#### **5.5 Suggested Areas for Further Research**

There is a need for more comprehensive data on the occurrence and concentrations of parabens in personal care products in Nigeria, as well as on the co-occurrence of inorganic and organic contaminants, including parabens and heavy metals present in indoor dust from both urban and rural areas of the country.

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## Appendix I



Atomic Absorbance Spectroscopy for analysis

**Source:** Author's Analysis, 2025

## Appendix II



Picture of Solid Phase Extraction process carried out in the Laboratory

**Source:** Author's Analysis, 2025

### Appendix III



High-Performance Liquid Chromatography–Ultra Violet Detection HPLC-UV Used for this Research

**Source:** Author's Analysis, 2025

## Bio Data

### A. PERSONAL DATA

|                |                                                                                               |
|----------------|-----------------------------------------------------------------------------------------------|
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| Date of Birth  | 24 <sup>th</sup> August, 1982                                                                 |
| Place of Birth | Warri, Delta State                                                                            |
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| Marital Status | Married                                                                                       |
| Name of Next:  | Mrs. Victoria Omoko,                                                                          |
| Address of Kin | D.S.C. Township, Warri, Delta State.                                                          |

### B. EDUCATIONAL BACKGROUND

#### Educational Institutions Attended with Dates and Qualifications

- Lead City University (**MSc. Analytical Environmental and Chemistry**) 2021- till date
- Joseph Ayo Babalola University (**BSc. Food Science and Technology**) 2018 - 2020
- Petroleum Training Institute, Warri (**HND SLT**) 2003 - 2005
- Petroleum Training Institute, Warri (**ND SLT**) 2000 - 2002

- College of Commerce, Warri, Delta State 1993 – 1999  
(Senior Secondary School Certificate)
- Torufa Primary School, Warri, Delta State 1988 – 199  
(Primary School Leaving Certificate)

### C. WORK EXPERIENCE AND POSITION WITH DATES

- Elixir Global Manufacturing Food Limited 2016 - to date  
(Quality Assurance Manager / Research & Development Manager)
- Procter & Gamble, Nigeria (Quality Assurance / Quality Control Leader) 2015 - 2016
- Procter & Gamble, Nigeria (Quality Assurance Coordinator) 2013 - 2015
- Procter & Gamble, Nigeria (Quality Control Analyst) 2008 - 2012

**D. Creative Work:** Developing new product formulations

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FSSC 22000, Lead Auditor Workshop, CAPA Workshop.

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### **The Univeristy Compliance Certification**

This is to certify that this Thesis was written by IDOGAR CAROLINE EBAKHALUMHE with Matriculation number LCU/PG/002943 in the Department of Chemical Sciences, Faulty of Natural and Applied Science, Lead City University, Ibadan, is in full compliance with the University format and style of Thesis.

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**Signature**

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**Date**