Alqalam Journal of Medical and Applied Sciences. 2026;9(10):3416-3431
https://doi.org/10.54361/ajmas.261038

Original article

Assessment of Heavy Metals and pH Levels in Commercial Blonde Hair Dyes Marketed in Benghazi, Libya: Human Dermal Exposure and Health Risk Assessment

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Abstract
In the environment, heavy metals are present in the air, water, food, and many consumer products. Some heavy metals are essential to the human body, but only in high concentrations. Heavy metals play an important role in the human organism and are called essential minerals, while others are not known to be beneficial to our health, or, more precisely, are toxic. The toxicity of heavy metals to humans is clearly caused by long-term or high-level exposure to common pollutants. High concentrations of heavy metals may cause health problems. It is known that heavy metals can be found in many cosmetic products, and one of these is hair color, where they can enter the body through the skin and the root of the hair. Various health problems can be caused if their concentrations are high in the body. From this point, it is more important to determine the content of heavy metals. So, this paper aims to determine the concentrations of heavy metals such as (Pb, Cr, Cd, Zn, Ni, Fe, and Mn) in hair dyes. Also, blonde hair dyes are used to produce brighter and darker hair shades. Ten blonde hair dyes produced in 2026 by different manufacturers were collected from different pharmacies located in Benghazi, Libya, and analyzed using wet digestion. The analysis of heavy metals was done by the atomic absorption spectrophotometry method. In all the analyzed blonde hair dye samples, heavy metals were detected, and the overall mean (n=10) concentration for each of Pb, Cr, Cd, Zn, Ni, Fe, and Mn was: 0.076, 1.335, 0.026, 5.774, 0.921, 16.652, 0.522 mg\Kg. The concentrations of heavy metals in the analyzed hair colours were different. The measured levels of heavy metals in hair dye have been compared with data from studies carried out in other countries. Evaluate the pH of the various brands of hair dyes available in the market. Most hair dyes have a pH in the 10.00-11.5 range. In general, the pH is outside the range of pH values for normal skin and hair pH values. Approximations of health risks in adults were obtained using the systemic exposure dose (SED), Hazard Index (HI), and Cancer Risk (CR) for adults. The CR values were mostly within the acceptable range, suggesting that the carcinogenicity risk was low. The Hazard Quotient (HQ) and HI in each sample were below the threshold of 1, indicating low non-carcinogenic risk. This study strongly recommended minimizing long-term exposure to toxic elements in hair dye formulations and ensuring safer consumer products.
Keywords. Hair Dyes, Heavy Metals, Ph, Dermal Exposure, Hazard Quotient, Carcinogenic Risk.

Introduction

Millions of people worldwide use hair dyes daily to alter or maintain their hair color, making it one of the most used cosmetic items in the world. Advanced analytical instrumentation has made it easier to detect trace metals and metalloids in cosmetics due to the increased availability of current analytical instrumentation, which can detect pollutants such as automotive oils, heavy metals, and plastics that may have come from raw materials, manufacturing processes, or packaging [1,2]. The process of altering the color of hair is known as hair coloring. Its primary purpose is cosmetic, such as covering gray hair, adopting a shade considered more fashionable or youthful, or restoring the original hair color. Cosmetics, by definition, are products applied to specific areas of the body, including the skin, hair, nails, lips, and eyes. Their intended functions include cleansing, adding fragrance, enhancing appearance, masking body odors, providing protection, and maintaining overall condition [3].

A cosmetic product refers to any substance applied to the body to enhance its appearance. One common practice within this category is hair coloring, which involves altering the natural color of hair. The primary purposes of this process include covering grey hair, adopting a more fashionable shade, or restoring the hair's original color. Hair dyeing, a tradition with ancient roots, entails treating hair with various chemical substances [4-6]. Historically, early hair dyes were crafted from natural sources like plants, metallic compounds, or a blend of both [7]. Today, commercial hair dyes have evolved into intricate formulations, often containing dozens of components that vary between manufacturers. Generally, these products include ingredients such as dyes, soap, antioxidants, modifiers, alkali, ammonia, fragrances, wetting agents, and other chemicals. Though used in minimal quantities, these ingredients contribute to specific properties, such as softening the hair's texture or adjusting the durability and quality of the dyeing process.

Cosmetic hair dye products have achieved widespread utilization globally, particularly among one-third of females aged over 18 years and 10% of males older than 40 years in developed nations [8]. A diverse array of hair dye formulations may encompass potentially hazardous constituents, including heavy metals, which are present in certain hair dye pigments [9,10]. Numerous scholars in Saudi Arabia, Iran, India, Turkey, Nigeria, and Brazil have documented varying concentrations of such metallic elements across different brands of hair dye [11]. Despite the known toxicological risks of

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Received*: 20-08-2026 -* ***Accepted****: 18-10-2026 -* ***Published****: 24-10-2026*

heavy metals, there is limited information on their specific occurrence, concentrations, and potential dermal dangers in hair dye formulations sold in various countries.

Analysis of heavy metals

Heavy metal ions, upon entering the human body, can form various compounds that interfere with cellular functions, potentially triggering a wide array of health issues. These disruptions often emerge from their interactions with functional groups in proteins, such as thiol (SH-), amine (NH_2-), and carboxylic acid (COOH-) groups [12]. Prolonged exposure to specific heavy metals may lead to serious health conditions, including cancer, developmental and reproductive abnormalities, neurological disorders, contact dermatitis, respiratory problems, as well as kidney and liver dysfunctions. Cardiovascular diseases and hair-related concerns, such as brittleness or loss, are also associated with prolonged metal exposure. Metals like cobalt (Co), nickel (Ni), and chromium (Cr) are prominent skin sensitizers, while arsenic (As), mercury (Hg), cadmium (Cd), antimony (Sb), and lead (Pb) are notorious for their severe toxicity and long-term detrimental effects [13]. The detection and evaluation of these metals in food, water, and various environmental settings remain critical areas of focus for fields such as chemistry, environmental science, and public health [14].

The exact occurrence, concentration, and potential dermal harm of hair dye formulations sold in various countries are poorly documented, leaving little information about their specific occurrence and concentrations in different formulations. Beauty products, including lipsticks and hair dyes, have been linked to heavy metal toxicity, prompting international health agencies, such as the FDA and WHO, to establish maximum permissible exposure limits for various cosmetic products [15,16].

Heavy metals are a term that refers to a group of elements that share similar chemical properties, with heavy metal being a more precise term. Copper, iron, and zinc are considered essential metals, while others, such as other metals, are not useful for our health or are toxic, and all of them play a crucial role in our daily activities. Heavy metals may lead to health problems in individuals with high levels of the metal in high concentrations [17]. Hair serves as a useful indicator for assessing environmental and occupational exposure to essential and trace elements [18,19]. Our bodies need some of these substances in varying amounts, but heavy exposure may result in overexposure. Metals can spread illnesses.

The level of metal toxicity is influenced by the amount absorbed, the exposure method, and the time frame of exposure, whether acute or chronic. Numerous disorders can arise from oxidative stress caused by free radical formation [19,20]. Hair coloring is eliminated from hair by oxidation through the use of hydrogen peroxide and hair whiteners, enabling hair dye to be removed. resulting in a question about the presence of such metals. The question is: What type of substances are checked in hair to identify heavy metals?

Cosmetic products contain more than permitted levels of heavy metals, such as Cd and Pb. Direct and regular testing of both imported and locally made cosmetic products is essential [21]. The poisoning of hair dye may be caused by certain heavy metals, such as lead, mercury, silver, bismuth, and arsenic, which are commonly found in hair coloring agents [22]. Different chemical substances are employed to imprint manufacturers' formulas and impart unique characteristics and features. The formula is likely to have fragrances, chemicals that make the formula creamy, foamy, or thick, or contribute to the overall action of the formula. Metals or metal compounds are added to herbal products that are not essential for the good health of the skin and are classified by WHO as carcinogenic metals [23]. Low levels of lead exposure can cause behavioral abnormalities, delayed learning and hearing, and permanent neurological damage, as well as adverse effects on reproductive, hepatic, and renal systems. Even though these metals are highly valued by humans and other organisms, the mere existence of personal products containing these metals may pose a serious health risk, such as allergic reactions. Nickel, chromium, and cobalt are commonly known allergens, but copper, manganese, and zinc are considered less severe allergens. The WHO states that herbal medicines establish maximum acceptable levels of heavy metals in cosmetics, which has resulted in several measures being taken and the introduction of controlled substances (i.e., reprocessing, sterilization, air pollution, and water pollution) to control the concentration of the metals [24]. Lead, Arsenic, Mercury, Cadmium, and Antimony are among the heavy metals found in cosmetic products. The content of heavy metals in hair can be changed with dyeing, but the effects vary depending on the type of hair dye applied.

Hair dye was thought by some to be a potential cancer risk, particularly in women who used the darker colors, as long as the study began, and the study continued for years. Some studies suggest that the use of hair dye daily may increase the risk of non-Hodgkin's lymphoma and multiple myeloma. Despite decades of conflicting evidence linking hair dye and cancer in the original research, until this time, no conclusive evidence has been found. Recently, a study published in the American Journal of Epidemiology has found compelling evidence supporting the claim. Directive 2012/21/EU on October 12, 2012, and Directive 76/768/EC on September 2009 and EU Regulation (EC) no 1223/2009 [25,26], which respectively limit the use of approximately 45 chemicals in hair colours and EU Directive 76/768/EC on make-up, respectively, in order to ensure that hair dyes do not use any more hazardous chemicals than those specified in previous Directives. Many commercial hair dyes come with complex formulas, including many different ingredients, and the formulas vary greatly from one producer to another.

The elements were chosen (Pb, Fe, Cd, Cr, Mn, and Ni) for their unique toxicity, as they are frequently assessed in previous research on hair dye and cosmetics and are recognized for their toxicological relevance, subject to regulated international conditions. The inclusion of potentially harmful substances, such as heavy metals and metalloids, in hair dye formulations, creams, and other cosmetics that often bypass formal regulatory controls results in public health

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Received: *20-08-2026 -* ***Accepted:*** *18-10-2026 -* ***Published:*** *24-10-2026*

concerns. Naqvi et al.'s research (2022) [27] indicates that in developing nations, the lack of monitoring systems or very low levels of monitoring, thereby encroaching on international standards, led to poor enforcement in specific countries, and this creates a regulatory environment in which defective products can reach consumers in the end. Evidence from studies suggests that some hair dye brands may still contain trace amounts of toxic metals, even when not used intentionally, occurring in the form of pigments. Based on evidence, it has been shown that some hair dye brands may contain detectable amounts of dangerous metals, even when not intentionally added in the form of pigments; for example, Khalili et al. (2019) [24] combined elemental analysis of hair dyes with dermal exposure assessment and Monte Carlo simulation. Their findings demonstrated that although several metals were present in the investigated products, the calculated hazard indices were below 1 under the exposure assumptions used in their study. These findings emphasize the importance of integrating concentration data with exposure assessment rather than interpreting metal concentrations in isolation. Mostafaii et al. (2022) [2] evaluated heavy metals in hair dyes and incorporated dermal sensitivity and carcinogenicity assessment. Their work demonstrated that the potential health implications of cosmetic metals depend not only on their concentration but also on exposure characteristics and toxicological parameters. Similar results were reported in Nigeria and Pakistan [28,29]. More recently, Silva et al. (2025) investigated potentially toxic elements in hair-dye products sold in Brazil and Paraguay and combined elemental analysis with dermal exposure, hazard quotient, hazard index, and carcinogenic risk assessment. Their study further demonstrated substantial variability in elemental concentrations between commercial products and highlighted the value of integrating chemical analysis with quantitative health-risk assessment [30].

pH of hair dyes

The pH level is the gauge of the acidity or alkalinity of a substance. It's on a scale of 0 to 14. pH levels are the primary factor that often leads salons to recommend their products as being healthier for hair. Alkaline hair color formulas are more likely to be effective in recoloring hair into silvery tones, so they must be able to penetrate the hair shaft and deposit color molecules into the hair. Nutrient formulas that cannot penetrate the hair are frequently less acidic than those that need to penetrate the surface more deeply. Semi- and quasi-permanent hair color typically have a pH range of 8.0 to 9.0, whereas temporary hair color usually has a pH rating around 7.0-8.0, and Permanent hair dyes that incorporate the oxidative process may possess a pH level of 9.0 to 11.0 depending on the type of pigment used. Human hair, skin, and sebum have a pH value between 4.5 and 5.5. The natural acidity in hair preserves the health of the hair and scalp, and consequently hair color and cuticle integrity, while also preserving hair smoothness, youthfulness, and a fresh appearance. Many people's hair products disrupt the pH balance of their hair. Alkaline substances will make the hair cuticle open and cause hair color to fade, while acidic substances will cause the cuticle to contract. Alkaline products that penetrate the hair strand further expand the hair strand, allowing color molecules to penetrate the cortex and penetrate the cuticle layer. Permanent colour contains ammonia or an alternative aniline derivative as the alkaline component. Small and large colour molecules are formed in the oxidative process of colour products, with the larger molecules being found near the cuticle layer and the smaller ones within the cuticle and cortex layers. Non-oxidative semi- and temporary colouring products are gentler than other options as they usually have an acidic pH and do not cause hair strands to swell as much as normal [21].

The objective of this study is to measure the levels of some heavy metals (Pb, Fe, Cd, Cr, Mn, and Ni) in blonde hair dye products of various brands available commercially in Benghazi pharmacies. Atomic absorption spectroscopy was used to quantify these elements, a sensitive and precise method for detecting multiple elements. In addition, the research aims to evaluate the level of risk associated with dermal exposure to metals by examining risk characterization indicators such as hazard quotient (HQ), hazard index (HI), cancer risk (CR) and PH in selected hair dye products from different brands frequently sold in local shops in Benghazi, with a view to providing information on the hazards associated with the use of these products.

Experimental

Stock solutions, working standards and calibration

Stock solutions of 1000 ppm for each metal were prepared from metal or salts of high purity (99.9%). Each metal or salt was first dried at 105 °C, cooled in desiccators prior to weighing, and transferred into 1L volumetric flasks.

To prepare 1000 ppm of Pb, Cr, Cd, Fe, Mn, Ni, and Zn solutions:

- Lead (Pb): 1.598g of lead nitrate were dissolved in 2% (v/v) HNO_3 and diluted to volume in a lL flask to make a standard solution of lead.
- Manganese and Zinc (Mn and Zn): 1g of pure metal Mn and Zn were each separately dissolved in a minimum volume of pure HNO_3 and diluted to volume in a 1 L volumetric flask with 2% (v/v) HNO_3.
- And 3.735g of potassium chromate (K_2CrO_4) was dissolved in 2% (v/v) HNO_3 and diluted to volume in a 1 L flask with distilled water to make standard solutions.
- Iron (Fe): 1.000 g of pure iron wire (or high-purity Fe metal) was dissolved in a minimum volume of 1:1 HNO_3 heated gently and diluted to volume in a 1L volumetric flask with 2% (v/v) HNO_3.
- Cadmium (Cd): 2.032 g of high-purity cadmium chloride, ($CdCl_2$) was dissolved in a minimum volume of concentrated HNO_3 and diluted to volume in a 1 L volumetric flask with 2% (v/v) HNO_3.

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Received: *20-08-2026 -* ***Accepted:*** *18-10-2026 -* ***Published:*** *24-10-2026*

- Nickel (Ni): 4.049 g of nickel nitrate, (Ni $(NO_3)_2$. $6H_2O$) was dissolved in a minimum volume of warm concentrated HNO_3 and diluted to volume in a 1 L volumetric flask with 2\% (v/v) HNO_3.
- The stock solutions were stored in plastic bottles and labeled appropriately. Working standards were freshly prepared from stock solutions by serial dilution. During serial dilution of stock solutions. Calibration curves of the elements under study were prepared by determining the absorbance of different concentration.

Sampling

Due to several technical and practical considerations, the medium blonde shade was used as a representative sample for the quantification of heavy metals in hair dyes. Blonde hair dyes are commercially popular in Libya, with consumers seeking moderate lightening or subtle color changes. Secondly, blonde dyes typically require more intricate compositions than darker tones due to their high concentration of base pigments and bleaching agents such as titanium dioxide and peroxide compounds, which can lead to the formation of metallic residues [24].Furthermore, blonde dye requires an extended period of skin contact with the scalp and requires frequent touch-ups to maintain color, which directly accounts for the increased possibility of dermal absorption of any remaining metals present. The relevance of this color for dermal exposure risk assessment is well-known, as it is used for evaluating non-carcinogenic risks and estimating carcinogenic risks such as the Hazard Quotient (HQ) and Hazard Index (HI) through simulation, particularly in this color [25].
Ten samples of common blonde hair dye brands we select from different local pharmacies in Benghazi, Libya which were manufactured by more than one country. The samples
were given a unique identification code (S1—S10) as shown in (Table 1). All samples were stored
in their original containers at room temperature (approximately 25 ◦C) in a clean, dry, and dark prevent potential degradation, samples were analyzed within one month of purchase. For the chemical analysis, a homogeneous portion of approximately 0.5 g from each sample was accurately weighed and used for digestion.

Table 1. The blonde hair dye samples from various brands purchased from local pharmacies.

No. of sample	Hair dye brand	Origin
S1	MODA COLOR	Italy
S2	ORO LUXE LOW AMMONIA	Italy
S3	LUSSO	Italy
S4	Bellissima	Italy
S5	SEA COLOR	Italy
S6	GARNIEA COLOR NATURALS	France
S7	Beauty color	France
S8	LOREAL PARIS	France
S9	MISS MAGIC	European
S10	BBROSE COLOR	China

Reagents and Chemicals

Analytical-grade nitric acid (65%, Sigma-Aldrich) and hydrochloric acid (37%, Sigma-Aldrich) were used for sample preparation. Standard solutions for calibration of lead, Chromium, Cadmium, Iron, Manganese, Nickel, and Zinc were prepared from a 1000 mg/l Standard Stock Solution of GFS Fishers' AAS Reference Standard. All the solutions were prepared in deionized water. Dilution correction was applied for samples diluted or concentrated during analysis.

Hair Dye Acid Digestion

0.5g of each hair dye sample was weighed and placed into a 25ml conical flasks separately. 6ml of 65% HNO_3 with 4ml of HCl was added [32]. The contents were mixed well by stirring thoroughly. The beaker was placed on a hot plate. Heating continued until the contents dissolved, then filtered (using Whatman filter paper No.42). The filtrate solution was diluted with deionized water to 50ml. The resulting solution was used for spectrophotometric determination of various metal analyses. According to safety rules in a chemical laboratory, this procedure was carried out in a fume hood.

Analysis of elements

Atomic absorption spectrophotometer (Model iCE 3000, Thermo Scientific, USA) furnished with a deuterium lamp (D_2) for background correction was used for the determination of trace elements and heavy metal concentrations. The hollow cathode (HC) lamps for Pb, Cd, Cr, Fe, Mn, Ni, and Zn were used as a radiation source at Wavelengths of 283.3**,** 228.8**,** 425.4, 248.3**,** 403.1, 232.0, and 213.9 nm, respectively. A hydride generator was used for As and Hg analysis. The flame was air-acetylene, argon, and N_2O-acetylene gas. Determination of Pb, Cd, Cr, Fe, Mn, Ni, and Zn by direct aspiration into an air–acetylene flame of an atomic absorption spectrometer. Standard solutions were prepared to obtain working solutions were used to obtain the calibration curves; lower-concentration standards were prepared daily from their stock standard solutions.

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Received*: 20-08-2026 -* ***Accepted****: 18-10-2026 -* ***Published****: 24-10-2026*

Health risk assessment based on data analysis

Assessment of Exposure

The Agency for Toxic Substances and Disease Registry (ATSDR) [33] has utilized Equation (1) to estimate the amounts of dermal exposure to heavy metals resulting from the use of hair colorants:

$$\boldsymbol{CDDdermal} = \frac{\boldsymbol{C \times SA \times SL \times ABS \times EF \times ED \times}}{\boldsymbol{AT \times BW}} \times 10^{-6} \qquad (1)$$

In this study, the estimation of CDD dermal Dose (mg/kg/day) resulting from skin exposure to hair dyes was based on the following values: C: average concentration of metals in hair dye (mg/kg), obtained by spectroscopic techniques; SA: exposed skin area (5700 cm^2 for adults) [27]; SL: skin adherence factor (0.07 $mg/cm^2 \cdot h$ for adults [34], or, for daily value, 16.8 $mg/cm^2 \cdot day$); and ABS: dermal absorption factor (0.001 for all elements) [30,34]. The number of days spent dyeing hair, determined by exposure frequency, is the EF at 200 days/year (out of 365 days, assuming a monthly dyeing session), the ED at 40 years; the body weight considered in the literature as a reference point *is BW*: 70 kg; AT: ED 365 days/year = 40 days/year; 365 days/year = 14,600 days [30,34].

This study used an exposed skin area (SA) of 5700 cm2 in adults to estimate the likelihood of dermal exposure to metal from hair dye applications. Generally, the estimate is conservative and considers the regular scalp and surrounding skin areas (forehead, ears, neck) that may contact the dyeing agent during the process. The USEPA's Exposure Factors Handbook (2011) and related cosmetic exposure studies have revealed that the USEPA has determined that adults typically have a scalp area ranging from approximately 500 to 700 cm^2. Despite the risk of spillage, dripping, and manual application, there is a likelihood that additional skin can be exposed after accounting for other factors such as spillage, dripping, and touching [35].

Risk Quotient (HQ) and Hazard Index (HI)

Considering the information previously available, equation (2) [26,36] was used to determine the HQ of the non-carcinogenic health risk quotient (HQ) based on the information provided.

$$HQ = \frac{CDDdermal}{RfD} \qquad (2)$$

$$HI = \sum_{k=1}^{n} \frac{CDDdermal}{RfDk} = \sum_{k=1}^{n} HQk \qquad (3)$$

The dermal reference dose is RfD (mg/kg/day), and CDD_{dermal} was used to determine the CDD_{dermal} value according to Equation (1). If HQ is greater than 1, it implies that certain adverse health effects may occur, while if HQ is less, it implies a lower probability of such effects. The sum of individual HQs was used to calculate the overall potential for non-carcinogenic health risks resulting from exposure to multiple elements using the Hazard Index (HI) calculated using Equation (3) by considering the cumulative HQs based on different factors or exposure scenarios [25, 36, 37].

According to the RfD values, Pb = 0.04, Cd = 1.25×10^{-5}, Cr = 1.95×10^{-2}, Fe = 0.7, Mn = 9.60×10^{-4}, Ni = 5.40×10^{-3}, and Zn = 0.30 [38,39].

Cancer risk assessment

Cancer Risk Assessment focuses on the possibility of a person or population developing cancer due to prolonged exposure to a carcinogenic substance. Typically, toxicological measures, including the cancer slope factor (SF) are frequently used to evaluate the risk of developing cancer and predicted exposure levels so predicted exposure levels are usually the basis for assessing the cancer risk per unit of daily consumption over a lifetime [40]. The evaluation creates a summation of hypothetical cancer risk and provides a numerical depiction that can help guide policy choices and public health initiatives.

Carcinogenic risk (CR) is the possibility of a cancer-causing event if an individual has been exposed to carcinogenic metals. By taking the cancer slope factor (SF) and multiplying it by the CDDdermal dose, one can calculate CR [41] by applying the following formula:

$$CR = CDD_{dermal} \times SF \qquad (4)$$

SF is the cancer slope factor for elements, where each of them has a corresponding cancer factor (SF. In this study, the dermal cancer slope factor amount was Cr: 20, Ni: 42.5, Pb: 0.017 [31,41] and Cd: 6.7 $(mg/kg/day)^{-1}$ [40,42], where these numbers of previous studies. International guidelines suggest that carcinogenic levels for individual and combined carcinogens should be within the 10^{-6} and 10^{-4} ranges.

Statistical Analysis

The results are expressed as the mean of the triplicates ± standard deviation. Origin 9.0 was used to perform the statistical analysis. The Shapiro–Wilk test was used to assess the normality of the data. One-way ANOVA was performed to determine whether there were significant differences in the mean concentrations of metals and Metalloids among the brands ($p < 0.05$). Post hoc comparisons using Tukey's HSD test confirmed which brand pairs differed significantly. In addition, Principal Component Analysis (PCA) was conducted to investigate the multivariate relationships among the concentrations of Pb, Cd, Cr, Zn, Mn, and Ni detected in different hair dye brands.

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Received: *20-08-2026 -* ***Accepted:*** *18-10-2026 -* ***Published:*** *24-10-2026*

Results and Discussion

Three parts will be used to break down the discussion of results and present it in a comprehensive manner in this section. Starting with Section 2.1 focuses on the quantification of metals in different hair dye brands sold in Benghazi, and the concentrations of these elements under test are discussed. Following by Section 2.2 examining the estimated daily doses of dermal exposures, as well as their relationship to reference values and impact on human health. Then, Section 2.3 provides an integrated overview of the risks associated with exposure to these metals (Pb, Cd, Cr, Zn, Fe, Ni, and Mn), including both non-carcinogenic (Section 2.3.1 and carcinogenic risks (Section 2.3.2), which are gathered from dermal exposure.

Levels of Heavy Metals in Hair Dye Products

Seven metals, including Pb, Cr, Cd, Zn, Ni, Fe, and Mn, were examined in ten commercially available blonde hair-dye products from Italy, France, China, and the European market. The study revealed that the composition of various metals in the products tested was not consistent across all products, indicating that the elements of hair dyes are highly variable, including product formulation, raw-material sources, pigments, manufacturing processes, and potentially the geographical origin of the products.

Table 2. Gives a summary of the concentrations of heavy metals in ten blonde hair dyes sampled from various pharmacies in Benghazi.

No. of sample	Pb	Cd	Cr	Fe	Mn	Ni	Zn
1S	0.082±0.012	0.022±0.035	None	10.265±0.005	0.712±0.012	1.342±0.001	3.124±0.108
S2	0.069±0.019	None	2.191±0.064	23.300±0.017	0.317±0.021	0.621±0.004	4.850±0.009
S3	0.092±0.023	0.019±0.012	2.233±0.009	10.601±0.024	0.171±0.017	0.276±0.008	3.272±0.034
S4	0.083±0.025	0.014±0.010	2.216±0.011	15.045±0.012	0.698±0.018	0.443±0.024	2.341±0.007
S5	0.058±0.019	None	2.170±0.019	15.705±0.018	None	0.962±0.027	5.421±0.003
S6	0.060±0.021	0.013±0.031	None	25.120±0.027	None	1.540±0.011	6.020±0.028
S7	0.072±0.016	0.020±0.013	1.972±0.026	20.819±0.018	0.274±0.014	1.233±0.018	9.000±0.023
S8	0.095±0.013	0.011±0.030	1.226±0.017	10.000±0.016	1.543±0.021	0.656±0.019	5.800±0.010
S9	0.064±0.012	0.093±0.020	1.347±0.020	14.260±0.021	0.690±0.015	1.782±0.026	8.912±0.023
S10	0.082±0.015	0.065±0.023	None	21.403±0.017	0.810±0.024	0.355±0.021	9.000±0.026
Ave.	0.076±0.013	0.026±0.03	1.335±0.988	16.652±5.644	0.522±0.470	0.921±0.530	5.774±2.511

*Ave. calculated for all ten samples.

Of toxicological importance, lead concentrations were comparatively low, ranging from 0.058 mg\Kg for sample S5 type SEA COLOR trademark, which was less concentrated than others, to 0.095 mg\Kg for sample S8 type LOREAL PARIS trademark, showing a higher concentration than the remainder of the samples. The mean concentration of lead was found to be 0.076 mg\Kg. The concentration of lead in samples (S5, S6 and S9 ≈ 0.06 mg\Kg), (S2 and S7 ≈ 0.07 mg\Kg), (S1, S4 and S10 ≈ 0.08 mg\Kg) while in samples (S3 and S8 ≈ 0.09 mg\Kg). Comparing the results with the mean concentration, it was found that the concentration of lead for sample S7 approximately equals the mean, while the concentration in samples S2, S5, S6, and S9 is lower than the mean, but the concentration in samples S1, S3, S4, S8, and S10 is higher than the mean, as shown in (Figure 1). In Iwegbue et al. 2016 measured the concentration of Pb in hair care product which varied from <LOQ to 425.000 µg/g but Khalil et al. 2019 [24] observed Pb concentrations of hair dyes was 0.45 µg/g. Mostafaii et al. 2021 [2] reported measurable Pb concentrations in commercially available hair dye samples investigated in the Iranian market. More recently, Silva et al. 2025 [30] quantified Pb in hair dye brands sold in Brazil, where concentrations ranged from 0.011 to 0.318 mg/kg.

In the body, if lead increase in tissues, especially bone tissues, and in the kidneys, liver, pancreas, and lungs tissues [42], Pregnant women and young children are especially vulnerable to this because in easy lead can pass the placenta and enter the fetal brain, also it can be transferred easily to infants via breastfeeding and lead stored in bone serves source of fetal lead exposure. After immediate exposure, within two to six weeks humans can get rid of 50 percent of the lead, but it takes 25 to 30 years to get rid of 50 percent of lead that has increased and piled up in the body over time [43]. The levels of Pb found in the present study are significantly lower than the recommended 10 mg/kg limit recommended by the FDA for lead in cosmetic lip products and externally applied cosmetics [44,45]. Over 95% of the cosmetics used externally and considered in FDA surveys had Pb levels below 10 ppm [46]. The current hair-dyed samples show significantly lower Pb concentrations than the reference value for Pb, highlighting the occurrence of this material in the present hair-dyed samples. That said, Nevertheless, the relatively low concentration of Pb should not be interpreted as evidence that exposure is completely without significance. Lead is a toxic element with no recognized beneficial physiological function, and its significance depends on the magnitude and duration of exposure. Furthermore, the FDA guidance concerns lead as an impurity in specified cosmetic products and should therefore be regarded as a regulatory benchmark rather than a universal toxicological threshold for all cosmetic exposure scenarios [44].

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Received: *20-08-2026 -* ***Accepted:*** *18-10-2026 -* ***Published:*** *24-10-2026*

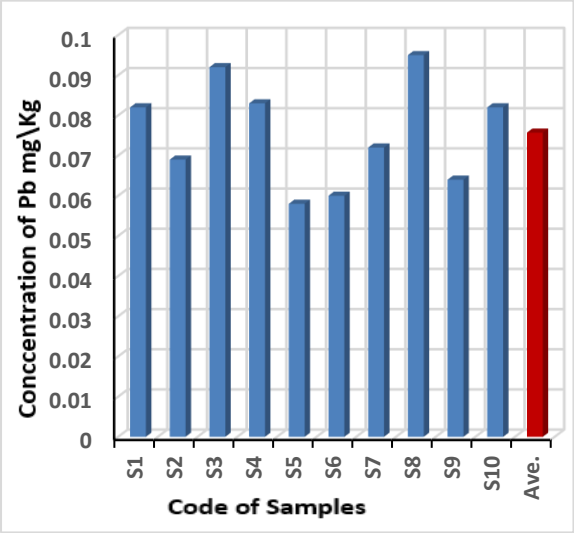


Figure 1. The lead concentration (mg\Kg) in hair dye samples

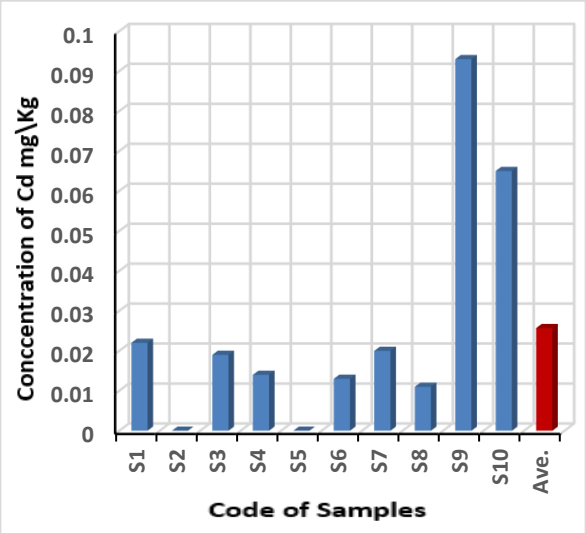


Figure 2. The cadmium concentration (mgKg) in hair dye samples

The pigmentation of cadmium in cosmetic products is a result of its color property, as it can be absorbed by the body and ingested, resulting in damage to the kidneys, liver, and bones, as well as difficulty in breaking bones. Both occupational exposure and rats have been linked to lung cancer due to exposure to cadmium, which has been found to cause lung cancer in people who breathe it. Cadmium is deemed "carcinogenic to humans" by the International Agency for Research on Cancer, and its substances are classified as human carcinogens by the United States Department of Health and Human Services [46]. Cadmium is a significant cell poison and can cause various effects, including cell death or cell proliferation. Neurological disorders, such as hyperactivity and learning disabilities in children, may arise due to its impact on the nervous system. In neuronal cells, cadmium induces oxidative stress, which produces protein damage and subsequently neurodegeneration. The presence of cadmium in various hair dyes does not have to be present in abundance in products to produce hypertension [47].

As noted from figure (2), there is no detected of cadmium in both dye samples S2 and S5, of brand ORO LUXE LOW AMMONIA and SEA COLOR. Cadmium showed the lowest overall mean concentration, approximately 0.026 mg/kg, although a relatively elevated value of 0.093 mg/kg was observed in S9 with the brand Miss Magic, and the lowest concentration was observed in S8 with the brand LOREAL PARIS (0.011 mg/kg). Samples from S1 to S8 had a concentration lower than the mean, while samples S9 and S10 had a concentration higher than the mean. The occurrence of Cd, even at relatively low concentrations, is of toxicological interest because Cd has no established physiological benefit and can accumulate following repeated exposure. Similar observations of low but detectable Cd concentrations in cosmetic and hair-care products have been reported previously [2,24,30,49]. Iwegbue et al. 2016 [48] found the concentrations of Cd to vary from <LOQ to 3.0 µg/g in hair care products, while Khalili et al. 2019 [24] reported a mean Cd concentration of 0.45 µg/g in studded hair dye products. Mostafaii et al. 2021 [2] found a mean Cd concentration of 0.525 µg/g in commercial hair dyes from the Iranian market. Silva et al. 2025 [30] observed Cd in hair dye brands sold in Brazil, ranging from 0.020 to 50.155 mg/kg.

Chromium was detected in seven of the ten samples, while three products (S1, S6, and S10) showed no detectable Cr (Table 2). The detected concentrations ranged from 1.226 mg/kg in S8 (LOREAL PARIS- France) to 2.233 mg/kg in S3 (LUSSO-Italy). Based on the individual values presented in the table, the calculated mean concentration is 1.335 mg/kg, as illustrated in (Figure 3). The concentration of most of the samples was higher than the average, except for sample S9, which was lower. Chromium has previously been detected in commercial hair dyes and hair-care products. Iwegbue et al. 2016 [48] found the concentrations of Cr in hair care products to be below the limit of quantification, at least in most samples. Chromium was detected in 27% of the brands tested at concentrations ranging from 0.2 to 4.2 µg/g. Mostafaii et al. 2021 [2] reported measurable Cr concentrations in commercially available hair dye samples investigated in the Iranian market and a mean Cr concentration of 48.15 µg/g. Silva et al. 2025 [30] observed Cr in hair dye brands sold in Brazil, ranging from 1.88 to 5.07 mg/kg.

In the current study, the samples were observed with elevated levels of Fe ranging from 10.000 to 25.120 mg/kg, with the highest concentration being found in sample S6 (Garnier Color Naturals), while the lowest was found in S8 (L'Oréal Paris), as shown in (Figure 4). The presence of Fe in cosmetic products may originate from mineral-based raw materials, pigments, or impurities introduced during manufacturing. Iwegbue et al. 2016 [48] reported substantial variation in Fe concentrations among different hair-care product categories, indicating that the concentration of Fe may be strongly dependent on product formulation and raw-material composition, where Iron is the most abundant metal in these cosmetic products, with concentrations ranging from 57.6 to 284 µg/g. Similarly, a study by Khalili et al. 2019[24] has demonstrated that the mean concentration of Fe was 1.19 mg/kg. The range of Fe concentration in the Silva et al. 2025 study [30] was 11.7-30.0 mg/kg. The transfer process for color in cosmetics and personal care products is done by Iron

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Oxides. Depending on the specific Iron Oxides or mixtures of Iron Oxides used, the color variation will range from orange, red, and yellow to black [49].

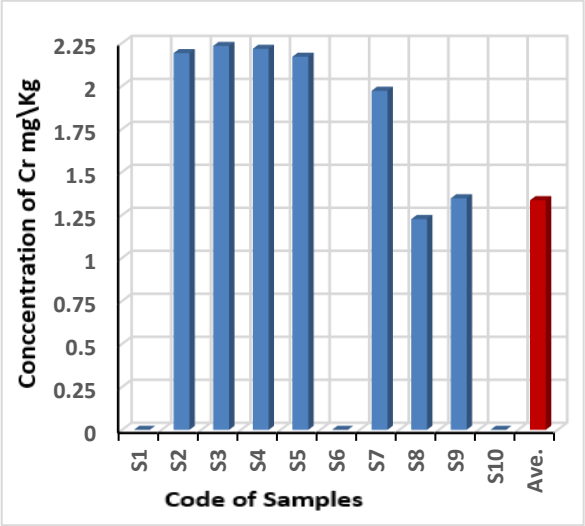


Figure 3. The chromium concentration (mg\Kg) in hair dye samples.

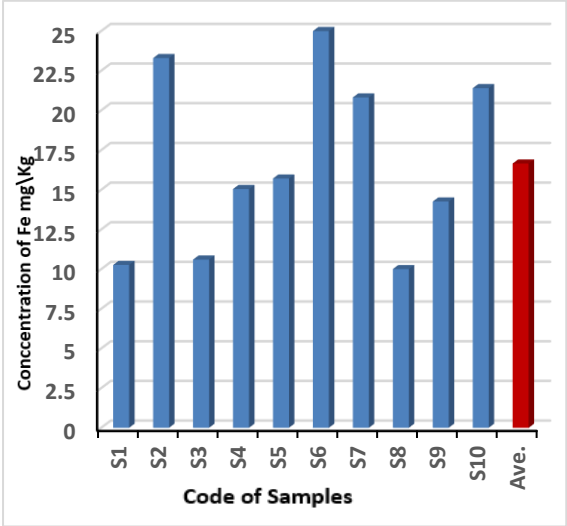


Figure 4. The Iron concentration (mg\Kg) in hair dye samples.

Iron oxides are considered gentle and non-toxic in cosmetic products, and they're applied to the surface of the skin. Several reports of allergic reactions to iron oxides have been reported, causing an allergy to nickel instead. Basically, people with sensitive skin problems are not affected by Iron oxides. Altogether, they're safe and non-vexing in the amounts found in cosmetic products [50]; excessive iron may lead to hemochromatosis, a severe disease that can damage the body's organs.

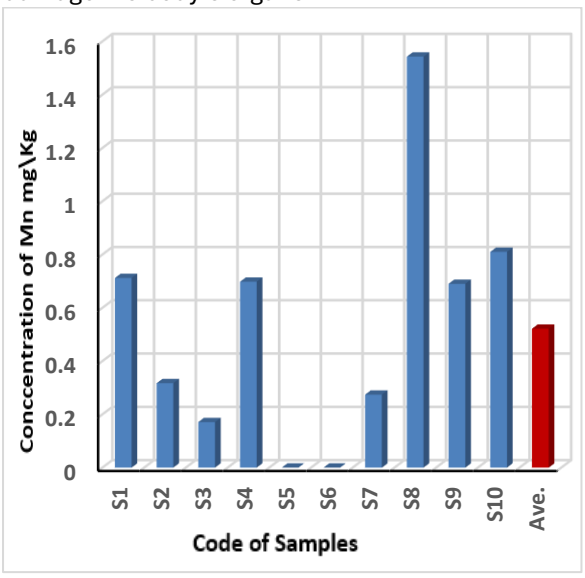


Figure 5. The manganese concentration (mg\Kg) in hair dye samples

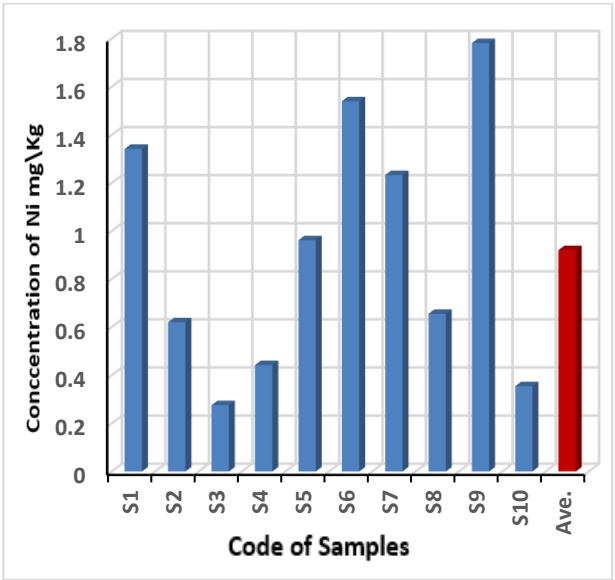


Figure 6. The Nickel concentration (mg\Kg) in hair dye samples.

The manganese levels were tested at concentrations ranging from 0.171 to 1.543 mg/kg, with a mean of 0.522 mg/kg. S8 (L'Oréal Paris) yielded the highest level of Mn, while S3 (Lusso) had the lowest. Mn was not detected in S5 and S6 according to the reported results; these are illustrated in (Figure 5). The variation between products suggests that Mn may be associated with raw materials or pigments rather than being uniformly incorporated into all hair-dye formulations. Previous study for Silva et al. 2025 [30] has also demonstrated considerable variation in Mn concentrations among commercial hair dye products that varied between 0.46 to 1.07 mg/kg.

In general, nickel occurs at low concentrations in the environment, and it also causes a variety of pulmonary adverse health effects, such as lung inflammation, fibrosis, emphysema, and tumours. Nickel in contact with human skin can be easily oxidized by sweat to form soluble and diffusible compounds that penetrate the stratum corneum through appendageal, trans cellular, or intracellular routes. Propensity of Ni to bind with amino-acid residues to form Ni-complexed proteins has been suggested as the main factor responsible for contact allergies and irritations caused by exposure to Ni [51]. Nickel concentrations ranged from 0.276 to 1.782 mg/kg, with a mean concentration of 0.921 mg/kg.

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The highest concentration was detected in S9 (Miss Magic), whereas the lowest was found in S3 (Lusso). Silva et al. 2025 [30] reported that Ni and other elements could be found in measurable quantities with respect to the heavy metals in Iranian hair dyes sold on the Iranian market. Their investigation revealed that Ni levels varied from 0.266 to 1.611 mg/kg. Mostafaii et al. (2022) [2] reported Ni levels of 4.15 mg/kg in blond hair dyes, 2.35 mg/kg in light brown dyes, and 2.40 mg/kg in dark brown dyes, which differ significantly from the values observed in this study. The evidence suggests that Ni is a common impurity in hair dyes, acting as an accidental impurity from pigments, metallic containers, or processing equipment, emphasizing that it is a natural contaminant present in the product.

Some researchers reported that chronic exposure of Cu and Zn-related products is associated with Parkinson's disease [52], and these elements might also act alone or together over time to induce the disease. In this study, there is a noticeable variation in the values of zinc concentrations, where zinc was the second most abundant metal, with concentrations ranging from 2.341 to 9.000 mg/kg. The highest concentrations were recorded in S7 (Beauty Color) and S10 (BBROSE COLOR), whereas the lowest concentration was detected in S4 (Bellissima). The mean Zn concentration was 5.774 mg/kg. The zinc concentration in each of the samples of S1, S2, S3, S4, S5 were less than the average but in the samples S6, S7, S9, S10 higher than the average. However, as illustrated in (Figure 7) there is one sample that is approximately equal to the mean. Iwegbue et al. [48] reported Zn concentrations ranging from 30.0 to 1080 µg/g in different categories of hair-care products, demonstrating that Zn can be an important component of the elemental profile of cosmetic formulations.

(Table 2) illustrated that the means of heavy metal concentrations in blond hair dye samples (n=10) were arranged in the following decreasing order: Fe > Zn > Cr > Ni > Mn > Pb > Cd.

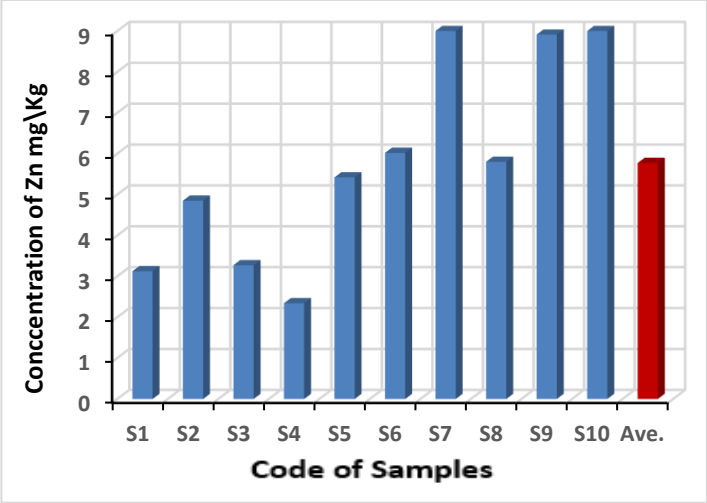


Figure 7. The concentration (mg\Kg) in hair dye samples.

Daily Dermal Exposure Dose (CDDdermal)

The daily intake of each metal through skin exposure to the investigated chemical hair dyes was calculated using equation (1) [33]. The results are illustrated in (Table 3). Moreover, Figure 8 displays the dermal *exposure dose (*CDD) level of the daily intakes of evaluated elements over time. Through cutaneous contact, exposure to hair dyes assists in the absorption of various substances into the human body. The dermal exposure dose (CDD) calculations demonstrated a wide range in exposure levels across the samples, with Fe, Mn, and Cr showing higher values than other metals, Pb, Cd, Zn, and Ni, as illustrated in (Figure 8).

Table 3. Daily dermal exposure dose (CDD_{dermal}) to heavy metals for adults, based on dermal exposure to metals from ten hair dye brands.

No. of sample	Daily dermal exposure dose (CDD_{dermal})						
	Pb	Cd	Cr	Fe	Zn	Mn	Ni
S1	$2.552E^{-10}$	$6.846E^{-11}$	-	$3.194E^{-08}$	$9.647E^{-11}$	$2.216E^{-09}$	$4.176E^{-09}$
S2	$2.147E^{-10}$	-	$6.818E^{-09}$	$7.251E^{-08}$	$1.509E^{-09}$	$9.865E^{-10}$	$1.933E^{-09}$
S3	$2.863E^{-10}$	$5.913E^{-11}$	$6.949E^{-09}$	$3.299E^{-08}$	$9.958E^{-11}$	$5.322E^{-10}$	$8.589E^{-10}$
S4	$2.583E^{-10}$	$4.357E^{-11}$	$6.896E^{-09}$	$4.682E^{-08}$	$7.282E^{-10}$	$2.172E^{-09}$	$1.379E^{-09}$
S5	$1.805E^{-10}$	-	$1.609E^{-08}$	$4.887E^{-08}$	$1.680E^{-10}$	-	$2.994E^{-09}$
S6	$1.867E^{-10}$	$4.046E^{-11}$	-	$7.817E^{-08}$	$1.867E^{-10}$	-	$4.792E^{-09}$
S7	$2.241E^{-10}$	$6.224E^{-11}$	$6.137E^{-09}$	$6.479E^{-08}$	$2.801E^{-11}$	$8.527E^{-10}$	$3.837E^{-09}$
S8	$2.956E^{-10}$	$3.423E^{-11}$	$3.815E^{-09}$	$3.112E^{-08}$	$1.805E^{-10}$	$4.802E^{-09}$	$2.041E^{-09}$
S9	$1.992E^{-10}$	$2.894E^{-10}$	$4.192E^{-09}$	$4.438E^{-08}$	$2.770E^{-10}$	$2.147E^{-09}$	$5.546E^{-09}$
S10	$2.552E^{-10}$	$2.023E^{-10}$	-	$6.661E^{-08}$	$2.801E^{-11}$	$2.521E^{-09}$	$1.105E^{-09}$

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Ave.	$2.356E^{-10}$	$7.998E^{-11}$	$5.090E^{-09}$	$5.182E^{-08}$	$3.302E^{-10}$	$1.623E^{-09}$	$2.866E^{-09}$

The CDD_{dermal} for Pb ranged from 1.805×10^{-10} to 2.956×10^{-10} mg/kg/day. Lead has no safe blood concentration, and it is highly toxic, especially for pregnant women, making it highly dangerous. Cell death through apoptosis and necrosis is one consequence of its accumulation in tissues or organs, which may occur over several generations even through low-dose dermal contact [53].

For Chromium (Cr) dermal exposure dose in (Table 3) varied from 3.815×10^{-9} to 6.949×10^{-09} mg/kg/day, considering that there was no evidence of hair dye exposure in any of the three samples (S1, S6, and S10). Hexavalent chromium is a powerful skin sensitizer and a significant trigger for allergic contact dermatitis. Contact dermatitis, as well as ulcerations and deep wounds known as 'chromeulcers' can result from exposure to chromium, particularly hexavalent chromium (CrVI), involving rubbing and killing chrome ulcers', nd can be caused by exposure to deep pockets or deep wounds. The effects of handling chromium compounds are often observed in workers in industries such as electroplating, tanning, and construction, which are all dependent on these compounds. Systemic absorption through intact skin is restricted, while damaged skin can allow for increased penetration, contributing to the total body burden. Chromium exposure has not resulted in any reported human deaths, but chronic skin contact is still a significant occupational danger due to its local and sensitizing effects, regardless of the frequency of exposure [54].

(Table 3) reveals that Cadmium (Cd) showed dermal exposure values ranging from 2.894×10^{-10} (S9) to 3.423×10^{-11} (S8) mg/kg/day, with no hair dye exposure detected in any samples (S2, and S5).

Iron (Fe) was found to have the highest dermal exposure doses among all evaluated elements, as per the findings of (Table 3). The highest Fe dose (7.817×10^{-08} mg/kg/day) was recorded for S6 (GARNIEA COLOR NATURALS-France), which exceeded the average value (5.128×10^{-08} mg/kg/day). The lowest Fe dose was 3.112×10^{-08} mg/kg/day. Iron absorption is not very high in intact skin; however, iron particles may cause mild irritation or skin stains. Iron toxicity can be classified as either corrosive or cellular. Basically, an excess of iron at the cell level causes metabolic processes in the heart, liver, and central nervous system to be disrupted. Iron enters cells and forms deposits in mitochondria, where it disrupts oxidative phosphorylation, facilitates lipid peroxidation, and facilitates the formation of free radicals by phosphorylating and subsequently destroying the mitochondrial pH balance. The shift of metabolism from aerobic to anaerobic pathways is accompanied by these processes, which lead to the death of cells [55].

According to (Table 3), manganese (Mn) dermal exposure dose ranged from 4.802×10^{-9} to 5.322×10^{-10} mg/kg/day. In terms of dermal toxicity, the risk of significant absorption of manganese (Mn) through intact human skin is very low. The ATSDR Toxicological Profile for Manganese states that exposure to manganese compounds through the skin and percutaneous penetration is minimal, resulting in systemic toxicity. Frequent or forcibly introduced contact with manganese dust or solvents can cause localized irritation or mild contact dermatitis, particularly for workers exposed to manganese dust or exposed solutions, where such exposure is not protected. Manganese is not a carcinogenic agent for the skin, and standard protective equipment and hygiene practices are used as the primary preventive measure [56].

Based on (Table 3), nickel (Ni) was detected with daily dermal doses ranging from 8.589×10^{-9} to 5.546×10^{-10} mg/kg/day. Nickel is a prevalent skin sensitizer that is a major contributor to allergic contact dermatitis, making it one of the most common skin sensitizers worldwide [57]. Local hypersensitivity reactions may develop in sensitized individuals if exposure to nickel or nickel-containing compounds through direct skin contact leads to increased sensitization. Classic symptoms, including itching, erythema, and eczema, may arise from contact with the affected area. Nickel-induced dermatitis is often a consequence of being exposed to excessive amounts of nickel, which is a common cause of nickel exposure. Nickel toxicity can arise from both dermal and systemic exposure, as demonstrated by the possibility of nickel-sensitive individuals developing systemic contact dermatitis after consuming nickel from their diet [57]. Allergies to nickel occur with hair dye formulations that contain trace amounts of the metal, especially if the user has a history of nickel sensitivity. The potential for contact dermatitis caused by excess nickel is significant in cosmetic ingredients. Therefore, minimizing content in cosmetic ingredients minimizes the residual nickel content while complying with regulations on consumer products containing high levels of nickel.

According to (Table 3), zinc (Zn) dermal exposure doses varied from 7.285×10^{-09} to 2.801×10^{-08} mg/kg/day among the investigated hair-dye samples. Zinc is an essential trace element in various physiological processes such as enzymatic activity, cellular metabolism, immune function, and tissue repair. Excess zinc exposure can cause harmful effects, particularly if the exposure is prolonged or elevated to high levels. Zinc is commonly not absorbed through dermal absorption through intact skin; therefore, the estimated dermal exposure in the present study indicates relatively low systemic exposure. Persistent skin damage or irritation can boost dermal exposure and therefore enhance the potential for penetration [58]. Although the calculated dermal doses were low, continuous occupational or repeated consumer exposure may contribute to cumulative exposure.

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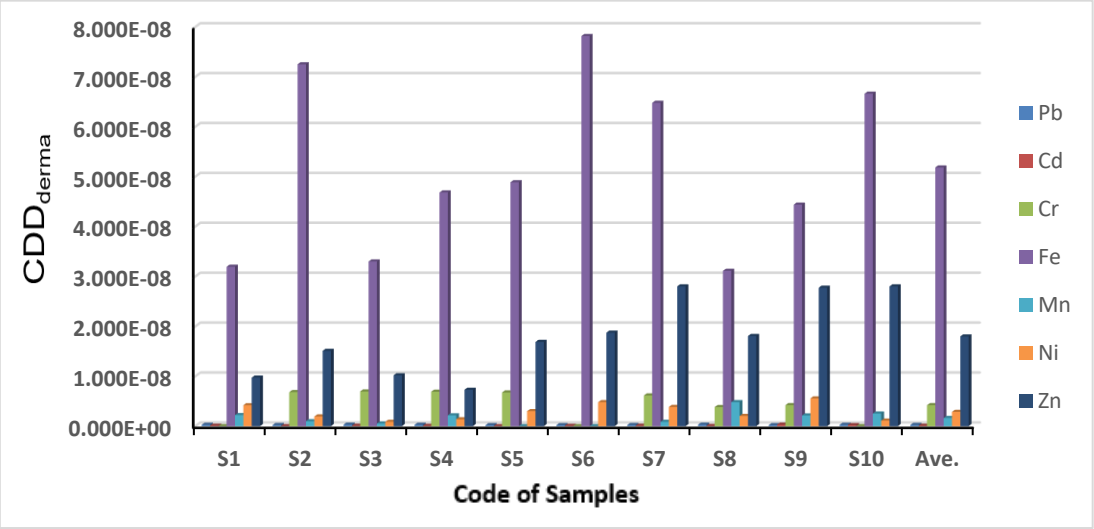


Figure 8. Levels of daily dermal exposure dose (CDD_{dermal}) in different hair dye products.

Risk characterization

Non-cancer risk assessment

Based on the RfD and CDD values, the non-carcinogenic risk assessment was carried out for adults, as shown in (Figure 9). The hazard quotient (HQ) for dermal exposure of adults to individual heavy metals was used to further assess dermal exposure routes (Table 4). No substantial health risk is anticipated for consumers when HQ and HI values are less than 1; however, values more than 1 suggest a possible worry for non-carcinogenic consequences [53].

The HQ values of any individual metal in this study did not exceed 1, indicating that the estimated levels of exposure to various metals were within global safety guidelines for non-carcinogenic effects. (Table 4) indicates that in all brands examined, cadmium (Cd) had the highest HQ value among all brands, being found in S9 (MISS MAGIC- European); HQ_{Cd} varied between 2.738×10^{-06} and 2.315×10^{-05}, followed by manganese and nickel, as shown in (Figure 9). Cadmium is the leading contributor to potential health hazards, as it poses the greatest potential for harm to health. Despite low HQ values for other metals tested, such as Cr, Pb, Fe, and Zn, they still make a significant contribution to the risk assessment.

Table 4. Hazard Quotient (HQ) and Hazard Index (HI) for blonde hair dyes samples calculated for adults.

No. of sample	HQ_{Pb}	HQ_{Cd}	HQ_{Cr}	HQ_{Fe}	HQ_{Mn}	HQ_{Ni}	HQ_{Zn}	HI
S1	$6.380E^{-09}$	$5.477E^{-06}$	-	$4.563E^{-08}$	$2.308E^{-06}$	$7.733E^{-07}$	$3.241E^{-08}$	$8.645E^{-06}$
S2	$5.368E^{-09}$	-	$3.496E^{-07}$	$1.036E^{-07}$	$1.028E^{-06}$	$3.580E^{-07}$	$5.030E^{-08}$	$1.903E^{-06}$
S3	$7.158E^{-09}$	$4.730E^{-06}$	$3.564E^{-07}$	$4.713E^{-08}$	$5.544E^{-07}$	$1.591E^{-07}$	$3.393E^{-08}$	$5.896E^{-06}$
S4	$6.458E^{-09}$	$3.486E^{-06}$	$3.536E^{-07}$	$6.689E^{-08}$	$2.263E^{-06}$	$2.554E^{-07}$	$2.428E^{-08}$	$6.465E^{-06}$
S5	$4.513E^{-09}$	-	$3.463E^{-07}$	$6.981E^{-08}$	-	$5.544E^{-07}$	$5.623E^{-08}$	$1.047E^{-06}$
S6	$4.668E^{-09}$	$3.237E^{-06}$	-	$1.117E^{-07}$	-	$8.874E^{-07}$	$6.243E^{-08}$	$4.303E^{-06}$
S7	$5.603E^{-09}$	$4.979E^{-06}$	$3.147E^{-07}$	$9.256E^{-08}$	$8.882E^{-07}$	$7.106E^{-07}$	$9.337E^{-08}$	$7.091E^{-06}$
S8	$7.390E^{-09}$	$2.738E^{-06}$	$1.956E^{-07}$	$4.446E^{-08}$	5.002^{E-06}	$3.780E^{-07}$	$6.017E^{-08}$	$8.434E^{-06}$
S9	$4.980E^{-09}$	$2.315E^{-05}$	$2.150E^{-07}$	$6.340E^{-08}$	$2.236E^{-06}$	$1.027E^{-06}$	$9.243E^{-08}$	$2.680E^{-05}$
S10	$6.380E^{-09}$	$1.618E^{-05}$	-	$9.516E^{-08}$	$2.626E^{-06}$	$2.046E^{-07}$	$9.337E^{-08}$	$1.921E^{-05}$
Ave.	$5.890E^{-09}$	$6.398E^{-06}$	$2.150E^{-07}$	$7.403E^{-08}$	$1.691E^{-06}$	$5.307E^{-07}$	$5.990E^{-08}$	$8.981E^{-06}$

By utilizing the Hazard Index (HI), the total number of HQs in each sample group (all samples) together demonstrates the resulting non-carcinogenicity of simultaneous exposure to multiple elements. The HI values in this study varied from 1.047×10^{-06} (S5) as the lowest HI value, with the highest HI value being 2.680×10^{-05} (S9), as illustrated in (Figure 10). The cumulative toxicological relevance of these elements has the potential to cause adverse health effects through prolonged exposure. Samples with higher HQ and HI values are more likely to present non-carcinogenic health hazards. Despite remaining, all HI values below 1 suggesting a low combined risk under the estimated exposure scenario. Nevertheless, they suggest a non-negligible simultaneous exposure to multiple metals [33].

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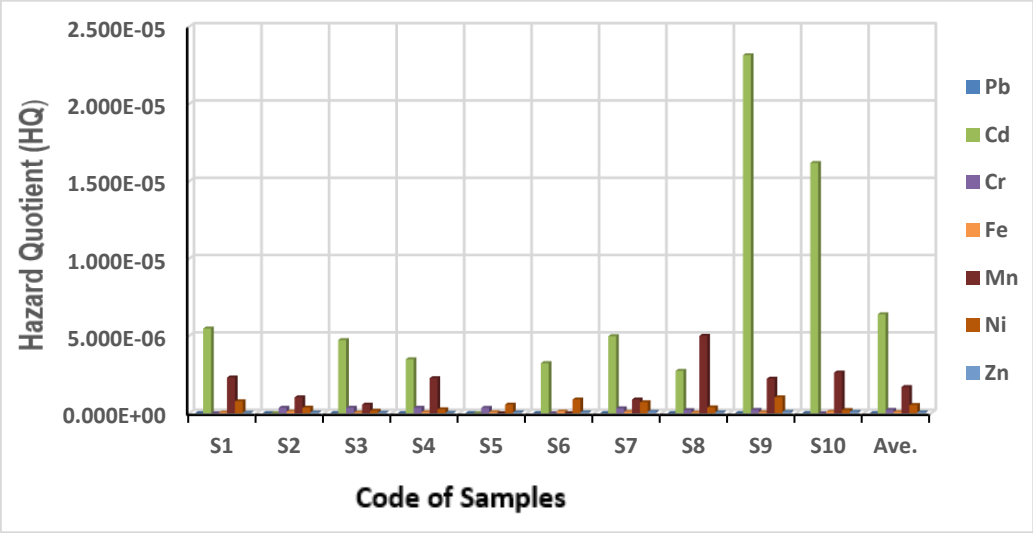


Figure 9. Hazard Quotient (HQ) values for hair dye products.

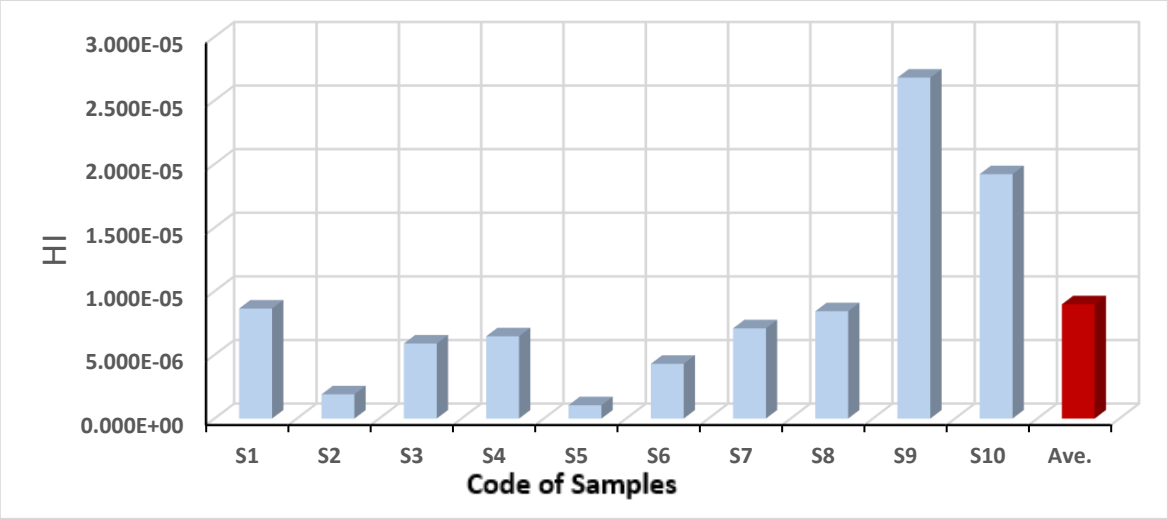


Figure 10. Hazard Index (HI) values for hair dye products.

The use of hair dyes that fall near the scalp can heighten the absorption potential, resulting in the possibility of microlesions and thinner skin, as well as an increased risk of cutaneous inflammation and decreased skin thickness.

In comparison to earlier studies with similar findings (Table 3), the magnitude of HQs is clearly significant. Khalili et al. (2019) [24] is one such case in point, as demonstrated by domestic hair dyes sold in Iran, which have HQs and HI, with values that remain below 1, suggesting cumulative exposure through frequent use. Mostafaii et al. (2022) demonstrate similar findings in their observations of the measurable formation of HQs and HIs [2] in Kashan, Iran, of Pb, Cr, Co, and Ni in hair dye products sold in the area, supported by evidence of the dermal route as an important concern. Ahmed et al. (2019) are an example of this. The evidence shown above supports the notion that bioavailability of metals like Pb and Cd from repeated dermal contact can potentially detect cumulative risk in biological samples sampled by users, even with low or no metal concentration [24].

The findings suggest that tighter quality control, continuous monitoring, and clearer labeling are necessary to reduce consumer exposure to heavy metals in cosmetic products. Regulatory agencies should also adopt and follow best international practices to ensure consumers are safe and to minimize health risks from chronic exposure to toxic and carcinogenic elements.

Overall, the calculated HI values in this study were not above the critical value of 1, which suggests that there is no non-carcinogenic health effect, the comparison suggests that some individual HQs for priority elements (e.g., Pb, As, Cr) emphasize the need to consider cumulative exposure, product labeling, and tighter regulation. The global literature repeatedly advocates for the monitoring of toxic metals in cosmetic formulations due to the potential health implications of chronic dermal absorption of these substances, which supports the observations of this study [24,30,2].

Cancer risk assessment

Heavy metals (HMs) are not biodegradable and tend to accumulate in the human body over time. This buildup not only alters normal cellular activities but also disrupts intracellular processes through oxidative stress, DNA damage, and cell

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death all of which are associated with diseases linked to cancer [59]. Carcinogenic risk (CR) is a tool used to gauge the probability of developing cancer due to specific exposures. The risk of cancer in a person is calculated by examining the amount of time they spend ingesting HMs found in cosmetics. The U.S. Environmental Protection Agency (USEPA) defines an LCR value as inconsequential if it is less than 1 × 10^{-6}, acceptable if it is between 1 × 10^{-6} and 1 × 10^{-4}, and undesirable if it is greater than 1 × 10^{-4} [60].

The CR calculated for Pb, Cd, Cr, and Ni in adults, as shown in (Table 5). The calculations carried out using different brands of blond hair dye are shown in the carcinogenic risk (CR) calculations. Assuming the consumer dyes their hair monthly and remains exposed for approximately 200 days per year, and an exposure duration (ED) of 40 years, which represents typical lifetime use of these products by a typical adult.

Table 5. *Carcinogenic Risk (CR) for Pb, Cd, Cr, and Ni values for hair dye products.*

No. of sample	CR_{Pb}	CR_{Cd}	CR_{Cr}	CR_{Ni}
S1	4.338E^{-12}	4.176E^{-10}	-	1.775E^{-07}
S2	3.650E^{-12}	-	1.364E^{-07}	8.215E^{-08}
S3	4.867E^{-12}	3.607E^{-10}	1.390E^{-07}	3.650E^{-08}
S4	4.391E^{-12}	2.658E^{-10}	1.379E^{-07}	5.861E^{-08}
S5	3.069E^{-12}	-	1.351E^{-07}	1.272E^{-07}
S6	3.174E^{-12}	2.468E^{-10}	-	2.037E^{-07}
S7	3.810E^{-12}	3.797E^{-10}	1.227E^{-07}	1.631E^{-07}
S8	5.025E^{-12}	2.088E^{-10}	7.630E^{-08}	8.674E^{-08}
S9	3.386E^{-12}	1.765E^{-09}	8.384E^{-08}	2.357E^{-07}
S10	4.338E^{-12}	1.234E^{-09}	-	4.696E^{-08}
Ave.	4.005E^{-12}	4.879E^{-10}	8.384E^{-08}	1.218E^{-07}

The results show that for all brands, the CR values for Pb remain in the very low category. The calculated CR values for lead (Pb), ranging from 3.069×10^{-12} to 5.025E×10^{-12} and cadmium (Cd), ranging from 2.088×10^{-10} to 1.765×10^{-9} were all below 10^{-}8, indicating a very low risk, far below the acceptable threshold for carcinogenic risk according to international guidelines (10^{-6}–10^{-4}). In contrast, the calculated CR values for chromium (Cr) and nickel (Ni), the estimated risks ranged between (7.630×10^{-8} -1.390×10^{-7}) and (3.650×10^{-8} -2.357×10^{-7}), respectively, with all brands falling within the low-risk classification.

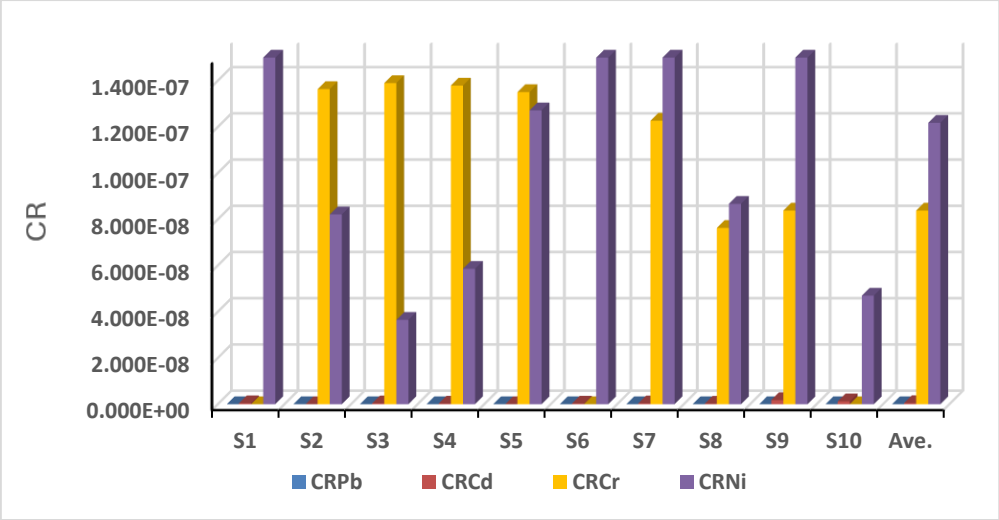


Figure 11. Carcinogenic risk (CR) values for hair dye products.

CR values for hair dyes are within acceptable ranges, but the presence of multiple carcinogenic elements increases the concern about cumulative risk and the potential for additive or synergistic effects, especially in individuals with prolonged and repeated exposure over decades. This conforms to regulations such as the European Union Cosmetics Regulation (EUEUs Regulation (EC) No., and the relevant regulatory bodies. 1223/2009) [27], which prohibits or limits the use of hazardous substances in cosmetic products and permits safe packaging. Furthermore, these estimates are highly conservative as they do not consider vulnerable groups such as pregnant women, adolescents, or those who have compromised skin barriers, which could potentially increase dermal absorption and susceptibility. Factors such as frequency of use, microabrasions on the scalp, concurrent exposure to other products, and frequency of use may also affect actual exposure, resulting in higher exposure levels than modeled scenarios.

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Received: *20-08-2026 -* ***Accepted:*** *18-10-2026 -* ***Published:*** *24-10-2026*

In summary, this study provides evidence for the need for more extensive toxicological studies, such as biomonitoring studies and bioavailability tests, to evaluate systemic absorption in realistic situations. To protect the health of consumers and to harmonize domestic regulations with international standards for the safety of cosmetic products, such measures must be implemented

pH of Hair Dyes Products

The pH range for ten hair dye samples was from 11.52 to 9.04, and the mean of all samples was 10.468. Of the ten samples of hair dyes tested, four had a pH approximately equal to 10 and four of the ten samples analyzed were 11.00, but one of sample has highest pH for sample S2 brand of ORO LUXE LOW AMMONIA and other one was lowest pH for sample S1 brand of MODA COLOR. The results of our study revealed that not all samples were within the range of skin pH (Table 6) and (Figure 12). Differences in pH among the ten products may be due to differences in formulation strategies and alkalizing ingredients, which may be reflected in the observed differences. Routine quality control and accurate labeling of hair dye products are crucial for the success of these findings.

It was observed that the pH values were alkaline. The alkaline pH of hair dyes is related to their formulation and purpose, as they are typically alkaline. Permanent oxidative hair dyes incorporate alkaline ingredients, such as ammonia or alternative alkalizing agents, to facilitate the penetration of dye precursors into the hair cortex by swelling the hair shaft and promoting the onset of dye precursors. The alkalinity level varies depending on the type, concentration, type, and formulation of alkalizing agents and the intended application of the product. Despite the alkaline nature of the pH samples in question, the impact of pH on product safety should not be considered independently tested.

Table 6. pH values of Hair Dyes Products

Sample	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	Ave.
pH	9.93	11.52	10.83	10.37	10.06	11.01	9.04	10.33	10.61	10.98	10.468

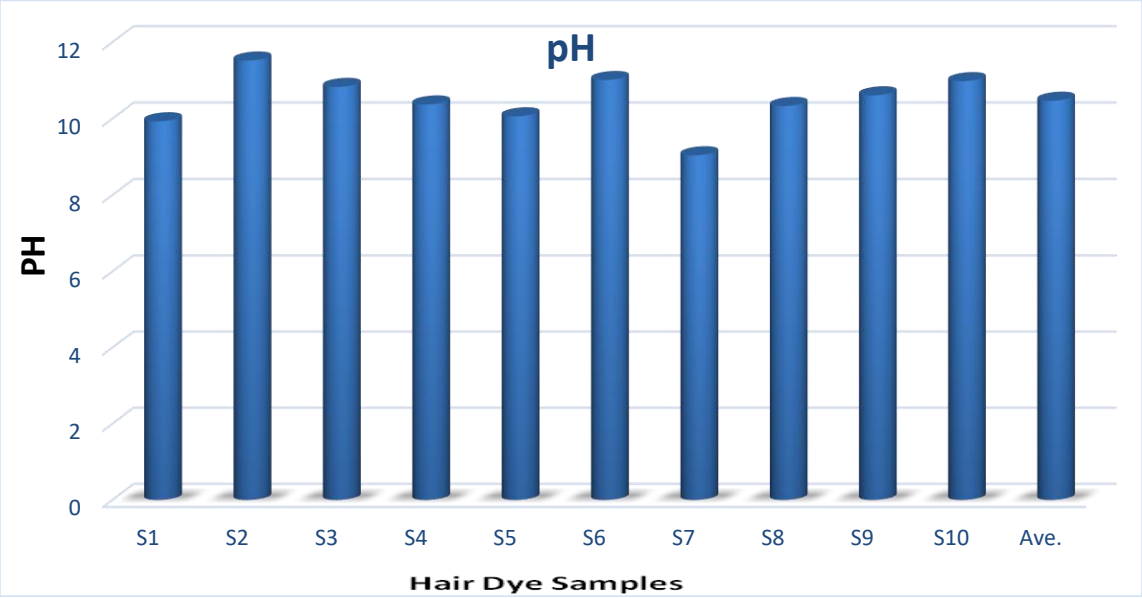


Figure 12. Comparative pH in hair dyes products.

Conclusions

In this study, heavy metals Pb, Cr, Cd, Zn, Ni, Fe, and Mn were detected in all analyzed samples of hair dye. The content of heavy metals in hair dyes differed between heavy metals concentration in the same dye from different manufacturers. Heavy metals that are released into the human body slowly due to the constant use of products may cause these metals to become toxic, leading to dangerous effects. The prolonged use of such products should be avoided, but the fact that both necessary and unhealthy components accumulate in the body as the product is used frequently should not be overlooked. The daily CDD dermal doses for the studied elements were low in absolute terms; they highlight that cumulative exposure through frequent use of hair dye can add significantly to total body burden. Concern is warranted for lead, cadmium, chromium, and nickel due to their known carcinogenic capacity and their capacity for dermal absorption.

The hazard quotients and indices (HI) for hair dye products demonstrated persistently low levels of non-carcinogenic risk, indicating no immediate health threat under standard use, and the HQ and HI remained below international thresholds in each product. Dermal exposure is unlikely to result in major carcinogenic outcomes, as indicated by Cancer Risk CR values that generally remained within the insignificant range ($<10^{-6}$). The findings indicate that maintaining quality control measures, monitoring metal impurities in cosmetic products, and conducting additional research are essential to better understand the long-term health effects of chronic dermal exposure to trace metals in hair dye products.

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Received: *20-08-2026 -* ***Accepted:*** *18-10-2026 -* ***Published:*** *24-10-2026*

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Received*: 20-08-2026 -* ***Accepted****: 18-10-2026 -* ***Published****: 24-10-2026*

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Received*: 20-08-2026 -* ***Accepted****: 18-10-2026 -* ***Published****: 24-10-2026*