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The science of color: How chemical dyeing processes transform hair structure

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Abstract

Hair colouring is both a chemical experiment and a personal aesthetic statement. This study investigates the molecular choreography behind oxidative and non-oxidative dyeing and examines its effects on hair structure. Using trichological microscopy, spectroscopic analyses, and published cosmetic-chemistry data, the paper reviews how hydrogen peroxide, alkalis, and dye precursors modify keratin, lift the cuticle, and increase porosity. Conversely, it shows how semi-permanent and direct dyes achieve colour with less structural disruption. Emerging technologies such as bond-repair additives, amino-acid buffers, and ammonia-free systems aim to preserve hair integrity while maintaining colour performance. These insights provide a biochemical foundation for balancing visual results with fibre health.

Keywords: Hair Dyeing; Oxidative Chemistry; Keratin Degradation; Hydrogen Peroxide; Bond Repair; Cosmetic Science

1. Introduction

Hair colouring has evolved from art to applied chemistry. Each shade results from oxidation–reduction reactions that alter natural melanin and introduce synthetic pigments within the hair cortex [1]. Human hair, composed primarily of α -keratin, consists of three layers the cuticle, cortex, and medulla held together by disulfide bridges that ensure strength and elasticity [2].

During colouring, the fibre is exposed to reactive substances that can swell the cuticle and modify keratin bonds [3]. The goal of modern formulation science is to achieve long-lasting, high-intensity colour while mitigating structural compromise. Recent innovations in amino-acid-based alkalizers, low-peroxide systems, and bond-repair complexes represent a significant step toward this objective [4, 5].

2. Materials and Methods

This review synthesises data from peer-reviewed sources published between 2015 and 2024, including *Journal of Cosmetic Science*, *International Journal of Cosmetic Science*, and

2.1. Dermatologic Clinics. The analytical framework comprised

- **Chemical mechanism review:** analysis of oxidative and non-oxidative dyeing chemistry, focusing on key intermediates (*p*-phenylenediamine, resorcinol) and oxidants (H_2O_2).
- **Microscopic evaluation:** comparison of SEM micrographs of untreated and dyed fibres [6].
- **Spectroscopic correlation:** interpretation of FTIR and Raman spectral changes associated with cystine oxidation [7].

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- **Formulation innovation analysis:** review of ammonia-free, bond-rebuilding, and natural pigment systems reported in patents and cosmetic-chemistry studies [8].

3. Results and Discussion

3.1. Chemical Mechanisms of Hair Dyeing

Permanent oxidative dyes rely on an alkaline pH ($\approx 9-10$) provided by ammonia or monoethanolamine (MEA). The alkalinity opens the cuticle and allows dye precursors to

penetrate the cortex. Hydrogen peroxide oxidises melanin and initiates the coupling of aromatic amines and phenols to form coloured polymers [1]. While this delivers durable results, it also oxidises keratin disulfide bonds, producing cysteic acid and weakening the fibre [2].

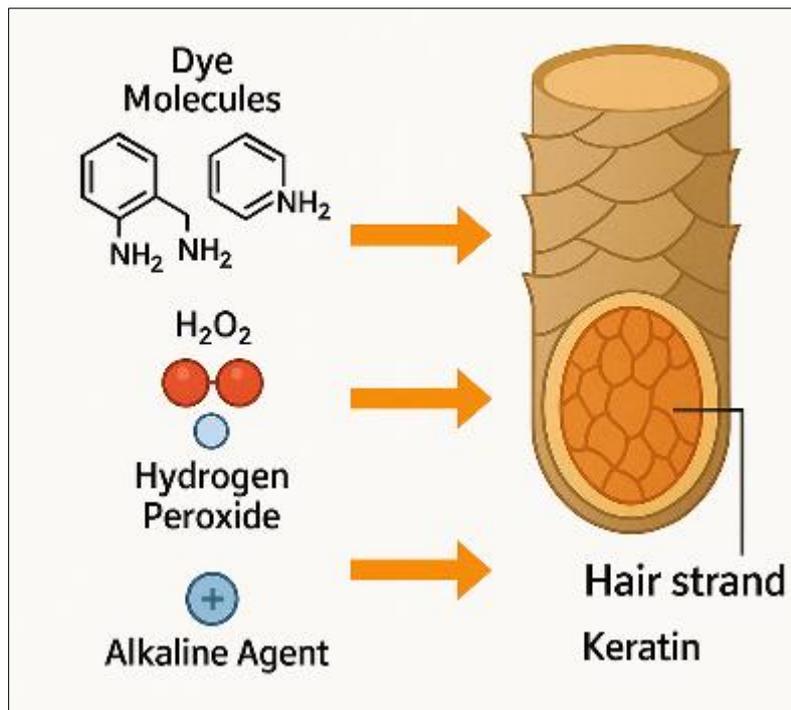


Figure 1 The chemical dyeing process

3.2. Structural Changes in Hair Fibres

Scanning electron microscopy demonstrates that oxidatively dyed hair exhibits raised cuticle scales and disrupted lipid layers, particularly the 18-methyl eicosanoic acid coating [6]. Porosity increases, mechanical strength decreases by up to 20 %, and water retention declines [3]. These effects contribute to brittleness and loss of shine.

3.3. Non-Oxidative Colouration

Semi-permanent dyes rely on large, pre-formed colour molecules that deposit on or just beneath the cuticle via ionic attraction. Because no oxidation occurs, keratin remains largely intact [1, 6]. However, these colours fade more rapidly due to shampooing and UV exposure.

3.4. Innovations in Damage Control

Modern cosmetic chemistry emphasises damage prevention. Compounds such as bis-aminopropyl diglycol dimaleate rebuild broken disulfide linkages, improving tensile strength [8]. Arginine-based alkalizers provide gentler cuticle lifting at lower pH values [5].



Figure 2 Advanced hair repair technologies

Acidic post-colour masks reseal the cuticle, reducing porosity and friction. Plant-based nanocarrier dyes offer eco-friendly alternatives that merge colour with conditioning [7].

4. Conclusion

The chemistry of hair colour is a dialogue between transformation and preservation. While oxidative systems deliver unmatched permanence, they compromise keratin integrity by cleaving bonds and eroding the cuticle. Non-oxidative and hybrid formulations now offer pathways to balance intensity and safety. Continued research into biomimetic, low-impact chemistries promises a future where beauty and biochemistry coexist sustainably.

Compliance with ethical standards

Disclosure of conflict of interest

The author declares no conflicts of interest related to this publication.

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