

Review

Ecotoxicological Aspects of Hair Dyes: A Review

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Abstract

Hair dyes are widely used across all socioeconomic groups and regions worldwide. However, some studies indicate that these products contain substances known to be toxic to a wide variety of organisms. Moreover, dyeing practices generate effluents that may carry the toxicity of hair dyes into the environment. Due to these facts, there is great concern about the impacts these products may have on the environment, as well as on the health of their users and professionals in the field of cosmetology. This scoping review analyzed 184 publications from major databases (PubMed, SciELO, Scopus, Google Scholar, and MEDLINE). Ultimately, 126 scientific studies published between 1981 and 2024 were included based on methodological rigor and their relevance to the One Health framework. According to the literature, the components of hair dyes can induce adverse responses in biological systems, ranging from reversible topical irritations to severe systemic effects. Among the studies evaluated, more than half reported significant toxicological or genotoxic associations related to oxidative dye components such as *p*-phenylenediamine and its derivatives. These compounds are frequently associated with various types of human cancers, including breast, prostate, bladder, skin, ocular cancers, and brain tumors. In addition to their effects on humans, hair dyes exhibit ecotoxicity, which may threaten the maintenance of ecosystems exposed to their residues. The reported environmental impacts result from effluent emissions after successive hair washes that release unreacted dye residues. Due to the low biodegradability of these compounds, conventional wastewater treatment methods are often ineffective, leading to environmental accumulation and changes in aquatic ecosystems, soil fertility, and trophic balance. Data on the toxicity of hair dye effluents remain scarce and sometimes contradictory, particularly regarding the effects of their transformation products and metabolites. Overall, the evidence underscores the need for continuous monitoring, updated risk assessments, and the adoption of advanced treatment technologies specific to beauty salon effluents. The information presented in this work may support further studies and guide public management agencies in developing policies for mitigating the impacts of hair dye pollutants within the One Health perspective.



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Keywords: environmental impacts; health risks; emerging contaminants; toxicity; hair dyes; dye metabolites

1. Introduction

Hair dye has gained worldwide popularity among different age groups and genders, commonly used for self-expression [1]. Approximately more than one-third of the female population in Asian countries, as well as in Europe and North America, is highly exposed

to hair dyes [2,3]. According to the International Agency for Research on Cancer [4], about 50–80% of women have used hair dyes. As for men, Technavio [5] reports that around 5.6% have already used hair dyes. In recent years, it is possible to notice an increase in the use of these cosmetics.

As an example, the market panel from the Brazilian Association of the Personal Hygiene, Perfumery, and Cosmetics Industry (ABIHPEC) indicated that global hair dye usage intensified further during the COVID-19 pandemic, resulting in a 5.8% increase in sales in 2020 compared to 2019 [6].

The changes in fashion trends and styles in Asian countries, which increasingly reflect Western preferences, have also contributed to the growing popularity of hair treatments. This trend has driven the expansion of the industrial sector, which was projected to reach \$40.08 billion by 2024 [6]. The global hair care market is projected to reach a valuation of USD 18.28 billion by 2029, growing at a compound annual growth rate (CAGR) of 3.7% from 2024 onward. A significant driver of this sector's expansion will be the pervasive influence of social media and digital content creation [7].

Nowadays in Brazil, hair dye consumption reaches approximately 51.4% of households, with 44.6% of users applying dyes at home rather than in salons [8]. Studies have shown that, regardless of whether hair dyes are applied at home or in salons, by professionals or nonprofessionals, only about 10–15% of the applied dye adheres to the hair fibers, while the remaining fraction is washed away and discharged as domestic wastewater without prior treatment [9,10]. This disposal poses significant environmental problems, as hair dye residues persist in water even after conventional treatment at wastewater treatment plants (WWTPs). Moreover, hair dyes alter the characteristics of receiving water bodies due to their color, diversity, reactivity, solubility, volatility, and stability [10].

Another environmental issue related to hair dyes is that most brands maintain their formulations confidential, further complicating the treatment of effluents generated by these products. Among the known components of various hair dyes are toxic and recalcitrant compounds such as *p*-phenylenediamine, *p*-toluenediamine, *o*- or *p*-aminophenols, *m*-substituted aromatic derivatives, resorcinol, and hydrogen peroxide [10]. Such environmental concerns have raised questions about the generation of wastewater from consumers, salons, and the cosmetics industry.

Although several studies have examined the toxicological and epidemiological implications of hair dye use in humans [1–4], the ecotoxicological dimension of these products remains comparatively underexplored. Most of the available reviews emphasize carcinogenic and occupational health aspects rather than the environmental fate, persistence, and effects of hair dye residues on aquatic and terrestrial organisms [9–12]. This evident gap in the literature highlights the limited understanding of how these contaminants interact with environmental matrices and bioindicators, reinforcing the importance of expanding ecotoxicological assessments to better comprehend their broader ecological relevance [10–12].

In this context, assessments of water quality and the pollutant burden in effluents are traditionally based on physicochemical measurements [11]. Although useful, these analyses do not provide a complete understanding of the true toxic effects that contaminants may exert [12]. In contrast, ecotoxicological approaches offer a broader and more detailed perspective, enabling the examination of the harmful impacts of effluents and of the environments that receive them [11–14].

The generation of liquid effluents in the cosmetics industry is influenced by two major factors: the frequency of equipment cleaning operations [13,14] and the type of product manufactured. Effluents commonly exhibit high chemical oxygen demand (COD), with elevated concentrations of organic compounds that are poorly biodegradable, such as preservatives, surfactant mixtures, dyes, and fragrances [15–17].

Given the issues presented, this study aims to compile updated information on the environmental impacts of hair dyes, as well as the risks these compounds pose to human health. Although many articles address the toxicity of hair dyes, there remains a gap regarding the impacts caused by salon effluents containing these dyes.

2. Review

Many products in the beauty industry may contain unregulated substances with high toxicity, posing risks to consumers and the environment. These products can release hazardous compounds, such as lithium hydroxide, calcium hydroxide, guanidine carbonate, and ammonium thioglycolate, many of which exhibit genotoxic properties [4,18,19]. In this context, beauty salons generate a wide variety of waste products, including alkalis, acids, relaxers, dyes, and other chemicals, which compromise public health and alter the environmental characteristics of the receiving areas [20].

Given the increasing concern about the environmental and health impacts of cosmetic products, recent studies have emphasized the relevance of the One Health framework in understanding how chemicals from hair dyes may affect human health, animal exposure, and environmental quality. This integrative perspective considers shared pathways of contamination, such as wastewater discharge and bioaccumulation in aquatic organisms, highlighting the interconnectedness of anthropogenic activities and ecosystem health. It also reinforces the need for coordinated surveillance, regulatory measures, and sustainable management practices to mitigate these risks [21].

Overall, the evidence reinforces that a One Health perspective is essential to comprehensively assess the toxicological and ecological implications of hair dye use and disposal.

3. Methodology

This exploratory review was conducted to identify and analyze scientific evidence addressing the composition, toxicological effects, and environmental behavior of hair dyes within a One Health framework. A systematic literature search was performed in the PubMed, Scopus, SciELO, Google Scholar, and MEDLINE databases. The search included publications from the last four decades, using combinations of the keywords “hair dye,” “effluent,” “toxicity,” “biodegradation,” “bioindicator,” and “One Health.”

Studies were included if they addressed: (i) the chemical composition, environmental fate, or ecotoxicological effects of hair dyes; (ii) wastewater or effluents generated by salons or cosmetic industries; or (iii) remediation or treatment technologies for dye-contaminated matrices. Review articles, original research papers, and case studies written in English, Portuguese, or Spanish were considered.

Exclusion criteria comprised duplicate records, studies not directly related to dyes, and those lacking methodological or quantitative detail. The quality and relevance of the selected studies were assessed according to methodological transparency and completeness of reported results.

From a total of 184 references identified, 126 studies met the inclusion criteria and were analyzed in depth. These works were grouped thematically according to their focus on human health impacts, toxicological mechanisms, environmental fate, and treatment or remediation approaches, allowing an integrated assessment across the One Health approach.

4. Types of Hair Coloring

4.1. Natural Coloring

Natural hair coloring typically derives from plants such as walnut (*Juglans regia*), which produces brown pigments; chamomile (*Matricaria chamomilla*), for yellowish hues;

henna (*Lawsonia inermis*); and indigo (*Indigofera tinctoria*), both used to achieve dark black tones [9,22].

The use of natural colorants of hair dates back approximately 4000 years [22]. According to Chua and Levell [23], during the 16th century, Venetian women followed recipes published in the *Diccionario Feminino* (1694), which offered formulas for modifying hair color. Among these formulas were mixtures of elderberry berries with wine to produce black tones, radish extract for light brown shades, and a combination of lime and saffron for blonde hues.

Natural dyes offer several advantages compared to synthetic colorants, the most notable being their low allergenicity, making them particularly suitable for individuals sensitive to oxidative dyes. However, their use is limited by lower formulation stability and a narrower range of colors compared to the shades available in permanent dyes [24,25]. Additionally, while natural dyes are non-toxic, their adherence to hair fibers is temporary [26], as their coloring agents are characterized by high molecular weight, which results in low affinity for keratin. Consequently, these substances either do not penetrate or penetrate only minimally into the hair shaft, remaining largely on the hair surface [27–29].

Currently, most natural hair dyes are based on henna, whose active coloring agent is Lawsone (2-hydroxy-1,4-naphthoquinone). This compound is extracted directly from the plant leaves or manufactured as a purified product, as illustrated in Figure 1 [30]. According to Semwal et al. [31], *henna* exhibits a reddish-brown color and contains bioactive compounds derived from essential oils, including alpha and beta-ionones, flavonoids, xanthenes (lawsone I, II, and III), and coumarin. In addition to its coloring properties, *henna* possesses astringent, anti-inflammatory, antifungal, and antibacterial properties.

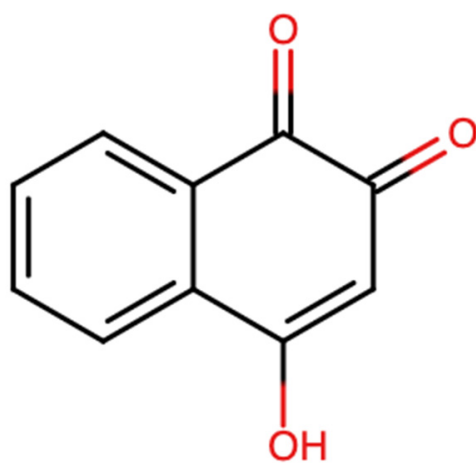


Figure 1. Structure of Lawsone (2-hydroxy-1,4-naphthoquinone), the natural dye extracted from *henna*. Images created using the Chemical Sketch Tool (Marvin JS 22.11.1, Chemaxon, Budapest, Hungary).

4.2. Synthetic Coloring

Synthetic dyes are formulated with low molecular weight compounds, often containing amines, amino-phenols, and phenols [32]. However, some of these compounds can pose risks to human health, such as amines, which are bioactive substances capable of inducing mutagenic or carcinogenic effects when absorbed percutaneously [22].

According to Gomes [33], synthetic hair colorants can be classified into temporary or semi-permanent dyes and oxidative or permanent dyes. Temporary dyes are primarily composed of diluted colorants in aqueous solutions, characterized by their acidic nature and weak affinity for hair keratin. The low affinity causes extremely weak bonds that produce a transient effect, leading to removal after just a few washes [26]. Generally, as

temporary synthetic dyes do not penetrate the hair cortex, they are considered to have lower toxicity to humans compared to permanent dyes [22,34–37].

Some of the primary acidic dyes used in temporary dye formulations are presented in the following table (Table 1).

Table 1. Structural and molecular formulas of acidic dyes used in temporary dye formulations and their known effects.

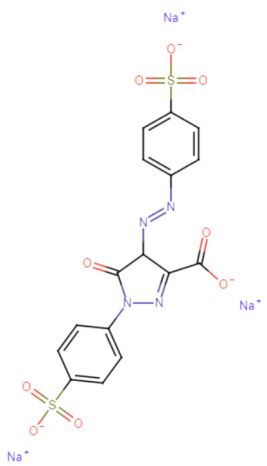
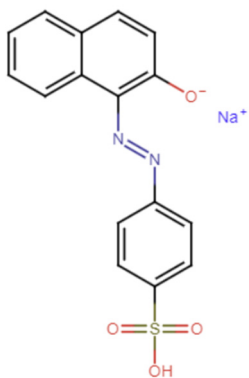
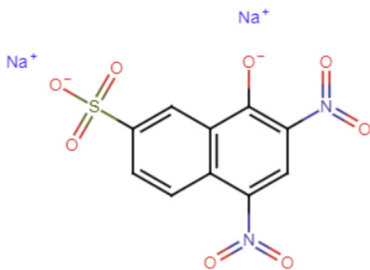
Dyes—INCI	Characteristics	Effects
Acid Yellow 23	 Formula: $C_{16}H_{12}N_4O_9S_2 \cdot 3Na$ CAS No. 1934-21-0	- No significant adverse effects were observed in rats during long-term feeding studies. - May cause skin and respiratory sensitization following prolonged exposure [38].
Acid Orange 7	 CAS No. 633-96-5 Formula: $C_{16}H_{12}N_2O_4S \cdot Na$	Not an ocular irritant in rabbits. - No evidence of skin sensitization. - Hematological alterations observed in an oral exposure study in rats. - No evidence of teratogenicity [39].
Acid Yellow 1	 CAS No. 846-70-8 Formula: $C_{10}H_6N_2O_8S \cdot 2Na$	- Causes skin irritation. - May cause skin sensitization after prolonged or repeated exposure [40].

Table 1. Cont.

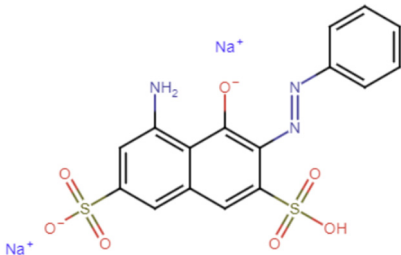
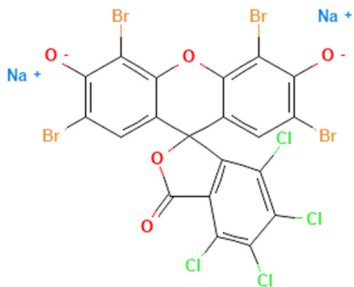
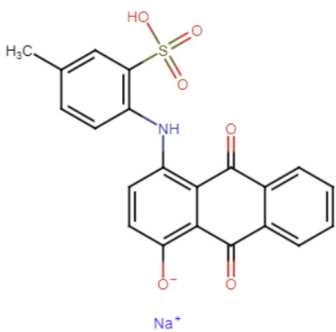
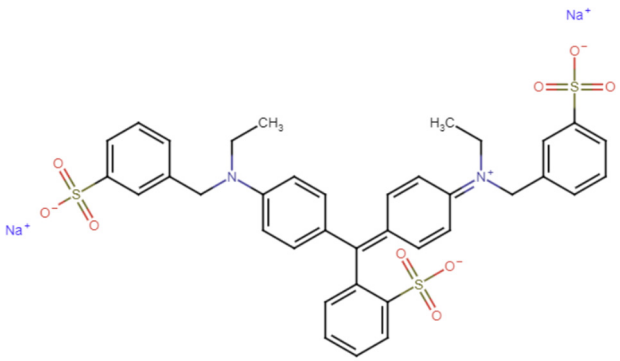
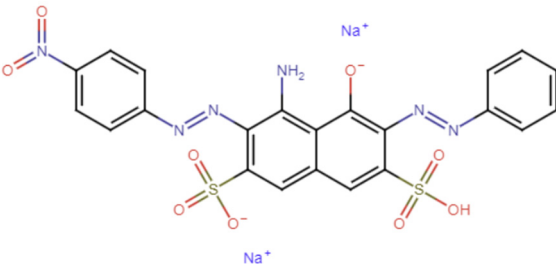
Dyes—INCI	Characteristics	Effects
Acid Red 33	 CAS No. 3567-66-6 Formula: C₁₆H₁₃N₃O₇S₂·2Na	Causes severe eye irritation (Serious eye damage) [41].
Acid Red 92	 CAS No. 18472-87-2 Formula: C₂₀H₄Br₄Cl₄O₅·2Na	- Causes severe eye irritation. - May cause damage to organs through prolonged or repeated exposure. - Harmful to aquatic organisms, with long-lasting effects [42].
Acid Violet 43	 CAS No. 4430-18-6 Formula: C₂₁H₁₅NO₆S·Na	- Exhibits corrosive effects. - Causes serious eye damage. - Harmful to aquatic organisms, with long-lasting effects [43].
Acid Blue 9	 CAS No. 3844-45-9 Formula: C₃₇H₃₆N₂O₉S₃·2Na	- Carcinogenic to rats after repeated subcutaneous injections, inducing fibrosarcomas. - No data available for humans. - Classified as carcinogenic by the IARC: Group 3 [44].

Table 1. Cont.

Dyes—INCI	Characteristics	Effects
Acid Black 1	 CAS No. 1064-48-8 Formula: C₂₂H₁₄N₆O₉S₂·2Na	May affect organs after prolonged or repeated exposure [45].

INCI, International Nomenclature of Cosmetic Ingredients; CAS, Chemical Abstract Service. Images created using the Chemical Sketch Tool (Marvin JS 22.11.1, Chemaxon, Budapest, Hungary).

Synthetic semipermanent dyes have low to medium molecular weight and commonly contain nitro groups and aromatic amines in their molecular structure, such as aminophenol and aminophenol esters, as listed in Tables 2 and 3. This type of coloring is similar to permanent synthetic dyes; however, due to its weak interaction with the hair fiber—primarily mediated by Van der Waals forces—its durability is shorter compared to permanent dyes (4 to 7 weeks) [22].

Table 2. Structural and molecular formulas of nitroanilines used in semipermanent dye formulations.

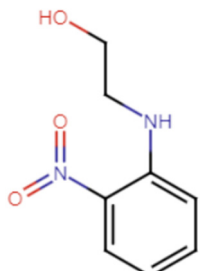
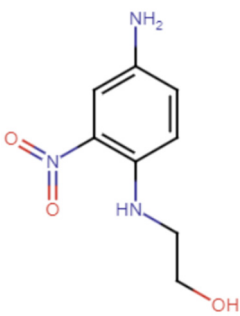
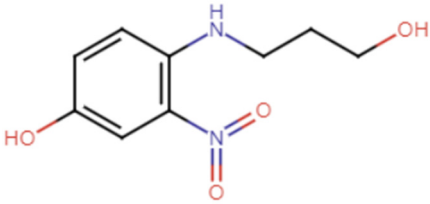
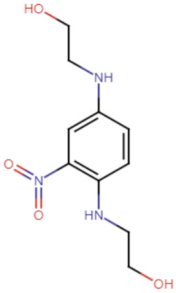
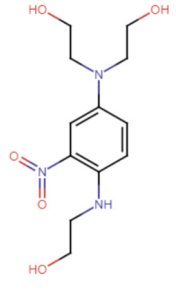
Dyes—INCI	Characteristics	Effects
HC Yellow No. 2	 CAS No. 4926-55-0 Formula: C₈H₁₀N₂O₃	- Harmful if ingested (Acute oral toxicity). - Causes skin irritation (Skin corrosion/irritation). - Causes severe eye irritation (Serious eye damage/eye irritation). - Harmful to aquatic organisms, with long-lasting effects [46].
HC Red No. 3	 CAS No. 2871-01-4 Formula: C₈H₁₁N₃O₃	- May cause an allergic skin reaction. - Causes severe eye irritation. - Specific target organ toxicity—single exposure. - Respiratory tract irritation. - Toxic to aquatic organisms, with long-lasting effects [47].

Table 2. Cont.

Dyes—INCI	Characteristics	Effects
4-Hydroxypropylamino-3-nitrophenol	 CAS No. 92952-81-3 Formula: C₉H₁₂N₂O₄	• May cause an allergic skin reaction. • Causes severe eye irritation. • Specific target organ toxicity—single exposure. • Respiratory tract irritation. • Toxic to aquatic organisms, with long-lasting effects [48].
N, N'-bis-(2-hydroxyethyl)-2-nitrophenylenediamine	 CAS No. 84041-77-0 Formula: C₁₀H₁₅N₃O₄	• Harmful in contact with skin. • Causes skin irritation (corrosion/skin irritation). • Causes serious eye irritation. • Harmful if inhaled. • May cause respiratory tract irritation [49].
HC Blue No. 2	 CAS No. 33229-34-4 Formula: C₁₂H₁₉N₃O₅	• May cause an allergic skin reaction. • Causes serious eye irritation. • May cause respiratory irritation [50].

INCI, International Nomenclature of Cosmetic Ingredients; CAS, Chemical Abstract Service. Images created using the Chemical Sketch Tool (Marvin JS 22.11.1, Chemaxon, Budapest, Hungary).

Permanent hair dyes are typically prepared with two components, which, when mixed, impart color through reactions on the surface and within the hair fiber [22]. The first component is an intermediate agent (*p*-diamines or *p*-aminophenols) or couplers (*m*-diamines or *m*-aminophenols) for strong alkaline formulations. These compounds swell the cuticle, allowing the molecules to penetrate the cortex. The second component is an oxidizing solution, such as hydrogen peroxide, which oxidizes the dye from the first component, imparting color to the hair strand.

Different coupler agents are available on the market, some listed in Table 4 [26]. The oxidation of these substances and their coupling with other modifiers allows the final color of the product, which has greater durability and offers a wide range of shades. This process typically involves primary intermediates such as *p*-phenylenediamine, which, upon oxidation, react with couplers to form larger chromophore molecules. These chemical reactions occur within the hair shaft, resulting in permanent color changes and enhanced resistance to washing and fading.

Table 3. Structural and molecular formulas of cationic compounds used in semi-permanent dye formulations.

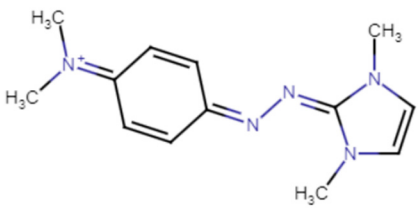
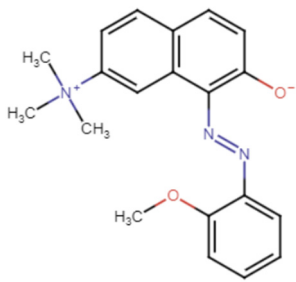
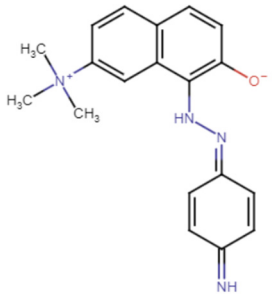
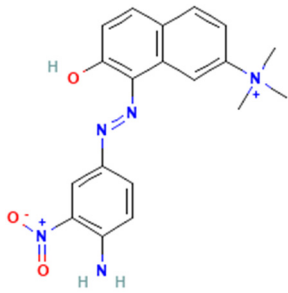
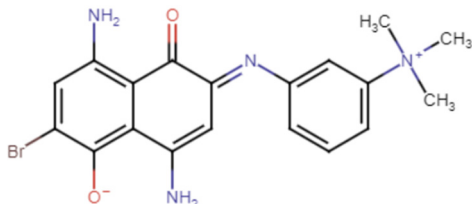
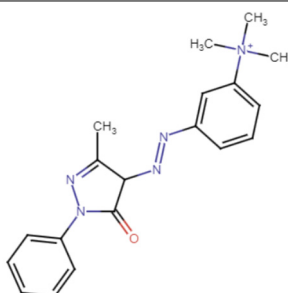
Dyes—INCI	Characteristics	Effects
Basic Red 51	 CAS No. 77061-58-6 Formula: $C_{13}H_{18}N_5 \cdot Cl$	• Harmful if swallowed. • Causes skin irritation. • Causes serious eye irritation. • Harmful if inhaled. • May cause respiratory irritation. • Very toxic to aquatic organisms, with long-lasting effects [51].
Basic Red 76	 CAS No. 68391-30-0 Formula: $C_{20}H_{22}N_3O_2 \cdot Cl$	• No evidence of skin sensitization. • No evidence of genotoxicity. • No evidence of teratogenicity [52].
Basic Brown 16	 CAS No. 26381-41-9 Formula: $C_{19}H_{21}N_4O \cdot Cl$	• May cause an allergic skin reaction. • Causes serious eye irritation [53].
Basic Brown 17	 CAS No. 68391-32-2 Formula: $C_{19}H_{20}N_5O_3 \cdot Cl$	• No evidence of skin sensitization. • No evidence of genotoxicity. • No evidence of teratogenicity [54].

Table 3. Cont.

Dyes—INCI	Characteristics	Effects
Basic Blue 99	 CAS No. 68123-13-7 Formula: $C_{19}H_{20}BrN_4O_2 \cdot Cl$	HCl - Causes serious eye damage. - Skin sensitizer (May cause contact dermatitis and/or urticaria) [55].
Basic Yellow 57	 CAS No. 68391-31-1 Formula: $C_{19}H_{22}N_5O \cdot Cl$	Cl⁻ - No evidence of genotoxicity. - No evidence of teratogenicity [56].

INCI, International Nomenclature of Cosmetic Ingredients; CAS, Chemical Abstract Service. Images created using the Chemical Sketch Tool (Marvin JS 22.11.1, Chemaxon, Budapest, Hungary).

Table 4. Molecular and structural formulas of reaction couplers.

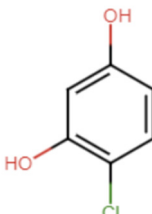
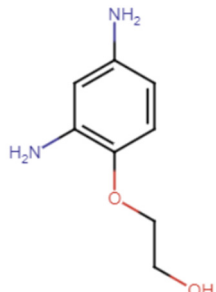
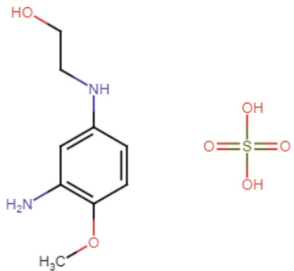
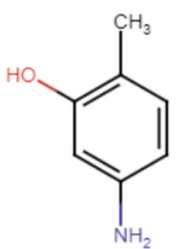
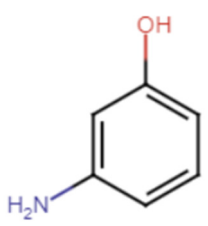
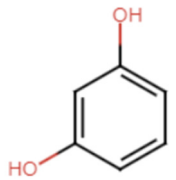
Couplers	Characteristics	Effects
4-Chlororesorcinol	 CAS No. 95-88-5 Formula: $C_6H_5ClO_2$	- Harmful if ingested. - Harmful if in contact with skin. - Causes skin irritation. - May cause an allergic skin reaction. - Causes serious eye damage. - Harmful if inhaled. - May cause respiratory irritation. - Toxic to aquatic organisms, with long-lasting effects [57].
2,4-Diaminophenoxyethanol HCl	 CAS No. 66422-95-5 Formula: $C_8H_{12}N_2O_2 \cdot 2HCl$	HCl - Causes skin irritation (allergic contact dermatitis). - Causes severe eye irritation [58].

Table 4. Cont.

Couplers	Characteristics	Effects
2-Amino-4-((2-hydroxyethyl)amino)anisole sulfate	 CAS No. 83763-48-8 Formula: $C_9H_{14}N_2O_2 \cdot H_2O_4S$	• Harmful if swallowed. • Causes skin irritation. • May cause an allergic skin reaction. • Causes serious eye damage. • May cause damage to organs through prolonged or repeated exposure. • Very toxic to aquatic organisms [59].
4-Amino-2-hydroxytoluene	 CAS No. 2835-95-2 Formula: C_7H_9NO	• Causes skin irritation. • May cause an allergic skin reaction. • Causes serious eye damage. • May cause respiratory irritation. • Very toxic to aquatic organisms [60].
<i>m</i> -Aminophenol	 CAS No. 591-27-5 Formula: C_6H_7NO	• Harmful if swallowed or inhaled. • May cause an allergic skin reaction. • Harmful by inhalation. • Very toxic to aquatic organisms [61].
Resorcinol	 CAS No. 108-46-3 Formula: $C_6H_6O_2$	• Harmful if swallowed. • May cause an allergic skin reaction. • Causes serious eye damage. • Causes damage to organs. • Very toxic to aquatic organisms [62].

INCI, International Nomenclature of Cosmetic Ingredients; CAS, Chemical Abstract Service. Images created using the Chemical Sketch Tool (Marvin JS 22.11.1, Chemaxon, Budapest, Hungary).

Due to the high fixation provided by the dye's affinity to the keratin in hair, reapplication of the product is only necessary when natural hair growth occurs, which happens approximately once a month [28]. Therefore, this coloring process can be considered irreversible, as removal is only achieved by cutting the hair strands [26]. However, the continuous use of permanent dyes can affect the hair shaft, leading to a loss of shine, strength, and softness [27].

5. Toxicological Effects on Human Health

5.1. Mechanistic and Cellular Toxicity

The toxicity of certain hair dyes and the ingredients present in commercial hair coloring products has been widely investigated. Despite the widespread use of these cosmetics, hair dyes pose risks to both users and professionals. There are adverse reactions they can trigger in biological systems, ranging from mild irritation or sensitization to more severe systemic effects [20,63]. Recent studies confirm that oxidative hair dyes, especially those containing aromatic amines like *p*-phenylenediamine (PPD), can lead to allergic and inflammatory responses, especially in occupational settings [64].

While up to 96% of PPD may remain unreacted during the dyeing process [9], this does not necessarily imply proportional systemic exposure. Dermal metabolism and first-pass detoxification mechanisms significantly reduce bioavailability [64–66]. Nonetheless, the persistence of residual PPD warrants further toxicological evaluation.

These reactions can vary depending on individual consumer factors, improper product use, or its composition. Studies have shown that the toxic effects of hair dyes are often associated with the presence of PPD, a substance found in over 1000 hair dye formulations sold worldwide [65]. Recent findings have reiterated the strong sensitizing potential of PPD, especially in repeated or prolonged exposures [66].

Other components under scientific scrutiny include precursors such as resorcinol. According to Lynch et al. [67], resorcinol acts as an endocrine disruptor, affecting the thyroid gland. There is also concern regarding azo dyes ($R-N=N-R'$), which have been reported to exhibit high toxicity [68,69]. New evidence confirms their potential to generate aromatic amines with genotoxic and mutagenic effects after metabolic transformation.

Since 1993, IARC has warned cosmetology professionals about the precautions they should take when exposed to hair dyes. However, this warning is often ignored, and beauty salons continue to be perceived as places of beautification and relaxation, where personal protective equipment (PPE) is frequently neglected [70]. Recent occupational health studies reinforce that many hairdressers still work in inadequately ventilated environments and without PPE, increasing their exposure to hazardous compounds. Despite significant advancements in products and techniques in this field, information regarding the toxicity and mutagenicity of most hair pigments remains scarce.

Among the limited toxicogenetic studies on cosmetic products, most focus on the components used in hair dyeing, such as pigments and certain additives [71], with little information available on the secondary compounds formed during the hair coloring process [22,72]. Recent investigations have highlighted the need for assessing both primary and secondary byproducts in hair dye metabolism, given their possible mutagenic risks. Furthermore, studies addressing the environmental and human health impacts of liquid effluents generated in beauty salons are also limited [73].

According to Nkansah et al. [19], the limited literature on this subject has prevented further studies from assessing the quality of wastewater from beauty salons as a source of environmental and public health hazards.

Despite a well-established body of evidence highlighting the toxic, mutagenic, and carcinogenic effects of synthetic dyes—particularly azo compounds—the mechanistic understanding of some compounds remains complex in the literature. In general, aromatic amines, generated by the reductive cleavage of azo bonds, undergo enzymatic bioactivation, mainly via cytochrome P450-mediated N-hydroxylation. This pathway leads to the formation of electrophilic intermediates capable of forming DNA adducts, initiating genomic instability and carcinogenesis [74].

In parallel, several dyes have been shown to elevate intracellular levels of reactive oxygen species (ROS), triggering oxidative stress, lipid peroxidation, protein oxidation, and

mitochondrial dysfunction [75]. These molecular perturbations often result in cytotoxic and genotoxic effects in both aquatic organisms and mammalian systems. Furthermore, several synthetic dyes have demonstrated endocrine-disrupting capabilities, interfering with hormonal pathways that regulate reproductive and developmental processes [76].

However, some ingredients, such as PPD, exemplify the complex toxicological profile associated with commercial formulations. Although quantitative exposure models suggest that concentrations below 0.67% may pose a minimal risk of sensitization in controlled use scenarios [77], other studies report unreacted PPD residues reaching up to 96% after product application, indicating potentially higher exposure levels and sensitization risks in the real world [66].

Such inconsistencies likely result from methodological heterogeneity, including variations in testing conditions, detection techniques, and assumptions about percutaneous absorption. Furthermore, a disproportionate reliance on *in vitro* assays and rodent models creates gaps in the extrapolation of toxicological effects to human settings, especially for chronic low-dose exposures. The toxicokinetics and cumulative impact of secondary metabolites, as well as exposure to complex mixtures in occupational settings such as hair salons, are rarely studied.

Nevertheless, these research gaps highlight the urgent need for standardized experimental protocols, long-term human exposure assessments, and comprehensive toxicokinetic profiles to increase the reliability of health risk assessments.

5.2. Epidemiological and Clinical Evidence

Until the 1960s, it was widely believed that personal care products, such as hair dyes, could only cause topical effects, as they were presumed to remain on the skin or the application area. However, in recent decades, studies have shown that topically applied products can be absorbed and potentially cause systemic effects in organisms [22]. More recent research confirms this systemic absorption, particularly highlighting that certain dye components may penetrate the skin barrier and enter the bloodstream [78].

According to De Oliveira et al. [22], hair dyes induce harmful effects on humans, affecting both consumers and professionals. Nevertheless, individuals exposed to these dyes are unaware of the potential harm these substances may inflict on their bodies. Numerous studies have raised concerns about the potential link between the use of permanent hair dyes and the incidence of cancer [79–81]. This concern persists, with newer studies suggesting a continued association between prolonged use of permanent hair dyes and increased cancer risk, especially among frequent users [82].

Several authors have reported associations between hair dye use and specific types of cancer. Among the observed adverse effects are hematopoietic disorders such as non-Hodgkin lymphoma (NHL), Hodgkin's disease, multiple myeloma, leukemia, and myelodysplastic syndrome (MDS). In this context, Thun et al. [83] suggested that prolonged use of dark permanent hair dyes, particularly black shades, is associated with an increased risk of fatal NHL and multiple myeloma in female users. These findings are reinforced by Zhang et al. [84], who identified an elevated risk of NHL among women who began using darker hair dyes prior to the 1980s. Furthermore, recent evidence supports a positive correlation between cumulative hair dye exposure, especially permanent black hair dyes, and the development of lymphoma and other hematological cancers [85,86].

The correlation between the use of hair dyes and the development of leukemia has also been documented by other researchers. Rauscher et al. [87] conducted a case-control study of cancer in the United States and Canada between 1986 and 1989, suggesting that prolonged use of hair dyes may increase the risk of acute leukemia in adults. Another case study conducted by Couto et al. [88] across hospitals in 13 Brazilian states, between 1999

and 2007, indicated that maternal exposure to hair dyes and chemical hair straighteners during pregnancy could be implicated in the etiology of leukemia in children under two years old. Similarly, new evidence suggests that prenatal exposure to certain hair dye chemicals may contribute to pediatric leukemia development.

A study conducted in Japan [89] investigated the potential relationship between hair dye use and the etiology of leukemia, specifically Myelodysplastic Syndrome (MDS). The authors observed a significant increase in the development of MDS among women who used hair dyes, identifying a dose–response relationship between the duration and frequency of use and the elevated risk.

Another cancer type was studied by Heikkinen et al. [90]. The authors related the intensive use of hair dyes to the impact on public health due to an increased incidence of mammary adenocarcinoma. Similarly, Stavraký et al. [91] associated the occurrence of breast cancer in women over 50 years old with hair dye use for more than ten years. Llanos et al. [92] observed a connection between the use of hair care products (including dyes, chemical relaxers, and conditioners) and breast cancer incidence in African American and white women in the United States. The authors noted a troubling rise in breast cancer cases linked to the use of these products. Ahmadi et al. [93] reported that women who used dark hair dyes had a 9% higher risk of developing cancer compared to non-users. Similarly, Gera et al. [94] found that hair dye use was associated with an 18.8% higher risk of breast cancer.

Bladder cancer is the most frequently reported carcinoma associated with hair dye use in the global literature. In Canada, a case study by Gaertner et al. [95] identified a statistically significant risk of bladder cancer among barbers occupationally exposed to hair dyes; however, the authors attributed this risk specifically to the use of hair brillantine rather than to the dyes themselves. Subsequent studies from Canada and Nordic countries have further identified occupational risks associated with hair dye exposure, reporting an elevated risk of bladder cancer among hairdressers in these regions [96]. In their analysis, Haldkale et al. [96] reported an increased bladder cancer risk specifically among male hairdressers, whereas in Nordic countries, a risk increase was observed among female hairdressers. The authors did not explicitly explain this demographic discrepancy, but they note that hairdressers are occupationally exposed to aromatic amine compounds, including benzidine, toluidine, and carcinogenic aromatic nitrosamines; this exposure is linked to an elevated risk of bladder cancer.

In Sweden, Czene et al. [97] conducted a study involving 38,866 women and 6824 male hairdressers, who were monitored for malignancies over 39 years. Their findings highlighted bladder cancer as the most significant concern among male hairdressers evaluated during the 1960s, with standardized incidence ratios (SIR) of 2.56. However, subsequent studies by the same authors in other periods showed that this high incidence was not maintained. Similarly, Skov et al. [98] reported increased risks of bladder cancer among male hairdressers of Swedish, Finnish, and Norwegian descent.

Despite these findings, the data linking hair dye components to carcinogenic effects remain inconsistent. Helzlsouer et al. [99], after a comprehensive literature review, concluded that existing evidence is not sufficiently consistent to demonstrate the actual risk of cancer development following hair dye exposure. Platzek et al. [100] also highlighted the inconclusive results of studies evaluating the genotoxicity of hair dye precursors, emphasizing the inherent need for further research. This conclusion is reinforced by newer systematic reviews that continue to emphasize the need for updated epidemiological evidence, especially in light of reformulated dye products.

Despite the large body of evidence, the discrepancies observed among epidemiological studies may be partly attributed to methodological heterogeneity and variations in

exposure assessment. Differences in study design, recall bias from self-reported hair dye use, lack of standardized exposure metrics, and reformulations in dye composition over time contribute to conflicting outcomes regarding carcinogenic risk [101–103]. Table 5 summarizes the main sources of methodological heterogeneity and their potential impact on epidemiological findings. These factors underscore the importance of more rigorous exposure quantification and mechanistic validation in future investigations, providing a foundation for the methodological improvements discussed in the following section.

Table 5. Summary of major cancer pathologies related to human exposure to hair dyes.

Type of Cancer	Study Type	References
HEMATOPOIETIC	Prospective study	Qin et al. [86]
	Prospective study	Thun et al. [83]
	Case–control study	Zhang et al. [84]
	Case–control study	Couto et al. [88]
	Case–control study	Rauscher et al. [87]
	Case–control study	Nagata et al. [89]
	Case–control study	Miligi et al. [85]
BREAST	Case–control study	Stavraky et al. [91]
	Case–control study	Llanos et al. [92]
	Meta-analysis	Heikkinen et al. [90], Xu et al. [104]
	Case–control, systematic review, and meta-analysis	Ahmadi et al. [93], Arshad et al. [82]
	Meta-analysis	Gera et al. [94]
BLADDER	Case–control study	Gago-Dominguez et al. [2]
	Case–control study	More et al. [105]
	Case–control study	Vecchia; Tavani [101]
	Case–control study	Nomura; Kolonel; Yoshizawa [106]
	Comparative study	Haldkale et al. [96]
	Experimental study	Andrew et al. [81]
	Evaluative study	Czene et al. [97]
	Evaluative study	IARC [4]
	Case study	Gaertner et al. [95]
	Epidemiological study	Skov et al. [98]
SKIN	Follow-up study	Czene et al. [97]
BRAIN TUMORS	Epidemiological study	Holly et al. [107]
	Case–control study	Mccall; Olshan; Daniels [108]
PROSTATE	Case–control study	Tai et al. [109]
	Observational study	Lim et al. [110]

6. Environmental Fate and Ecotoxicology

The hair coloring process typically begins with applying dye to the hair for approximately 30 min, followed by rinsing with running water to remove residues that did not penetrate the hair shaft [10]. At the end of this process, small amounts of dye adhere to the hair shaft, while the majority of the components used during coloring are discharged into the environment as salon wastewater [111].

Among the components of this cosmetic, synthetic organic dyes are essential ingredients [4]. Globally, the most produced dyes include Acid Red 33, Acid Violet 43, Acid Yellow 1, Basic Orange 31, Basic Blue 99, Basic Brown 16, Basic Brown 17, Basic Red 76, Basic Yellow 57, Basic Yellow 87, and Disperse Red 17 [112].

Some synthetic organic dyes used in hair coloring exhibit slow biodegradation or are even non-biodegradable. This makes salon wastewater particularly challenging to treat using conventional methods employed by WWTPs [113,114]. With the continuous

increase in hair dye use, the removal of these compounds from the environment has become increasingly difficult and concerning. The accumulation of these residues in the environment can alter water conditions, affect aquatic life, interfere with soil fertility, and disrupt ecosystem balance. Additionally, it poses risks to human health. This concern is amplified by the lack of regulations regarding the disposal of salon waste, which often ends up in the sewage system without any prior treatment [115]. Furthermore, the environmental impact of waste generated during the industrial production of cosmetics must also be considered [116]. Recent work highlights that conventional treatment systems are largely ineffective against many of these compounds and underscores the need for advanced remediation technologies.

To strengthen the contextualization of environmental and occupational safety thresholds for hair dye ingredients, it is essential to reference established national and international regulatory frameworks. The European Union's Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) regulation, along with the EU Cosmetic Products Regulation (EC) No 1223/2009, strictly controls the permissible concentrations of hazardous aromatic amines such as PPD and toluene-2,5-diamine in hair dyes, mandating rigorous safety assessments and labeling obligations [117]. Similarly, in the United States, the Food and Drug Administration (FDA) enforces labeling requirements warning about the potential carcinogenicity of certain coal-tar hair dye ingredients, while expert panels like the Cosmetic Ingredient Review (CIR) regularly evaluate their toxicological profiles [117]. However, gaps remain in global monitoring and the consistent restriction of known harmful compounds such as lead acetate, which is banned in the EU but still conditionally permitted in the U.S. [118]. Incorporating these benchmarks clarifies the scope of regulated compounds and highlights areas where updated global alignment is necessary.

Water usage in the cosmetics industry occurs in several ways. Initially, water is incorporated into the product itself. It is also used in other processes, such as washing equipment, pipes, and floors, but also in cooling systems and steam generators. After use, this water becomes contaminated with residues from each industrial process, resulting in complex liquid effluents containing, among other substances, cosmetic ingredient residues with toxic, irritating, and/or corrosive properties [13]. The generation of liquid effluents in the cosmetics industry varies depending on the frequency and method of equipment cleaning and the type of product manufactured. These effluents typically exhibit high chemical oxygen demand (COD), elevated concentrations of organic compounds, intense coloration, substantial suspended solids, variable pH, and significant levels of heavy metals and chlorinated organic compounds [13]. A recent study reaffirmed that wastewater from cosmetics production remains a major contributor to the pollutant load in urban effluents [118].

The environmental monitoring of hair dye residues demands the use of advanced analytical techniques capable of detecting trace-level contaminants in complex matrices such as water, sediments, and biota. Despite the increasing concern regarding their persistence and ecotoxicological impact, limited attention has been given to how these compounds are identified and quantified in real-world environmental samples [118].

Techniques such as high-performance liquid chromatography with diode-array detection (HPLC-DAD), gas chromatography-mass spectrometry (GC-MS), and liquid chromatography-tandem mass spectrometry (LC-MS/MS) have been widely employed for this purpose due to their high sensitivity, selectivity, and ability to simultaneously detect multiple compounds. For example, LC-MS/MS methods have achieved detection limits as low as 0.01 µg/L for aromatic amines and oxidative hair dye intermediates in surface waters [119]. These analytical approaches are critical for assessing contamina-

tion in environmental compartments and informing regulatory frameworks, especially given the low biodegradability and potential for bioaccumulation of many hair dye components. However, significant monitoring gaps persist due to the lack of standardized protocols, insufficient temporal sampling, and the frequent exclusion of dye metabolites or transformation products from routine environmental assessments.

In addition to chromatographic approaches, inductively coupled plasma (ICP) techniques, such as ICP-Optical Emission Spectrometry and ICP-Mass Spectrometry, have been increasingly employed as complementary analytical tools for quantifying metallic and elemental constituents in hair dye formulations and related effluents. These techniques offer high precision and sensitivity for detecting trace metals such as lead, cadmium, chromium, nickel, copper, and zinc, which may derive from pigments, stabilizers, or manufacturing impurities. Recent studies have demonstrated the usefulness of these methods for assessing the toxicological and environmental relevance of potentially hazardous elements present in hair dyes [120–122]. When combined with chromatographic analyses such as LC-MS/MS, ICP-based techniques enable a more comprehensive characterization of both organic and inorganic pollutants, thereby supporting source identification, improving data comparability, and strengthening environmental risk assessments.

For instance, azo dyes can undergo reductive cleavage to form aromatic amines, such as aniline, which is classified as a probable human carcinogen [117]. Metabolite profiling, including advanced analytical methods such as liquid chromatography for detecting aromatic diamines in wastewater and biota, can significantly inform risk assessments by revealing the persistence and transformation products of these compounds [118]. Early chromatographic studies demonstrated the detection of aromatic diamines in commercial dyes [123]; however, recent analyses employing LC-MS/MS and high-resolution chromatography have provided more accurate quantification and identification of these compounds in cosmetic matrices [84,118,119]. Understanding these pathways is crucial for designing effective wastewater treatment solutions and for assessing occupational exposure, given the proven links between oxidative dye metabolites and genotoxic effects [117].

Recent studies have increasingly highlighted the role of advanced treatment technologies in effectively removing dyes from industrial wastewater, particularly in textile effluents. Advanced oxidation processes (AOPs), such as ozonation and photocatalysis, offer high mineralization rates of recalcitrant organic compounds. For example, photocatalytic membrane systems combined with ozonation have achieved dye removal efficiencies up to 97.2%, demonstrating their potential for industrial application [124]. These findings underscore the importance of implementing cutting-edge technologies to overcome the limitations of conventional treatment methods and enhance the sustainability of wastewater remediation.

Published data document the presence of synthetic organic dyes in surface waters [84,125], sediments [22,126], and native fish [127]. These findings confirm that synthetic organic dyes constitute a significant environmental concern for aquatic ecosystems. However, the full ecological impact of these dyes remains inadequately characterized, underscoring the need for more targeted and rigorous environmental monitoring of this contaminant class [128]. A recent review further highlighted the lack of routine regulatory testing for these compounds, despite their confirmed detection in surface waters [120].

Environmental monitoring of hair dye residues in salon effluents, surface waters (rivers and lakes), and drinking water can provide valuable insights into the hazardous nature of these compounds, contributing to better control over the release of commercial dyes. Additionally, such monitoring can support current legislation and environmental regulatory agencies by establishing requirements for implementing more efficient techniques for

both monitoring water resource quality and treating effluents contaminated with hair dyes [32,129].

Recent studies have highlighted the presence of dye traces contaminating various aquatic ecosystems [22,125,130,131]. However, there is an urgent need for further research to elucidate the persistence, biotransformation potential, fate, and biological effects of these compounds in the environment. Regarding their impact on organisms, such effects can be assessed through ecotoxicological studies [132].

Several compounds commonly found in hair dye formulations (e.g., PPD, resorcinol, and various azo dyes) have been increasingly associated with ecotoxicological risks in aquatic environments. Recent studies have demonstrated that residues from beauty salon effluents containing hair dye products cause significant acute toxicity to aquatic organisms. In a recent study, hair salon effluents exhibited lethal effects in *Daphnia similis*, *Artemia salina*, and *Danio rerio*, and also sublethal effects of *D. rerio* larvae, confirming the high toxicity of its contaminants [73].

A derivative of PPD, 6PPD, has been shown to induce multigenerational developmental and reproductive toxicity in *Daphnia magna* at concentrations as low as 0.02 µg/L, including reduced offspring and cumulative maternal effects [133]. Additionally, oxidative hair dyes such as henna formulations containing PPD have been shown to induce cardiovascular defects, mortality, and morphological deformities in zebrafish (*Danio rerio*) embryos at concentrations between 100 and 600 µM [134].

Azo dyes, such as Direct Blue 15, have also demonstrated significant toxicity. For instance, *Ceriodaphnia dubia* showed an LC₅₀ of 450 mg/L, and *Danio rerio* embryos exposed to 100–500 mg/L exhibited yolk sac edema, skeletal deformities, and heartbeat inhibition after 144 h [135].

These toxicological endpoints, combined with the known bioaccumulative behavior of such compounds, reinforce the need to integrate physicochemical parameters—such as partition coefficients (log K_{ow}), sediment sorption (K_{oc}), and degradation half-lives—into environmental risk assessments of hair dye pollutants [136].

Understanding the environmental fate of these persistent pollutants also requires physicochemical insights. Reactive Red 120 has a log K_{ow} of ~3.8, indicating moderate lipophilicity and potential bioaccumulation in aquatic organisms [137]. In addition, synthetic dyes with high soil organic carbon partition coefficients (K_{oc} > 10,000 mL/g) tend to strongly adsorb to sediment, limiting mobility in water but increasing persistence in benthic environments. Moreover, under low-light aquatic conditions, photolytic degradation half-lives (DT₅₀) can exceed 60 days, reflecting high stability and poor biodegradability [138]. These characteristics contribute to the long-term ecological risks associated with dye-derived pollutants.

Building on the physicochemical insights discussed, it is evident that the environmental dynamics of hair dye pollutants are far less understood than their effects on human health. While the contamination of aquatic systems by hair dyes and salon effluents is well-documented, quantitative data on their concentrations in environmental matrices remain scarce, with reported levels varying widely across geographic regions and analytical methods [73]. Equally, the fate and transport mechanisms, such as adsorption/desorption dynamics, partitioning between water, sediment and biota, and photolytic or microbial transformations, remain poorly characterized in the literature [10]. Furthermore, ecotoxicological studies frequently provide acute toxicity data without consistent endpoints or standardized exposure conditions, limiting reliable comparative risk assessment and hindering extrapolation to chronic or trophic transfer scenarios. Notably, the potential for bioaccumulation and trophic transfer of persistent aromatic amines or other transformation intermediates from hair dye formulations remains largely unexplored, despite recent

biomonitoring evidence of trace element accumulation in dyed hair samples [139]. Filling these research gaps through integrated monitoring programs, standardized toxicological methods, and targeted investigations of trophic pathways is essential to accurately assess the long-term ecological risks posed by hair dye pollutants.

The increasing concern regarding the environmental fate of residues originating from hair dyes has led to ecotoxicological studies aimed at assessing the effects of these compounds on different bioindicators. Recent research has examined the acute and chronic toxicity of effluents from beauty salons and active components of hair dyes (e.g., PPD, resorcinol, and azo dyes) in aquatic, microbial, and terrestrial organisms. These studies demonstrate that dye formulations exhibit high organic loads, low biodegradability, and the presence of substances with bioaccumulative and mutagenic potential, capable of affecting soil bacteria, fish, and microcrustaceans alike [140].

Recent ecotoxicological evidence has underscored the acute toxicity and biochemical perturbations associated with oxidative hair dye constituents and their related effluents. Gonçalves et al. [73] assessed the toxicity of beauty salon effluents contaminated with hair dyes on multiple aquatic bioindicators, including *Daphnia similis*, *Artemia salina*, and *Danio rerio*. The study reported toxicity for *Daphnia similis* ($EC_{50} = 0.54\text{--}3.43\%$), *Artemia salina* ($LC_{50} = 3.87\text{--}8.33\%$), and *Danio rerio* ($LC_{50} = 4.25\text{--}8.18\%$), indicating pronounced acute toxicity even at low effluent concentrations [73].

Complementarily, Tapia-Salazar et al. [141] investigated the toxicological and enzymatic effects of the aromatic amines PPD and 2,5-diaminotoluene (PTD), which are primary intermediates in oxidative hair dye formulations. Using the *Artemia salina* model, the authors determined LC_{50} values of 52–165 mg/L for PPD and 24–396 mg/L for PTD, alongside significant oxidative stress and enzymatic disruption, confirming their capacity to induce sublethal biochemical damage.

In mammalian models, Singh et al. [142] conducted acute and short-term toxicity assays on *p*-aminodiphenylamine, a compound structurally related to oxidative dye intermediates and reported an oral $LD_{50} = 0.847$ g/kg in rats, with notable hepatic and hematological alterations following exposure.

Collectively, these findings substantiate the ecotoxic and toxicodynamic potential of oxidative hair dye ingredients and their effluents. However, there remains a pronounced research gap concerning the ecotoxicological assessment of hair dye formulations and their associated effluents. The limited number of systematic studies addressing these contaminants restricts the comprehensive understanding of their chronic toxicity, bioaccumulation behavior, and trophic transfer potential under realistic environmental conditions. This gap underscores the necessity of advancing integrated analytical approaches, standardizing toxicity testing protocols, and developing predictive models that accurately reflect environmental exposure scenarios.

7. Conclusions

This study provides a comprehensive foundation for the development of evidence-based policies aimed at safeguarding environmental quality, preventing ecological degradation, and promoting sustainable socio-economic practices. The findings highlight substantial regulatory deficiencies, particularly the absence of specific effluent discharge standards for beauty salons and the lack of mandatory monitoring for persistent, bioaccumulative, and toxic (PBT) substances frequently detected in hair dye formulations. Among the identified contaminants, aromatic amines, phenylenediamines, and resorcinol require heightened regulatory attention due to their carcinogenic potential, endocrine-disrupting effects, and aquatic toxicity.

In addition to these regulatory shortcomings, current scientific evidence remains constrained by significant methodological limitations. Numerous studies rely on short-term laboratory assays characterized by non-standardized exposure conditions, limited biological diversity, and variable analytical precision. Such inconsistencies compromise reproducibility and hinder the extrapolation of results to real environmental contexts. Moreover, quantitative data regarding environmental concentrations, transformation pathways, and bioaccumulation dynamics of hair dye constituents remain fragmented and geographically inconsistent.

Future research efforts should focus on developing standardized analytical and monitoring frameworks, conducting long-term and multispecies ecotoxicological assessments, and evaluating the efficiency of advanced wastewater treatment technologies in removing persistent dye residues. Priority research areas include: (i) comprehensive toxicokinetic and metabolic characterization of key dye precursors and transformation products; (ii) large-scale environmental monitoring of dye-derived contaminants in wastewater, sediments, and biota across diverse regions; (iii) mechanistic investigations into mixture toxicity and potential synergistic or additive effects; and (iv) occupational exposure studies addressing chronic low-dose effects among cosmetology professionals. Strengthening the scientific basis in these domains is essential to support regulatory decision-making, promote the substitution of hazardous substances, and align chemical management strategies with the objectives of the United Nations Sustainable Development Goals.

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