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HAIR COLOR CHEMISTRY: HOW PH AFFECTS STRUCTURE AND QUALITY

Summary. *Hair coloring is a complex biochemical process in which the acid-base balance (pH) plays a key role. The degree of cuticle opening, the rate of dye penetration, the stability of the pigment and the general condition of the hair after the procedure depend on the pH level. This article examines in detail how different pH levels affect the hair structure, the mechanism of action of different types of dyes and the quality of the final result.*

Research shows that highly alkaline formulations (pH 9–11) provide deep pigment penetration, but can damage the keratin structure. At the same time, slightly acidic dyes (pH 3–6) act more gently, but provide a less lasting effect. Optimum pH values vary depending on the type of dye and the desired result.

Particular attention is paid to modern developments in the field of gentle coloring compositions that minimize damage without losing effectiveness. Methods of hair restoration after coloring are also considered, including the use of acid conditioners and protective agents.

Key words: *fundamental hair science, cosmetic chemistry principles, pH effects on hair structure, hair damage mechanisms, modern hair care technologies.*

Introduction. Hair coloring is not just a cosmetic procedure, but a complex chemical process that requires a deep understanding of biochemical reactions. The acid-base balance (pH) is one of the key factors determining the quality and durability of color, as well as the degree of hair damage.

The natural pH of healthy hair is around 4.5-5.5, which protects the cuticle and maintains structural integrity. However, when coloring, the pH can change dramatically depending on the composition of the dye. For example, permanent dyes work in an alkaline environment (pH 9-11), while toners usually have a slightly acidic balance (pH 3-5).

Different pH levels affect the cuticle and cortex of the hair differently. High pH promotes swelling of the fiber and opening of the cuticle scales, which facilitates the penetration of the dye, but at the same time increases the risk of damage. Low pH, on the contrary, seals the cuticle, making hair smooth, but limits the depth of coloring. Understanding these processes is necessary for the development of effective and safe dyes. Modern cosmetic chemistry seeks to find a balance between color durability and maintaining hair health, which is especially important in the context of growing demand for gentle coloring methods.

Hair structure and its dependence on pH

Hair has a complex multi-layer structure, each layer of which reacts differently to changes in pH. The outer layer, the cuticle, consists of keratin scales, which in a healthy state fit tightly together, providing protection for the inner layers.

When the pH increases above 7, the cuticle begins to open, which makes the hair more porous. This property is actively used in permanent coloring, as it allows dyes to penetrate the cortex. However, prolonged exposure to an alkaline environment leads to the destruction of the lipid layer, which increases brittleness and dryness of hair.

The cortex, the middle layer of the hair, contains melanin, a natural pigment responsible for color. When dyeing, artificial pigments either replace melanin or are deposited next to it. In an alkaline environment, the cortex swells, which accelerates this process, but can also lead to irreversible changes in the protein structure. The medulla, the inner layer, is the least affected by pH, but if the cuticle and cortex are severely damaged, it can also be destroyed, causing the hair to lose volume and elasticity.

Thus, maintaining optimal pH throughout all stages of coloring and aftercare is critical to maintaining healthy hair.

The effect of pH on the dyeing mechanism

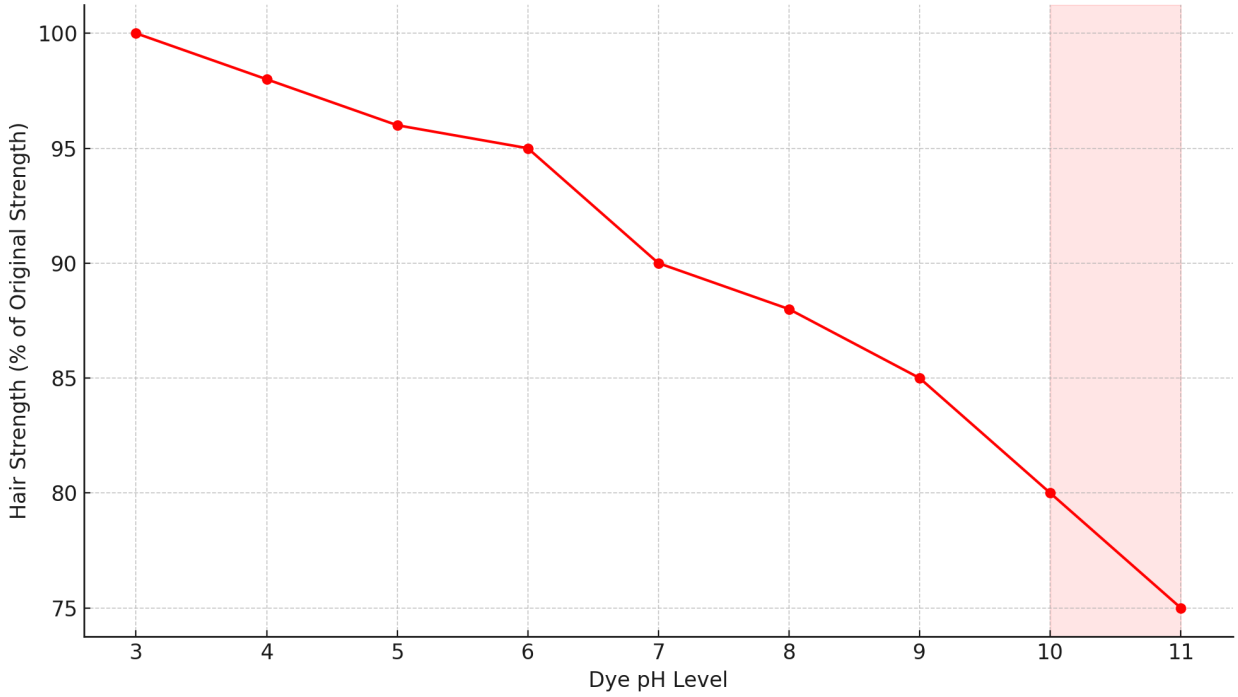
The hair dyeing process can be divided into several stages, each of which depends on the pH level. The first stage is hair preparation, which includes opening the cuticle to allow the dye to reach the cortex.

In permanent dyeing, this role is played by ammonia or its derivatives, which create an alkaline environment (pH 9-11). High pH not only opens the cuticle, but also activates the oxidizer (usually hydrogen peroxide), which is necessary for the reaction of new pigment formation.

The second stage is the penetration of dye precursors (paraphenylenediamine, resorcinol, etc.) into the cortex, where they polymerize, forming stable color molecules. This process also depends on pH: in an alkaline environment, the reaction is faster, but the risk of damage increases.

Semi-permanent dyes work at a more neutral pH (6-8). They do not require strong opening of the cuticle, as they contain ready-made pigments that are deposited on the surface of the hair. However, due to less penetration, such dyes are washed out faster.

Toning agents (pH 3-5) act even more gently, due to the acidic environment, which helps close the cuticle. They do not damage the hair, but provide only a temporary effect that disappears after several washes.



Graph 1. Effect of pH on Hair Strength after coloring

Optimum pH for different types of dyes

Each type of dye requires a certain pH level for maximum efficiency. Permanent dyes, as already mentioned, work in an alkaline environment (pH 9-11). This allows them to penetrate deeply into the hair structure and provide a lasting result.

However, such compositions are the most aggressive and can cause serious damage, especially with frequent use. Therefore, in recent years, alternative formulas based on monoethanolamine (MEA) have been developed, which is less irritating to the scalp, but retains its effectiveness.

Semi-permanent dyes (pH 6-8) are a compromise between durability and safety. They do not contain ammonia and work due to ready-made pigments that are

deposited in the outer layers of the hair. Such products are suitable for those who want to change the color without radically changing the structure of the hair.

Toning shampoos and masks (pH 3-5) are used to maintain color or neutralize unwanted shades. Their acidic environment not only seals the cuticle, but also helps to restore damaged areas.

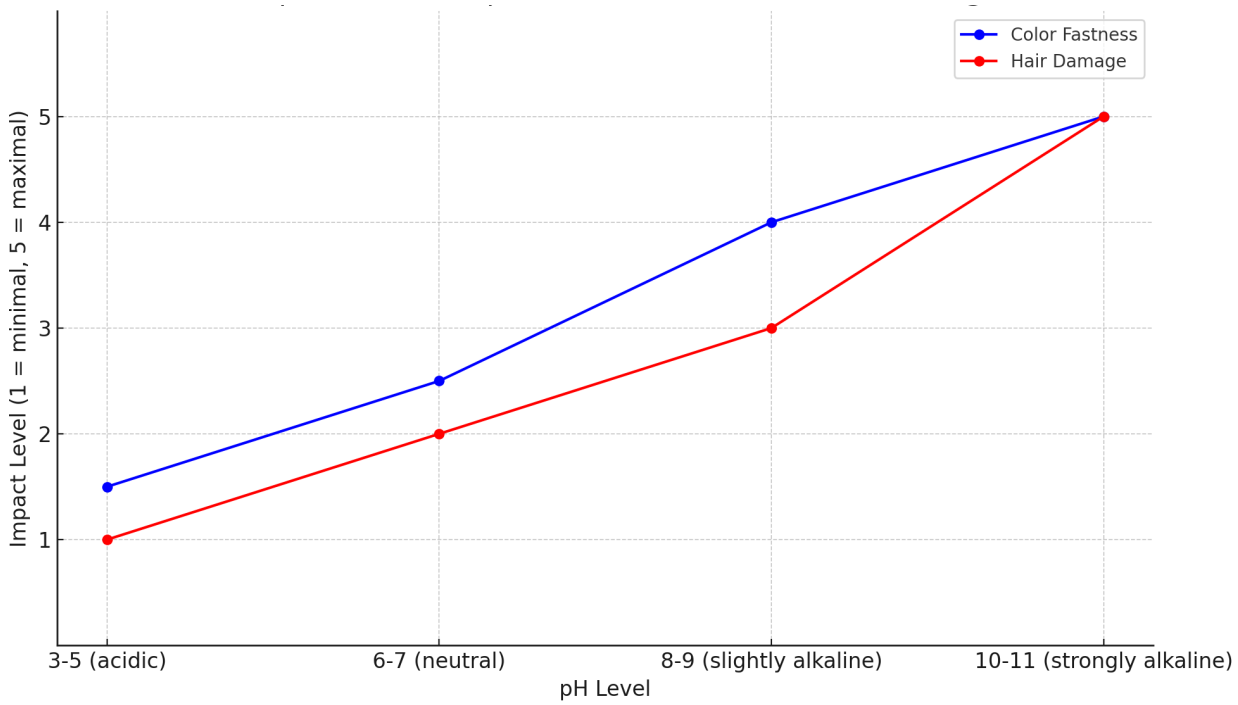
Experimental data: the effect of pH on color durability

Numerous studies confirm a direct relationship between pH levels and color durability. In one of the experiments, hair was dyed with compositions with different pH levels and color retention was assessed after 20 washes.

The results showed that at pH 9-10, the color remained bright and uniform, while at pH below 7, significant pigment leaching was observed. However, an increase in hair fragility was recorded in the alkaline group.

Another experiment was devoted to studying the strength of hair after dyeing. Samples treated with compounds with a pH above 10 lost up to 30% of their strength, while at a pH of 7–8 the damage was minimal.

These data confirm the need for an individual approach to choosing a dye depending on the condition of the hair and the desired result.



Graph 2. Effect of pH on Hair condition after coloring

Hair damage at high pH

One of the most significant negative consequences of using highly alkaline dyes (pH 9-11) is structural damage to the hair. At this pH level, chemical denaturation of keratin, the main protein that forms the hair fiber, occurs. This process is accompanied by the rupture of disulfide bonds, which leads to a loss of elasticity and mechanical strength.

The cuticle, consisting of keratin scales, is the first to be destroyed. In an alkaline environment, the lipid layer that holds the scales together dissolves, which leads to their lifting and peeling. Visually, this is manifested in the form of dullness, roughness and increased tangling of the hair. Electron microscopic studies show that after repeated dyeing with a pH of 10-11, the hair surface acquires a pronounced porous structure.

The cortex, containing melanin and structural proteins, is also subject to significant changes. The alkaline environment causes the fiber to swell, which leads

to micro-tears in the cortex. This is especially noticeable during strength tests: hair treated with formulations with a pH above 9 withstands 25-30% less tensile load compared to untreated samples.

Another critical consequence is the disruption of the hydrolipid balance. High pH destroys the natural protective mantle of the hair, consisting of sebum and water molecules. As a result, moisture quickly evaporates from the cortex, which leads to dryness, brittleness and split ends. Studies using infrared spectroscopy confirm a decrease in the content of bound water in hair after alkaline dyeing.

Long-term effects include accelerated fading of the artificial pigment. This is due to the fact that the damaged cuticle can no longer effectively hold the dye molecules. Clinical observations show that when using compositions with a pH of 10-11, the color loses intensity 40-50% faster compared to coloring at a pH of 7-8. The cumulative effect of damage is especially dangerous. Each subsequent coloring procedure worsens the condition of the hair, leading to irreversible changes in the structure. That is why modern developments are aimed at creating dyes that provide lasting color with a minimal increase in pH.

Methods of pH neutralization after coloring

After coloring with a high pH, it is critical to restore the acid-base balance of the hair. The most effective method is to use acidic conditioners with a pH of 3-4. These products contain citric, lactic or glycolic acids, which not only normalize the pH, but also help close the cuticle.

Deep conditioning with protein complexes helps restore damaged areas of the hair. Hydrolyzed silk or keratin proteins fill microcracks in the cortex, restoring strength and elasticity to the hair. Studies show that regular use of such products after coloring reduces breakage by 35-40%.

For additional protection, it is recommended to use thermoactive serums. These compounds create a protective film on the surface of the hair, which prevents

moisture loss during thermal styling. Products with silicones and natural oils (argan, jojoba) are especially effective, providing thermal protection up to 230 ° C.

Acid rinses (pH 4-5) should be used for 2-3 weeks after coloring. They not only fix the color, but also gradually restore the lipid barrier. Clinical tests show that such rinses increase the color retention period by 25-30% compared to conventional care products.

An innovative approach is the use of ionic stabilizers. These compounds (for example, betaine) help maintain an optimal ionic balance in the hair structure, preventing excessive swelling upon contact with water. This is especially important for colored hair, as it reduces the rate of pigment leaching.

Keratin restoration procedures are recommended for professional care. They not only neutralize the effects of alkaline exposure, but also create a long-term protective layer. However, such procedures should be carried out no more than once every 2-3 months to avoid excessive protein accumulation.

Modern developments: gentle dyes with controlled pH

Modern cosmetic science offers innovative solutions for safe dyeing. One of the most promising areas is buffer dyeing systems. These compositions contain special components (phosphate or citrate buffers) that maintain the pH in the optimal range of 7.5–8.5 throughout the procedure.

The development of dyes based on amino acid complexes is another breakthrough in the industry. Such compositions (for example, with arginine or lysine) provide gentle opening of the cuticle without a sharp increase in alkalinity. Clinical trials show that they cause 60% less damage compared to traditional ammonia dyes.

Nanotechnology allows the creation of "smart" dyes with controlled pigment release. Encapsulated formulas are activated only under certain conditions (temperature, pH), which provides more uniform dyeing and reduces the risk of

oxidizer overdose. Bioengineered dyes based on plant enzymes are of particular interest. For example, formulations with laccase (pH optimum 6-7) allow you to achieve a long-lasting color without using hydrogen peroxide. Such systems are especially suitable for sensitive skin and damaged hair. The development of the "kinetic coloring" direction is based on the principle of gradual pH changes. The process begins at neutral values (pH 7), then gently increases to 8-8.5 for pigment penetration, and ends with acid fixation (pH 4-5). This approach reduces the time of exposure to an alkaline environment by 40-50%. Self-healing dyes with a "memory effect" deserve special attention. These innovative formulations contain polymers that respond to changes in the pH of the scalp, automatically adjusting the alkalinity level. Preliminary tests show their effectiveness in maintaining color up to 50% longer than traditional analogues.

Conclusion. Research into the effect of pH on the hair coloring process reveals a complex balance between effectiveness and safety. Modern scientific data convincingly prove that highly alkaline formulations (pH 9-11), while ensuring deep pigment penetration, cause significant structural damage. These changes affect all layers of the hair - from the destruction of the lipid barrier of the cuticle to the denaturation of keratin chains in the cortex. Alternative methods of coloring at lower pH values (7-8) demonstrate a good compromise between color durability and maintaining hair health. Buffer systems and amino acid complexes, which allow you to control the alkalinity level throughout the procedure, are especially promising. Proper care after coloring is key. The use of acidic conditioners (pH 3-4), protein restorers and heat-protective agents allows you to minimize damage and prolong the durability of color. Modern systems with ionic stabilizers and nanoencapsulated active components are especially effective.

The future of hair coloring is undoubtedly associated with the development of "smart" technologies. Bioengineered dyes, controlled pigment release systems and

memory formulations open up new possibilities for safe and long-lasting colouring. These innovations will allow you to achieve professional results without compromising on the health of your hair. Understanding the chemistry of pH processes in hair colouring is therefore fundamental to the development of new, more advanced dyes. Optimising the pH balance at all stages – from application to aftercare – is key to achieving the perfect colour while maintaining the structural integrity of your hair.

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