Proceedings of CONF-MSS 2026 Symposium: Advanced Composite Materials and Polymer Chemistry
DOI: 10.54254/2755-2721/2026.AD34187

Analysis of the Working Principle of Hair Dye

Huixi Yang

Zhengzhou No.7 Senior High School, Zhengzhou, China
yhx025879@qq.com

Abstract. Hair dying has been an important part of humans' life from ancient times to modern days. It is common to see people have their hair dyed since hair dying makes people appear unique, pretty, and attractive. Also, people sometimes change the color of their hair to follow the contemporary hot trend. By analyzing the principle of hair dye, the quality of the dyes and the dying process can be improved. Consequently, hair dying will become safer, healthier and more convenient. From beauty to safety, people will benefit a lot from the analysis of the hair dyes. In terms of the principle of hair dying, hair dyes can be classified into oxidative and non-oxidative dyes, and considering the duration of dyes, non-oxidative hair dyes can be further classified into temporary dyes and semi-permanent dyes. This review adopts a literature analysis and case study approach. The analysis shows considerable differences between the three types of hair dyes, involving their duration, methods of use, and potential risks to individuals.

Keywords: hair, dye, temporary, permanent

1. Introduction

Hair dye, which is a cosmetic product used to color hair, can be classified into three categories: temporary, semi-permanent, and permanent [1]. Among these types of hair dyes, permanent hair dyes are generally oxidative, while the former two are non-oxidative. Hair dyeing is a process in which dye molecules form inter-molecular interactions of varying strengths with protein chains on or inside the hair to achieve coloration [2]. However, given that the dyeing mechanisms of different hair dyes are not the same, some hair dyes may cause harm to both the hair and human health [3]. This research uses both literature analysis and case analysis. To provide a comprehensive understanding of the mechanisms of hair dyes, this paper first presents a simple overview of hair structure. Then, this paper subsequently offers a systematic analysis of the working mechanisms, durability, and potential health impacts of oxidative dyes, as well as temporary and semi-permanent non-oxidative dyes.

By dividing hair dyes into three categories, this study conducts a systematic analysis of their working mechanisms. The findings may contribute to future improvements in formulation development and the refinement of the dyeing process.

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2. Hair structure

To understand the working principles of hair dyes, it is necessary to first gain a basic understanding of hair structure. Several principal factors that have an influence on the appearance of hair include the arrangement of multiple hair fibers, a suitable cross-sectional shape, a well-organized cuticle structure, and a pore-less internal structure [4]. Additionally, not only serves as an adornment, hair also moderates temperature, avoiding the head and skin from being exposed to excessive sunlight exposure. There are about 90,000 to 150,000 hair fibers on human's head, and the hair grows at a rate of approximately 1 cm every month (0.37 mm daily). Usually, people shed hair from 50 to 100 fibers per day. The average hair diameter ranges from 15 to 110 μm, depending on race.

The hair is composed of three main structural layers: the cuticle, cortex, and medulla, as shown in Figure 1, which reveals the arrangement of these layers. The cell membrane complex (CMC) acts as an intercellular adhesive that binds adjacent cells together while serving as a pathway for substance transport. It also significantly influences pigment penetration and fluorescence properties. The cuticle is the outermost layer, consisting of overlapping scale-like cells arranged along the hair. It provides chemical resistance and helps regulate water content to maintain physical properties.

Consisting of about 90% of the hair's total weight, the cortex is the primary component of hair. The elongated cylindrical cells contain abundant keratin, which provides hair with mechanical strength. Melanin granules within the cortex determine hair color and protect the hair from UV radiation in sunlight.

Figure 1 illustrates the hierarchical microstructure of human hair, detailing the structural components (including the cuticle, cortex, and medulla) and the subcellular organization of keratinized fibers that underpin hair's mechanical properties and permeability to dye molecules. The medulla is the innermost region, which is often discontinuous or absent in human hair. It does not significantly affect the overall structural properties of the hair fibers.

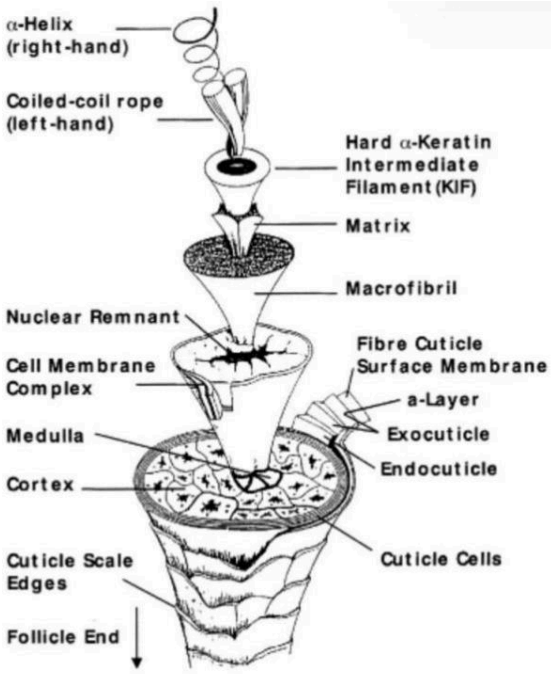

Figure 1. Microstructure of human hair

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Non-oxidative dyes do not involve chemical oxidation. Temporary dyes remain on the hair surface and are removed after one wash, while semi-permanent dyes partially penetrate the outer cortex and generally last for several washes. In contrast, oxidative dyes, which are usually permanent hair dyes, will enter the intercuticular regions when the dyeing process starts, and then it travels across the non-keratinized regions of the endocuticle and the intercellular cement. They then enter the keratinized regions and finally reach the macrofibrils, where they are incorporated into the matrix. This results in long-lasting color [4, 5].

3. Non-oxidative hair dyes

3.1. Temporary non-oxidative hair dying

This kind of hair dye uses large acid or basic dye molecules with relatively high molecular weight. Temporary hair dyes are composed of water-soluble acidic and basic dyes. These molecules are not able to penetrate the cortex because they do not open the hair cuticle and therefore can only stay on the surface of the hair temporarily, being deposited on the outer layer of the hair shaft. For this reason, they are generally regarded as more benign compared with permanent systems, since they do not chemically modify the internal structure of the hair.

The acidic (anionic) and basic (cationic) characteristics make the molecules easily dissociate in water and interact mainly through ionic or electrostatic attractions with the amino acid residues on the cuticle surface, rather than diffuse deeply into the fiber. As a result, these dyes can be removed in the first wash or by a single shampooing, depending on the formulation. In other words, this kind of pigment cannot alter the color of the hair thoroughly or permanently. It can only make the hair reflect a certain color by forming a superficial coating on the hair surface [3, 6, 7].

To have hair dyed in this way, people can just apply products like shampoo, gel, emulsion, conditioner, or solution (liquid) to their hair. They do not require the use of ammonia or an oxidizing agent, which further distinguishes them from semi-permanent and permanent dyes. It is worth mentioning that once the application process is complete, a single wash is required so that the unabsorbed dyes on the hair can be removed, which further accounts for the brief duration of the color.

3.2. Semi-permanent non-oxidative dyes

The primary ingredients of these dyes include basic or cationic dyes that have a low molar mass. Formulated at a relatively high pH value, these dyes promote the opening of the cuticle, allowing the dyes to penetrate slightly into the cortex. Due to their small molecular size and high affinity for hair keratin, they can bind to the hair fiber through weak polar interactions and electrostatic attractions. Hence, compared with temporary non-oxidative dyes, they can last longer. However, since no oxidizing reaction occurs during the dyeing process, the color molecules are not permanently formed inside the cortex, and the color effect can only withstand about 3–6 washes.

The dyeing process is simple and usually takes about 10–40 minutes, followed by rinsing. These products are commonly available in cosmetic products such as lotions, shampoos, mousses, and emulsions. In order to achieve even application, the formulations with ideal viscosity are needed to prevent them from flowing during the application process. In some cases, different types of dyes may be combined in one formulation to achieve a more uniform color result and improved wash resistance [3, 6, 7].

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Plant dyes are also a type of semi-permanent dye. For instance, henna, the most widely used plant dye, yields a reddish-orange color. In commercial hair dye products, it is frequently mixed with other dyes to broaden the range of available color options. This dye has a high solubility in hot water and adheres to hair keratin easily. Another plant dye is chamomile. It can enhance the shine of hair and produce a yellowish tint [3].

Another type of semi-permanent dye is metallic hair dye, which was widely used to turn white hair black in the past. These dyes are traditionally derived from silver salts and lead. In this type of hair dyeing, the darkening process of the hair is gradual, which makes the result more natural and satisfying. However, metallic dyes are generally only used for dark-colored hair dyeing and cannot produce bright colors such as pink and orange [3].

4. Oxidative dyes

This kind of hair dyeing is the most widely used because it not only lasts for a long time, but also offers a wide range of colors and shades. It occupies about 70–80 percent of the synthetic hair dye market worldwide. The formation of permanent hair dyes mainly involves four components: coupling bases, reaction modifiers, alkalizing compounds, and oxidizing agents. Coupling bases can act as color developers. When reaction modifiers are used alone, they do not produce significant colors. However, when they act as primary intermediates and oxidants, they can modify the color. The function of alkalizing compounds is to provide a suitable pH environment for the occurrence of the oxidation reaction in hair dyeing. Common alkalizing compounds include ammonia water. The reducing agents serve to slow down the reaction of bases with reaction modifiers, and prevent the dye from reacting prematurely during packaging and sale [3].

The color formation takes place within the mixture, involving complex reactions between precursors and couplers in the presence of an oxidizing agent. The alkaline environment required for the reaction to occur is usually created using ammonia hydroxide, which promotes the opening of the cuticle and allows the dye molecules to penetrate into the cortex. Then, oxidation of the primary intermediates happens, followed by their reaction with the coupling agents, generating a colorful complex with high molar mass within the cortex. Due to their large molecular size, the newly formed pigment molecules cannot easily diffuse out of the hair fiber, resulting in long-lasting stable color that resists to shampoo washes, light exposure, friction with clothing, and other external factors. Part of the reaction may also occur at the cuticle surface, and those molecules can be washed away during the first washes. Finally, after the dyeing process is completed and the hair is rinsed, the pH value gradually returns to its normal level, the cuticle closes again, and the dye molecules are locked inside the hair shaft. As a result, oxidative permanent hair dyeing provides long-lasting color and high coverage, even up to 100% of white hair strands [3, 6, 7].

However, the oxidative reaction occurring during the dying process will harm the cortex and the melanin chain in the hair. This will make the hair fragile and lose elasticity. The protein on the cuticle will be damaged as well, which leads to the result that the cuticle can not arrange and overlap in a normal way. Besides, some ingredients in the dyes are toxic, and hair dye ingestion is one of the most common methods to commit suicide in undeveloped countries [8]. For instance, PPD, the main compound in permanent hair dyes, has been shown to have several toxic effects. During the dyeing process, PPD can penetrate the skin and be absorbed through the airway, especially in hair salons where workers are exposed for a long time. After entering the body, it may cause allergic contact dermatitis, skin irritation, and respiratory problems. Some people may even develop strong allergic reactions after repeated exposure. In addition, when PPD is oxidized during the dyeing process, it can form reactive substances. These substances may interact with proteins and other components in

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cells, which could lead to harmful effects. Therefore, long-term exposure to PPD may pose health risks, particularly for hairdressers who frequently use permanent hair dyes [7, 8].

5. Conclusion

The increasingly popular trend of hair dying is gradually making the study of hair dyes more significant. Based on research on hair structure, dye composition, chemical properties, and application methods, clear differences can be observed among temporary non-oxidative, semi-permanent non-oxidative, and oxidative hair dyes. Temporary non-oxidative dyes use large water-soluble acidic or basic molecules that remain on the hair surface.Without opening the cuticle, they interact mainly through weak ionic attractions and are easily removed after one wash. Hence,their color effect is superficial and short-lasting, but their damage to hair structure and potential health risks are relatively low.

When it comes to semi-permanent non-oxidative dyes,they contain smaller molecules with higher affinity for keratin. Under mildly alkaline conditions, the cuticle opens slightly, allowing limited penetration into the cortex. Although no oxidation occurs and the color is not permanently formed inside the hair fiber, these dyes can resist about 3–6 washes, providing a longer-lasting effect than temporary dyes,while causing less structural damage than permanent dyes.

In contrast, oxidative permanent dyes will cause large dye molecules to form in the cortex and become trapped as the cuticle closes, resulting in durable color and high gray-hair coverage. However, the oxidation process can damage keratin proteins and melanin, weaken hair elasticity, and increase fragility. Moreover, ingredients such as PPD may cause allergic and toxic effects with repeated exposure. Therefore, although oxidative dyes offer superior color durability, they present greater potential risks to both hair health and human health.

This paper classifies these dyes mainly according to their actual oxidizing effects, without taking into account other important factors such as material and energy consumption or environmental pollution. However, the potential harm caused by waste to human health and the environment should not be overlooked. In the future, researchers may work together to further investigate these issues, promoting hair dying to become a more sustainable and safer industry.

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