



# Hair Reconstruction Before, During, and After Chemical Procedures: Principles and Methods without Brand Affiliation

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## Abstract

*The present work reviews the pathophysiology of chemically induced hair damage and systematizes evidence-based approaches to prevention and reconstruction across the full procedural cycle, namely at the “before”, “during”, and “after” stages. The discussion centers on major pathways of chemical destruction of the keratin matrix, including oxidative conversion of cystine with formation of cysteic acid, as well as the acceleration of radical cascades driven by transition-metal ions via the Fenton reaction. In addition, the biochemical logic and reactive capacity of several current classes of reconstructors are analyzed: Michael acceptors, itaconic-acid copolymers, biomimetic peptides, and gluconamide-based complexes, considered as systems aimed at selective modification of functional groups, stabilization of intermolecular interactions, and increased resistance of the fiber to subsequent chemical loads.*

*The performance of these compounds is interpreted strictly within the domain of verifiable data derived from scanning electron microscopy (SEM), differential scanning calorimetry (DSC), Raman spectroscopy, and dynamometric testing. This framing supports comparability of outcomes in terms of cuticle morphology, thermal stability of the keratin structure, shifts in spectral damage markers, and parameters of strength and strain behavior.*

*Marketing constructs are deliberately excluded; only process chemistry and reproducible measurements are considered. The material therefore provides a fundamental basis for the development of professionally grounded protocols for hair protection and reconstruction.*

**Keywords:** Hair Reconstruction, Chemical Damage, Disulfide Bonds, Cysteic Acid, Fenton Reaction, Chelation, Bond-Building, Instrumental Evaluation.

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## INTRODUCTION

For an extended period, the cosmetic industry largely confined itself to optical and tactile “normalization” of the hair canvas through conditioning components that form short-lived hydrophobic films on the fiber surface. Escalating demand for high-intensity color practices (total blonding, multi-step lightening schemes) and for procedures of targeted texture modification has brought into focus the need for systems that not only compensate for consequences but also modulate the chemical cascades of destruction while they are unfolding. Human hair is a keratinous structure with no metabolic activity and, consequently, no endogenous repair mechanisms [6,7]. As a result, damage to the protein matrix is functionally irreversible and may be compensated only by external interventions that provide artificial “crosslinking” or structural replacement of lost elements.

The contemporary reconstruction paradigm relies on biomimetic strategies and the toolset of engineering chemistry, implying that each stage of chemical processing is paired with a targeted therapeutic influence. At the stage of preliminary preparation, priority shifts to removal of factors that accelerate oxidative processes, first of all the elimination of catalytically active impurities. Intra-procedural support is oriented toward forming alternative

covalent and ionic interactions within the keratin network, a concept commonly termed “bond-building” in professional practice. The concluding stage is aimed at restoring the lipid barrier and normalizing the isoelectric balance, which together determine surface stability and the predictability of fiber behavior after aggressive exposure.

The economic relevance of the direction is reflected by the dynamics of the professional-care segment: the product category associated with bond restoration demonstrates accelerated growth rates and, in practice, is consolidating as a marker of high-quality service standards [2]. In this context, detailed interpretation of the molecular mechanisms underlying such systems acquires practical value for technologists, formulation chemists, and practitioners focused on reducing the frequency and severity of iatrogenic hair damage.

Objective of the work: to develop brand-independent principles and methods for hair reconstruction before, during, and after chemical procedures based on damage mechanisms and objective instrumental validation.

Scientific novelty: hair reconstruction is presented, for the first time, as an integrated stage-based “pre-intra-post” protocol in which prevention of metal-catalyzed oxidation, intra-procedural formation of alternative interactions, and

post-procedural stabilization of pH and barrier function are linked to measurable changes in SEM/DSC/spectroscopy readouts and mechanical strength.

Authorial hypothesis: sustainable retention of hair strength and thermal stability under chemical exposure is achievable only when three links are executed simultaneously, namely chelation and pre-saturation, intra-procedural interception of reactive centers with formation of new interactions, and post-procedural normalization of ionic and lipid balance; otherwise, the effect remains predominantly surface-level and short-lived.

### CHAPTER 1. BIOPHYSICAL AND BIOCHEMICAL ARCHITECTURE OF HUMAN HAIR

A detailed understanding of the substrate of exposure is required for a deep interpretation of damage and reconstruction mechanisms. Hair is a complex, highly organized biocomposite with distinctive physicomaterial properties determined by its protein-lipid architecture [6,7].

#### Hierarchical Organization of Keratin

Keratin proteins constitute the main share of hair dry mass (approximately 65-95%). These fibrous proteins are enriched in sulfur-containing amino acids, above all cysteine, which accounts for the pronounced capacity to form covalent crosslinks.[6,7,21] The cortex, which provides the primary contribution to mechanical strength and elasticity of the hair shaft, is organized as a hierarchical multi-level system ranging from molecular conformations to supramolecular aggregates assembled into cortical cell structural units.

At the basic level, keratin consists of polypeptide chains packed as alpha-helices, serving as a fundamental “scaffold” motif. Alpha-helices then associate into supercoiled coiled-coil structures stabilized by networks of intramolecular hydrogen bonds and hydrophobic interactions; such associations underlie the formation of intermediate filaments (IF).[6,7] These filaments do not exist in isolation: they are embedded within an amorphous matrix enriched in cystine and represented by keratin-associated proteins (KAP), which function as a “cementing” phase that provides adhesion and spatial fixation of fibrillar elements.[6,7] At a higher level, bundles of microfibrils and filaments, unified by the matrix, form macrofibrils that are further packed into elongated, spindle-shaped cortical cells, thereby defining the strength characteristics of the hair shaft.[6,7]

Disulfide bonds formed between cysteine residues (cystine bridges) have particular importance for maintaining cortical integrity because they provide resistance to prolonged deformation and constrain creep. In the cystine-rich matrix, the density of such crosslinks is especially high; therefore, chemical actions directed at reduction or oxidation of disulfide bonds preferentially affect the “adhesive” phase and lead to redistribution of mechanical loads between filaments and matrix.[6,7] This results in shifts of elastic

modulus, brittleness, and resistance to rupture, as well as the emergence of microdefects at sites of heterogeneous degradation of the protein crosslinking network.

Cortical functional properties are governed not only by covalent bonding but also by dynamic noncovalent interactions that are sensitive to hydration and acid-base conditions. Water acts as a plasticizer of the protein matrix, weakening a portion of hydrogen bonds and increasing mobility of polymer segments, thereby temporarily raising deformability and lowering shaft stiffness. When pH shifts, the degree of ionization of protein side groups changes, affecting electrostatic repulsion and macromolecular packing as well as permeability of intercellular structures; collectively, these effects can alter friction between fibrils and redistribute local stresses under bending and tension.[6,7]

An additional contribution to variability of hair mechanics comes from microstructural heterogeneity of cortical cells and spatial orientation of macrofibrils. Anisotropy of filament alignment, differences in matrix density, and variation in crosslink distribution create regions of unequal stiffness and elastic recovery, which matters for curl formation, shape retention, and failure patterns under repeated loading. In parallel, the presence of melanin granules and other inclusions may act as loci of stress concentration, influencing initiation of microcracks and the rate of damage accumulation during thermal and chemical exposure.[6,7]

#### Chemical Bonds: The Basis of Strength

Mechanical stability of the protein-fibrillar framework is not created by a single dominant bond but by a constellation of interactions of different nature and bond dissociation energies operating synchronously across levels of organization. It is this combined architecture of covalent crosslinks and abundant reversible contacts that provides stiffness, elasticity, and a capacity for limited restructuring as external conditions change.[6,7]

Within this network, disulfide bridges (S-S) are among the most energy-intensive elements. They represent covalent crosslinks between two cysteine residues formed by oxidation of thiol groups to yield cystine. Their bond dissociation energy is often estimated at approximately 60 kcal/mol, which makes them key determinants of thermal stability and resistance to wet deformation.[6] Controlled reduction followed by re-oxidation of disulfide bridges underlies chemical reshaping of the shaft (permanent waving, straightening). By contrast, during bleaching and other oxidative exposures, uncontrolled transformations of disulfides may occur with formation of more highly oxidized sulfur derivatives and a decrease in functional crosslink density, expressed as loss of strength and increased brittleness.[5,6]

Ionic (salt) bonds arise from electrostatic attraction between positively charged amino groups (for example, side chains of lysine and arginine) and negatively charged carboxyl groups

(aspartic and glutamic acids). Their contribution becomes especially evident under conditions where the covalent network remains largely intact while the ionization state of functional groups changes. Such interactions are highly sensitive to pH: when the medium shifts into strongly acidic or strongly alkaline ranges, charge screening and disruption of a portion of ionic “nodes” occurs, accompanied by swelling, altered porosity, and a temporary loss of order; upon return of pH toward physiologic values, a substantial fraction of ionic contacts can be restored.[7,21]

Hydrogen bonds are among the weakest in terms of energy of a single interaction, yet their very high number within the keratin system makes them a critical source of elasticity and viscoelastic response. These contacts form between electronegative atoms (oxygen, nitrogen) and hydrogen atoms within polar groups of proteins and matrix. Water molecules effectively compete for participation in hydrogen bonding; therefore, hydration noticeably weakens a portion of intranetwork contacts, increasing extensibility and reducing elastic modulus, while drying allows the hydrogen-bond network to be substantially reconstructed, returning mechanical characteristics toward baseline.[6,7]

Isopeptide bonds are comparatively rare covalent crosslinks between amino-acid side chains (classically between the epsilon-amino group of lysine and the carboxamide group of glutamine or a related carboxyl group), arising enzymatically or induced by heating and prolonged exposure. Their relevance is associated less with their frequency than with an effect of “irreversible fixation” of local matrix segments and interfibrillar contacts, which can increase stiffness and reduce relaxation mobility of the protein network, thereby enhancing a tendency toward brittle failure under cyclic loading.[6,7]

From a practical standpoint, the key factor is not isolated strength of individual bonds but cooperative function and redistribution of stresses across structural levels. Under primary mechanical exposure and short-term hydration, hydrogen bonds and a portion of ionic contacts preferentially “unlock”, enabling reversible deformation. Under prolonged stress, particularly in the combined presence of moisture, alkaline pH, and temperature, the risk increases for transition from reversible restructuring to accumulation of microdefects because matrix plasticity rises while fibrillar elements begin to experience local overloads.[6,7]

Chemical damage also proceeds in a cascade-like manner: changes in the disulfide system rarely remain limited to a simple S-S cleavage. Oxidative processes can shift balance toward modifications of sulfur-containing groups, reducing the capacity for correct re-crosslinking and increasing hydrophilicity of certain protein domains. Against this background, water penetrates structural gaps more readily, intensifying disorder of hydrogen contacts and facilitating pH-induced disruption of salt bridges; cumulatively,

degradation manifests as reduced tensile strength, increased surface roughness, and diminished tolerance to repeated styling.[5,6,7]

A further modifying factor relates to thermal exposure: heating can simultaneously accelerate relaxation of noncovalent bonds and induce formation of new covalent crosslinks, including isopeptide bonds, thereby changing the balance between elasticity and brittleness. Accordingly, even at comparable degrees of external damage, divergent mechanical profiles may appear - from a more “soft” material with high deformability under hydration to an excessively rigid and brittle profile after overheating, where irreversible crosslinks constrain mobility of the protein network and increase the likelihood of crack formation under bending.

### Cell Membrane Complex (CMC) and Lipids

The intercellular space at the cuticle-cortex interface is filled by the cell membrane complex (CMC), which is functionally comparable to an intercellular “cement” providing cohesion and coordinated operation of individual cellular plates. Structurally, the CMC is a layered system in which a protein-enriched delta-layer is combined with beta-layers that are predominantly lipid in nature; this configuration produces both mechanical continuity and barrier selectivity, governing diffusion of water and low-molecular substances along the hair shaft.[6,7]

Lipid components of the beta-layers serve as a hydrophobic interlayer with low permeability and relatively high structural mobility, whereas the protein-rich delta-layer acts as a more “rigid” phase stabilizing intercellular contacts. As a result, the CMC becomes a key regulator of surface tribology: its condition largely determines the coefficient of friction, propensity to tangling, and the rate of shaft impregnation by aqueous and organic media. When CMC integrity is compromised, the probability of micro-delamination of cuticular plates increases, and defects at the cuticle-cortex boundary form more readily, accelerating damage progression under mechanical loading.[6,7]

Among surface lipids, 18-methyleicosanoic acid (18-MEA) occupies a special position. This branched fatty acid is covalently anchored on the epicuticle surface via a thioester linkage. The lipid anchor creates a distinctly hydrophobic shield that limits excessive wetting, reduces adhesion, and lowers friction between fibers. Loss of 18-MEA is considered an early and sensitive marker of chemical damage: the surface rapidly shifts toward a more hydrophilic state, water uptake and roughness increase, and visually apparent manifestations include reduced shine and a “dull” appearance of the shaft. [6,7]

Destruction of 18-MEA and associated reorganization of CMC beta-lipid layers is cumulative. Initial loss of the hydrophobic surface layer facilitates penetration of reagents and water into intercellular domains, creating conditions for further

leaching and oxidation of lipids and weakening of protein-lipid interfaces. At the mechanical level, this translates into increased interfiber adhesion and greater damage during combing; at the barrier level, it accelerates diffusion of chemical agents toward deeper protein targets, raising the risk of secondary alterations in the keratin matrix and disruption of the disulfide network.[5,6,7]

From the standpoint of hair materials science, the CMC can be described as an interfacial composite layer with a pronounced role of phase boundaries: processes concentrated here often determine the transition from a surface defect to structural damage of the entire fiber. Stability of the lipid component, including 18-MEA, supports low surface energy and a favorable tribological profile, whereas degradation of this phase shifts balance toward increased hydration, higher friction, and accelerated accumulation of microcracks along intercellular lines. In this way, CMC condition becomes a central factor linking “cosmetic” manifestations (shine, smoothness, manageability) with deeper changes in the strength properties of the shaft.[6,7]

## **CHAPTER 2. PATHOPHYSIOLOGY OF CHEMICAL DAMAGE: MOLECULAR MECHANISMS OF DEGRADATION**

Chemical procedures inevitably disturb the native bond balance within the hair fiber. A clear view of the underlying chemistry of degradation makes it possible to design targeted protection strategies.

### **Oxidative Stress Mechanisms during Bleaching**

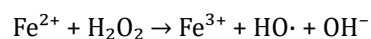
Bleaching is among the most aggressive chemical insults to the hair shaft because it combines high alkalinity with an intense oxidative burden. Technologically, the process relies on the synergism between an alkaline component (ammonia, ethanolamine), which promotes fiber swelling and loosens intercellular contacts, and oxidants (hydrogen peroxide, persulfates) that generate reactive species. Elevation of pH increases the ionization of acidic protein groups, strengthens electrostatic repulsion, and weakens a portion of salt bridges and hydrogen bonding; as a result, cuticle scales lift more readily, while the diffusion barriers of the CMC transiently lose compactness. Against this background, the oxidative mixture penetrates into the cortex, where the principal pigment and protein targets are concentrated.

Depigmentation begins with melanin breakdown: hydroxyl and perhydroxyl radicals attack conjugated double-bond systems and functional fragments that form chromophoric groups. Disruption of these structural motifs eliminates optical absorption in the visible range and therefore produces lightening. Yet radical chemistry in the cortex is not confined to pigment. In parallel, sulfur-containing nodes of the keratin network are affected—most notably disulfide bridges (Cystine–S–S–Cystine), which function as key crosslinks and stabilize the architecture of the fibrillar–matrix composite.

Under controlled conditions, it is assumed that after a transient cleavage, a fraction of disulfide bonds may subsequently reform as redox conditions shift. At high oxidative potential, however, an alternative, unfavorable pathway dominates. Sulfur within the disulfide node undergoes over-oxidation to intermediate forms (cysteine S-monoxide, S-dioxide), which then convert to cysteic acid (Cysteic Acid, R–SO<sub>3</sub>H). Formation of cysteic acid is irreversible and is accompanied by the emergence of a negatively charged sulfonate group that generates persistent electrostatic repulsion and prevents close approach of polypeptide chains, making reformation of the original crosslinks thermodynamically and kinetically difficult [6]. As a result, the keratin matrix loses a portion of its mechanical “nodes,” the fraction of defective domains increases, and damage manifests as reduced tensile resistance and greater brittleness under repeated loading.

Persulfates frequently act as an additional amplifier of oxidative stress. Beyond raising the overall oxidizing capacity of the system, they can generate sulfate radicals and other high-energy species, particularly at elevated temperature and in the presence of catalytic impurities. Such a radical environment is poorly selective: reactive attack spreads across a broad spectrum of protein and lipid functional groups, including backbone amide bonds, aromatic side chains, and interfacial components of the cell membrane complex. In practice, primary melanin depigmentation is often accompanied by a secondary rise in cortical porosity and water uptake, because partial loss of matrix bonding and a shift in surface chemistry facilitate diffusion of water and subsequent reagents deeper into the fiber.

A major determinant of oxidation kinetics and “harshness” is the presence of transition-metal ions in hair, introduced exogenously (water, environment, cosmetic deposits) or accumulated preferentially at damaged sites. Copper and iron ions can catalyze hydrogen peroxide decomposition with formation of highly reactive hydroxyl radical through Fenton-type reactions:



The resulting HO· is characterized by extreme reactivity and a lack of directed specificity; it can attack peptide bonds within the protein backbone in a stochastic manner, initiating macromolecular fragmentation and subsequent leaching of protein mass [10]. The shift from predominantly “crosslink-focused” damage (modification of disulfide nodes) toward backbone disruption qualitatively changes the degradation profile: irreversible material losses become more prominent, micro-delamination of structural domains increases, and defect accumulation accelerates—defects that are not compensated by restoration of noncovalent contacts during drying or pH normalization.

Experimental data indicate that even relatively low copper levels can markedly intensify oxidative destruction. The presence of Cu in the 20–50 ppm range has been associated

with a pronounced rise in carbonyl groups as a marker of protein damage and with a measurable decline in hair tensile strength [13]. Carbonylation reflects oxidative modification of amino-acid residues and correlates with loss of polymer-network integrity, whereas cysteine acid accumulation signals irreversible transformation of sulfur-containing crosslinks and a long-term shift in the electrical balance of the matrix [6]. Together, these changes generate a durable “brittle composite” phenotype in which the capacity to distribute stress uniformly between fibrillar and amorphous phases is reduced.

A further consequence of the radical-driven cascade is remodeling of interfacial regions, including the CMC. Damage to lipid lamellae and protein–lipid interfaces enhances diffusion of reagents and water, increases inter-fiber friction, and facilitates mechanical lifting and abrasion of the cuticle. In this way, the chemical stage becomes reinforced by a mechanical one: weakening of the intercellular “cement” reduces the resistance of the cuticular envelope to combing and cyclic bending, while increased cortical porosity amplifies swelling heterogeneity and local stress concentrations. Within such a system, metal-catalyzed  $\text{HO}\cdot$  formation acts as a driver that accelerates the transition from superficial defects to deep fragmentation of the protein backbone [10].

### Damage during Chemical Straightening and Perming

Procedures designed to permanently reshape the hair shaft (curling, straightening) are based on deliberate modification of sulfur-containing crosslinks in the keratin matrix, because disulfide bridges define the stable geometry of the macromolecular network and resistance to sustained deformation. In practice, either reductive systems (thioglycolates, sulfites, and related electron donors) or highly alkaline hydroxide-based formulations are used, producing chemically and mechanically distinct scenarios of cortical rearrangement.

Thio-reductive processes proceed via reduction of the disulfide bond, converting cystine bridges into two sulfhydryl groups ( $-\text{SH}$ ). At the molecular level, this is equivalent to temporarily “untying” nodes within the keratin network, increasing polypeptide mobility and permitting redistribution of chain orientation under external mechanical fixation (rollers, tension during straightening). The critical risk zone lies in neutralization and fixation: if oxidation of thiols is insufficient or uneven, a portion of bonds does not reform, while another portion forms in altered configurations. This reduces the density of effective crosslinks and leaves the keratin matrix functionally “underbuilt.” Such a state is associated with reduced tensile strength, increased creep in a wet environment, and a higher likelihood of progressive damage under subsequent thermal and mechanical loading.

A significant determinant of outcomes in thio-based procedures is diffusion nonuniformity of reagents within the shaft. Because penetration of the reducer and the subsequent

fixing agent is constrained by the state of the cuticle and the cell membrane complex, concentration gradients develop across the cortex thickness. Consequently, some domains may undergo deep reduction, whereas others remain only partially modified, creating a “mosaic” crosslink landscape and local zones of stress concentration. At the macroscopic level, this presents not only as variability of results along the length but also as increased brittleness in regions where reduction was substantial and subsequent re-oxidative fixation was incomplete.

Alkaline straightening based on hydroxides (sodium, potassium, or systems generating hydroxide ion in situ) operates via a fundamentally different chemical mechanism known as lanthionization. Under strongly alkaline conditions, hydroxide ions attack the disulfide bridge, converting a fraction of cystine linkages into lanthionine-type crosslinks of the C–S–C form (a stable thioether), with elimination of one sulfur atom from the original disulfide node [4]. This pathway is irreversible and effectively “re-stitches” the keratin network, altering the amino-acid profile and the distribution of crosslinks [4].

The mechanical consequences of lanthionization follow from the fact that disulfide bridges provide a specific combination of strength and viscoelastic adaptability, whereas newly formed C–S–C linkages change chain mobility and the energy landscape of local rearrangements. Loss of a portion of “elastic” disulfide nodes and their replacement with more chemically inert thioether crosslinks reduces the matrix’s capacity for reversible relaxation under cyclic deformation and increases susceptibility to brittle fracture, particularly when combined with dehydration and thermal exposure [4]. In addition, high alkalinity promotes swelling and disordering of interfacial structures, which facilitates mechanical cuticle damage and amplifies nonuniform stress distribution under subsequent loads.

It is also important that under hydroxide treatment, chemical transformation rarely remains confined to disulfide nodes. Extreme pH values increase the likelihood of side reactions affecting the protein matrix and intercellular components, thereby accelerating deterioration of barrier properties and increasing porosity. Collectively, this yields a damage profile in which a pronounced and durable geometric reshaping is achieved, but at the cost of irreversible changes in keratin architecture and increased brittleness due to reduced functional “plasticity” of the crosslink network [4].

### Loss of the Lipid Barrier and Hydrophilization

An alkaline environment with pH above 9 initiates hydrolytic cleavage of the thioester bond through which 18-methyleicosanoic acid (18-MEA) is covalently anchored on the epicuticle surface. Destruction of this monolayer exposes underlying protein domains and alters the physicochemical surface profile: hydrophilicity rises sharply, the density of polar groups increases, and net surface charge shifts toward

electronegativity due to ionization of acidic functional fragments [5]. This restructuring is not merely a “cosmetic” effect, because it changes both inter-fiber interactions and transport of moisture and reagents in near-surface structures.

Loss of 18-MEA increases surface energy and strengthens the adhesive component of friction. Under fiber–fiber contact, this manifests as a higher coefficient of friction and, consequently, increased propensity for tangling: fibers more readily “catch” on one another, and micro-roughness of the cuticle plays a more prominent role in mechanical interlocking [5]. At the same time, increased negative charge under certain ionic conditions can produce a complex balance between electrostatic and adhesive forces; in practical terms, the dominant contribution is typically the combined effect of roughness and hydration, which increases resistance to sliding.

Surface hydrophilization facilitates water sorption and accelerates its penetration into intercellular regions of the cuticle and deeper into the cortex via CMC diffusion pathways. Increased hydration is accompanied by cortical swelling and the development of internal stresses, because different hair components (cuticle, intercellular “cement,” cortical substance) swell to different extents. Upon subsequent drying, cyclic stress redistribution and local shrinkage gradients arise, promoting micro-delamination of cuticular plates and accelerating defect accumulation at layer boundaries [5].

Optical manifestations of degradation are closely linked to cuticle geometry. With loss of the hydrophobic 18-MEA anchor and increased hydration, cuticle scales become more lifted and “loosened,” tight apposition is disrupted, and micro-roughness increases. This shifts light reflection from predominantly specular behavior toward more diffuse scattering, perceived as reduced shine and visible “dullness” [5]. Thus, loss of luster is not an isolated phenomenon but an indicator of reduced ordering of surface relief and barrier function.

From the standpoint of colloid and surface chemistry, removal of 18-MEA represents a shift from a predominantly lipidic, low-energy surface to a protein-enriched, more polar and reactive one. Such a transition increases the capacity of the surface to bind water, electrolytes, and polar organic components, altering the hydration-shell structure and the nature of inter-fiber contact. Under mechanical load, this raises the contribution of “sticky” friction and facilitates formation of microdamage along cuticle-scale edges, especially during repeated wet–dry cycling [5].

A further consequence of alkaline exposure is a change in the diffusion accessibility of internal targets. Increased hydrophilicity and disordering of near-surface layers facilitate transport of oxidants, reducers, and surfactants into the CMC region and then into the cortex, creating preconditions for cascade damage in which surface loss of the lipid barrier precedes deeper protein modification. In this sense,

hydrolysis of the 18-MEA linkage should be viewed as an early event that can increase hair susceptibility to subsequent chemical and thermal loads while simultaneously worsening tribology, moisture exchange, and optical properties of the shaft [5].

## **CHAPTER 3. STAGE I: PRE-PROCEDURE RECONSTRUCTION AND CHELATION**

Given the catalytic role of metals in oxidative degradation, the preparation step (“pre-treatment”) is no longer optional and instead functions as a mandatory safety protocol. The primary objective is to deactivate metals and to preload the cortex with protective agents.

### **Chelation Chemistry: Neutralizing Catalysts**

Chelating agents (chelators) are compounds capable of forming multiple coordination bonds with metal ions simultaneously. As a result, the metal is “captured” in a stable cyclic configuration—often described as a claw-like complex—shifting it into a chemically low-reactivity state while increasing solubility and thereby facilitating removal from the system.

Chelator performance in salon-relevant conditions is fundamentally nonuniform and is determined both by the spectrum of ions bound and by competitive interactions in aqueous media. EDTA (ethylenediaminetetraacetic acid) is a classical chelator with strong affinity for hardness ions, particularly calcium and magnesium. However, in the presence of substantial  $\text{Ca}^{2+}$  excess, typical of hard water, binding of transition metals may become less effective: the stability of copper and iron complexes under such conditions can be functionally insufficient. In addition, Fe–EDTA-type complexes have been described, under certain environmental parameters, as capable of expressing pro-oxidant potential, which in theory reduces the protective effect during oxidative processes [13].

Biodegradable chelators of the newer generation include EDDS (ethylenediaminedisuccinate) and N,N-dicarboxymethyl alanine. For this group, enhanced selectivity toward transition-metal ions has been reported, persisting even against a background of high  $\text{Ca}^{2+}$  concentrations. This feature has clear applied relevance because copper, in particular, is regarded as a key trigger of radical transformations that can intensify oxidative damage to the fiber [13].

Gluconates and glucose derivatives (gluconic acid and its salts) act as effective iron sequestrants in alkaline media. This property makes them technologically appropriate components for direct incorporation into lightening powders and dyes, where an alkaline pH range is a functionally imposed condition [18].

A separate direction is represented by so-called molecular traps. Polymer systems based on polyethyleneimine, along with specialized low-molecular-weight compounds including

MAZ (methyl acetyl zingerone), are being developed for targeted binding of copper within the hair structure in order to exclude its participation in Fenton-type reactions and the coupled generation of highly reactive species [12].

Instrumental studies support that pre-treating hair with chelating sprays or shampoos prior to lightening is associated with clinically meaningful effects. A reduction in protein loss in the 20–40% range has been reported, and is linked to suppression of hydroxyl radical generation and, accordingly, attenuation of radical-induced destruction of protein structures [11, 13]. Increased uniformity of the lightning background is also noted; this is interpreted as prevention of localized exothermic zones (“hot spots”) that arise when metals accumulate unevenly and oxidative reactions intensify in discrete areas [20]. In addition, reduced expression of greenish and coppery tones has been described, attributable to diminished metal interactions with dye components and the downstream formation of undesirable color nuances.

### **Amino-Acid Pre-Loading**

A second pre-preparation strategy involves saturating the cortex with low-molecular-weight polar amino acids and their derivatives. A key advantage of this approach is that small amino-acid molecules—such as arginine, glycine, and histidine—can diffuse into deeper layers of the hair shaft, whereas large protein structures under comparable conditions show substantially more limited penetration.

Arginine is characterized by a positively charged guanidinium group, enabling pronounced electrostatic interaction with negatively charged regions of damaged keratin. Through this anchoring, arginine functionally acts as a molecular “anchor,” stabilizing weakened zones of the protein matrix and creating additional binding points within the fiber structure [21].

For histidine and phenylalanine, an increase in resistance to tensile load has been reported, indicating reinforcement of the shaft’s mechanical characteristics. Histidine, beyond its structural effect, is described as a compound with radical-scavenging properties and a potential role as a secondary copper chelator, which becomes relevant under oxidative conditions that can accelerate protein degradation [21].

An additional protective aspect is associated with formation of a “sacrificial layer.” Exogenously supplied amino acids, as well as low-molecular fractions of hydrolyzed keratin, can act as preferential substrates for oxidation, intercepting the reactivity of hydrogen peroxide and thereby reducing competitive oxidative damage to endogenous hair proteins [22].

Mechanical testing results support the practical relevance of such pre-treatment. In tensile tests, prior application of amino-acid solutions or low-molecular hydrolyzed keratin has been associated with better preservation of elastic modulus after UV exposure and chemical challenge compared with control [23].

## **CHAPTER 4. STAGE II: INTRA-PROCEDURE PROTECTION—BOND-BUILDER CHEMISTRY**

The central innovation of the past decade has been the possibility of running a chemical reaction inside the hair concurrently with its ongoing degradation, aiming at immediate repair. This class of additives, commonly referred to as “plexes” (bond builders), operates in aggressive media (high pH, oxidizers) and is directed toward preserving or re-creating covalent and ionic interactions.

### **Mechanism I: Michael Addition and Dimaleates**

The emergence of this category is associated with a technology built around bis-aminopropyl diglycol dimaleate, which is often treated as a reference model for subsequent developments. The active molecule is characterized by two terminal maleate fragments connected by a flexible spacer. The maleate group belongs to  $\alpha,\beta$ -unsaturated carbonyl systems and functions as a typical Michael acceptor, which determines its reactive orientation toward nucleophiles.

The functional mechanism is expressed under conditions of disulfide-bond damage in keratin. When an S–S crosslink is cleaved within the protein matrix, thiol groups (–SH) are formed. In this context, thiols behave as strong nucleophiles and can undergo conjugate addition across the double bond of the maleate fragment, i.e., react via the Michael mechanism. Because the molecule is bifunctional and contains two reactive maleate termini, sequential reaction with two thiol centers is possible. The key technological effect is attributed to kinetic advantage: interaction of the dimaleate with thiols proceeds faster than their oxidation into cysteic acid. As a result, reactive –SH centers are preferentially diverted into formation of a new linkage, which reduces the probability of irreversible modifications, “intercepts” the consequences of the original disulfide break, and stabilizes hair’s protein architecture via newly formed covalent bridges [6].

### **Mechanism II: Gluconamide Polymerization and Ionic Networks**

An alternative concept is implemented in systems based on “sugar chemistry,” primarily hydroxypropyl gluconamide and hydroxypropyl ammonium gluconate. These compounds are low-molecular-weight and strongly polar; their structures contain multiple hydroxyl (–OH) and amide (–CONH–) fragments that provide extensive hydrogen-bonding potential, as well as protonatable or cationic amine centers that enable ionic interactions with charged regions of the protein matrix.

After penetrating into the cortex, gluconamide derivatives initiate formation of a dense network of hydrogen and electrostatic bonds with polar amino-acid residues of keratin. Upon subsequent dehydration and thermal exposure, polymerization-type transformations within the fiber bulk have been described, leading to formation of a spatially organized three-dimensional matrix. This internal structure

functions as a mechanical “framework” that supports conformational stability of keratin  $\alpha$ -helices and reduces the likelihood of destabilization and breakdown under damaging conditions [18].

The practical relevance of this approach is particularly pronounced in hair with pre-existing structural deficit, where disulfide crosslink density is reduced while the fraction of accessible polar centers for noncovalent binding, by contrast, increases. According to test reports, use of such systems is associated with a multiple increase in resistance to tensile load; strength gains have been described as up to three-fold [32].

Additional reinforcement is attributed to changes in the micromechanics of the interfibrillar space. The resulting hydrogen- and ion-bonded network increases cohesion between keratin domains and reduces mobility of macromolecular segments, thereby lowering creep and limiting local stress concentration during stretching. Through moisture retention and partial compensation of porosity, polar sugar derivatives can help equalize water distribution within the cortex, constraining swelling–shrinkage cycles that accelerate fatigue damage accumulation. Collectively, these effects support protein secondary structure stability and improve the functional durability of hair under repeated thermal and chemical exposures.

### Itaconic-Acid Copolymers

Itaconic acid, a succinic-acid derivative that is also an unsaturated dicarboxylic system, is considered a promising bio-monomer for engineering protective polymer architectures. The combination of vinyl functionality with two carboxyl groups creates a high chemical “density” of reactive centers, enabling multiple routes toward film-forming and crosslinked structures. In cosmetic matrices, such a monomeric fragment allows coatings to be produced that adsorb stably on keratin-containing substrates and form a barrier layer that limits adverse physicochemical impacts.

The reactivity of itaconic acid is expressed, first, through Michael-acceptor behavior, which enables nucleophilic addition—including by thiol and amine groups—yielding functionalized derivatives. Second, the presence of a double bond supports radical polymerization and copolymerization, allowing deliberate control of molecular weight, branching, and crosslink density. This dual chemical nature enables fine tuning of the mechanics of the resulting film, from more mobile segmented chains to dense networks with pronounced resistance to deformation.

In cosmetic products, itaconic acid is often combined with amino acids, notably arginine, as well as with panthenol, forming functional copolymer systems. Arginine, carrying basic groups, can participate in ionic interactions with carboxylates, enhancing adhesion to surface keratin regions and stabilizing polymer deposition. Panthenol, acting as a

hydrophilic plasticizer and a carrier of hydrogen-bonding potential, helps reduce film brittleness and improves elasticity without loss of integrity. The resulting copolymers create a flexible yet strong network within and on the surface of hair, increasing resilience and resistance to bending [33].

At the fiber level, the effect of these systems is determined not only by film formation but also by the character of intermolecular interactions with the protein matrix. Carboxyl groups enable hydrogen bonding and electrostatic contacts with polar keratin regions, which can reduce surface roughness and partially “screen” cuticle defects. When accessible nucleophilic centers exist within the substrate (e.g., side-chain amines), mild Michael-type additions may occur, potentially improving resistance of the formed coating to wash-off and mechanical abrasion.

Technological performance of itaconate-containing systems depends materially on formulation parameters: acid–base state (pH), ionic strength, presence of co-initiators and chain regulators, and compatibility with surfactants, cationic conditioning components, and silicone phases. Control of carboxyl-group neutralization determines the balance between solubility, tendency toward coacervation, and efficiency of deposition on hair. Optimization of molecular weight and chain-length distribution can simultaneously increase film strength while avoiding excessive stiffness that might amplify brittleness under repeated styling cycles.

Validation of claimed mechanical and barrier effects typically relies on a combination of physicochemical and instrumental methods: assessment of bending modulus and tensile strength, measurement of combing forces, analysis of changes in porosity and water sorption, and surface microscopy to document the degree of cuticle leveling. Wash-off kinetics and coating stability under thermal and photo-exposure are also considered, because durability of the conditioning effect is determined by preservation of film continuity. In the context of sustainable development, the biogenic origin of itaconic acid and the feasibility of producing functional copolymers with tunable degradation further increase interest in this class of bio-monomers for modern hair-protection systems [33].

### Biomimetic Peptides

One of the most promising directions in contemporary hair reconstruction is the use of recombinant peptides, for example sh-oligopeptide-78 and KeraBio K31, whose amino-acid sequences reproduce selected fragments of human keratins. Unlike protein hydrolysates, which represent a statistically heterogeneous mixture of peptide fragments, biomimetic peptides are designed with structural and chemical complementarity to damage zones within the keratin matrix in mind.

The functional efficacy of these molecules is attributed to the combination of a strictly defined sequence and an optimized

molecular mass, enabling targeted “integration” into defects of polypeptide chains and producing a “molecular patch” effect. Stabilization of this incorporation is supported by an ensemble of multiple noncovalent interactions (hydrogen bonds, ionic and hydrophobic contacts), and when cysteine

residues are present, additional anchoring via disulfide-bridge formation is plausible.

A table (Table 1) is presented below summarizing the results of a comparative analysis of mechanisms of action for the main classes of intra-procedure reconstructors.

**Table 1.** Comparative analysis of mechanisms of action for the main classes of intra-procedure reconstructors (compiled by the author based on [7, 16, 27, 33, 36]).

| Compound class      | Representative (INCI)              | Target interaction  | Stabilization mechanism                           | Wash-off resistance               |
|---------------------|------------------------------------|---------------------|---------------------------------------------------|-----------------------------------|
| Dimaleates          | Bis-Aminopropyl Diglycol Dimaleate | S–S (thiols)        | Covalent crosslinking (Michael addition)          | High (permanent crosslink)        |
| Gluconamides        | Hydroxypropyl Gluconamide          | H-bonding, ionic    | Formation of a hydrogen-ionic matrix              | Medium/High (structure-dependent) |
| Organic acids       | Maleic Acid, Citric Acid           | Ionic, salt bridges | Structural densification, pH balance, chelation   | Low/Medium (wash out)             |
| Biomimetic peptides | sh-Oligopeptide-78                 | Peptide chain       | Biomimetic integration into structure             | High (progressive)                |
| Copolymers          | Itaconic Acid Copolymers           | Ionic, covalent     | Polymerization and crosslinking (Michael/radical) | High                              |

As a result, restoration of viscoelastic properties becomes possible along the extent of the polypeptide chain, rather than predominantly through transverse “crosslinking” of structural elements [36].

## CHAPTER 5. STAGE III: POST-PROCEDURE RESTORATION AND HOMEOSTASIS MAINTENANCE

After the chemical reaction is completed and aggressive agents are removed, the physicochemical parameters of hair remain disturbed: the cuticle is lifted, pH is shifted toward alkalinity, and the hydrophobic layer is depleted. The “post” stage is directed toward restoring barrier properties.

### pH Normalization and Restoration of Ionic Interactions

Hair keratin is an amphoteric biopolymer containing both acidic and basic functional groups; accordingly, the net charge of the fiber is governed by the acidity of the surrounding medium. For intact hair, the isoelectric point lies in the pH 3.67–4.0 range, where the numbers of positively and negatively charged centers are approximately balanced. Shifting pH into the alkaline domain—typical of coloring and lightening—raises the fraction of deprotonated carboxyl groups and produces a pronounced excess negative charge. In this setting, electrostatic repulsion within the protein matrix increases, swelling of the cortical substance intensifies, and cuticle scales adopt a more lifted configuration. Simultaneously, ionic interactions weaken and salt bridges that normally stabilize keratin-domain architecture are disrupted.

Loss of ionic-bond integrity in alkaline media has not only structural but also transport consequences. Permeability of surface layers increases, diffusion access to the intercellular cement expands, and migration of low-molecular-weight

components and water accelerates. Increased porosity facilitates leaching of pigment molecules and reduces retention of conditioning agents because the number of “anchor” sites available for fixation declines. A further contributor is altered charge distribution at the surface: when negatively charged groups predominate, retention of anionic and certain neutral functional additives becomes less favorable, and the need for directed restoration of electrostatic balance grows.

Acidic neutralization after alkaline exposure is therefore considered a key stabilization step. Application of formulas in the pH 3.0–4.5 range, incorporating citric, lactic, or tartaric acids, promotes protonation of amine groups and partial restoration of ionic pairs between oppositely charged fragments along the polypeptide chain. Returning to a more acidic environment reduces swelling intensity, favors tighter interdomain packing, and produces a physical “contraction” of the cuticle—often described in practical terminology as a “locking” effect. This shift in equilibria reduces porosity, improves barrier performance of surface layers, and supports retention of pigments and care components within the hair structure [7].

The effectiveness of acidification is determined not only by the target pH but also by the buffer capacity of the system, the diffusion rate of the acid, and the ability of the anions to complex inorganic impurities. Polyprotic acids (e.g., citric acid) can additionally bind metal ions that catalyze oxidative processes and accelerate degradation of coloring molecules, indirectly improving color durability. At the same time, organic acids differ in molecular weight and hydrophilicity, which affects penetration depth and distribution uniformity within the fiber, as well as the kinetics of restoring intermolecular contacts.

The acidic step also creates favorable conditions for subsequent deposition of cationic conditioning polymers and quaternized surfactants. As pH approaches the region where keratin amine centers are partially protonated, the number of potential sites for electrostatic and hydrogen-bond anchoring of film-forming components increases. In practice, this is expressed as a more uniform surface film, reduced friction coefficient, and less mechanical damage during combing. Neutralization therefore performs a dual function: structural “closure” of the cuticle is coupled with increased efficiency of care-ingredient deposition.

At the same time, excessive acidification and uncontrolled acidity can produce undesirable effects: enhanced extraction of certain low-molecular fractions, increased irritant potential for the scalp, and impaired sensory properties due to overly rigid films or incompatibility with other formulation components. For this reason, the pH 3.0–4.5 interval is treated as a technologically and biophysically justified compromise, providing sufficient protonation and salt-bridge recovery without risking aggressive impact on the protein matrix and lipid barrier [7].

### Restoring Hydrophobicity (F-Layer Restoration)

Loss of the surface layer of 18-methyleicosanoic acid (18-MEA), covalently linked to cuticular proteins via thioester fragments, drives a radical shift in hair interfacial properties: the surface transitions from predominantly lipophilic to distinctly hydrophilic. This transformation is accompanied by increased wettability and friction coefficient, faster swelling upon contact with water and detergents, and progressive mechanical wear of the cuticle. As a result, sliding of cuticle scales relative to one another is impaired, the probability of microchipping and delamination rises, and fiber resistance to bending and stretching declines—creating conditions for breakage during repeated styling and washing cycles.

Because practical restoration of the original covalent “anchor” chemistry of 18-MEA on the cuticle surface is effectively unattainable, biomimetic substitution strategies are employed to reproduce the key function of the lost layer: formation of a low-energy hydrophobic boundary. Such approaches rely on adsorption and coacervate deposition of amphiphilic molecules that can attach to anion-enriched defective sites and orient hydrocarbon segments outward. A central requirement is formation of a stable but not fully occlusive film. Excessive sealing worsens moisture diffusion and may promote internal stress accumulation, whereas a moderately permeable structure reduces friction while preserving physiologically acceptable water exchange.

Cationic surfactants and lipid components represent baseline tools for this functional substitution. Compounds such as behentrimonium chloride and cetrimonium chloride carry permanent positive charge and are efficiently attracted to negatively charged regions of damaged hair, where alkaline and oxidative procedures increase the fraction

of deprotonated carboxylates and sulfonic groups. Due to amphiphilicity, the molecules orient so that the polar “head” anchors at the surface while hydrophobic alkyl tails face outward, forming a lipid-like interface and lowering surface energy. This reduces wettability, facilitates combing, and partially compensates for loss of the native fatty-acid barrier, while simultaneously acting as a matrix that helps retain other film-forming ingredients [21].

Quaternized and amino-functional silicones represent a more durable branch of biomimetic restoration. Amodimethicone and its derivatives contain amine groups that become protonated in acidic media and gain pronounced affinity for anionic centers of damaged keratin. The resulting silicone film combines mechanical strength with regulated permeability: it reduces friction and abrasive wear while not fully blocking water-vapor transport. A significant advantage is selective deposition on the most damaged regions, where negative charge density and microporosity are higher; this selective distribution is commonly described as “smart deposition.” Owing to high hydrophobicity and resistance to wash-off, such systems provide prolonged protection and a pronounced anti-friction effect at relatively moderate coating mass [6].

Ceramides and phytosterols act primarily in a different compartment—within the intercellular cement of the cuticle, where lamellar lipid organization is normally present. Under damage, lipid lamellae become fragmented and disordered, increasing diffusion permeability and promoting fiber dehydration. Incorporation of ceramides and sterol fractions supports “filling” of defects and partial restoration of lamellar packing, reducing uncontrolled water migration and lowering moisture loss, thereby stabilizing mechanical characteristics and decreasing cuticle brittleness. Functionally, this approach is comparable to barrier-lipid restoration in the stratum corneum, yet it is implemented on a keratin substrate with different porosity parameters and ionic architecture [7].

Additional value of biomimetic substitution is linked to surface tribology and control of soil adhesion. A hydrophobized, low-energy film reduces particle sticking and decreases inter-fiber cohesion, increasing strand mobility and reducing the likelihood of mechanical knots and localized kinks. In practice, optimal formulation architecture often relies on combining cationic surfactants as “adhesion promoters,” silicones as long-lived anti-friction film formers, and lamellar lipids (ceramides/sterols) as restorers of the intercellular phase. This allows different levels of damage to be addressed and yields a more stable sensory and protective profile [6, 7, 21].

### Prolonged Peptide Therapy

Within post-procedure care, a stable shift is observed toward leave-in formats containing biomimetic peptide complexes (K18, KeraBio). Unlike classical conditioning

systems, whose effects are expressed primarily at the level of the cuticle and inter-fiber tribology, peptide compositions are designed with penetration into the fiber interior and interaction with the cortical protein matrix in mind. Their functional orientation is less about creating an external film and more about attempting partial restoration of intrafiber connectivity disrupted by alkaline and oxidative exposure, thermal styling, and mechanical fatigue.

The kinetics of leave-in peptide effects are governed by diffusion processes and by the condition of transport pathways within the hair. Achieving a clinically meaningful outcome requires a dwell time—commonly on the order of ~4 minutes—needed for movement of low-molecular fractions from surface layers into the cortical zone. Under increased porosity and loosening of the inter-macrofibrillar space after chemical exposure, penetration rates rise; at the same time, the risk of nonuniform distribution increases. For this reason, technological solutions often include optimization of peptide-component charge and hydrophilic-lipophilic balance, as well as inclusion of moisturizing co-agents that stabilize the aqueous phase and support transport during application [36].

At the cortical level, peptide systems are treated as “functional fillers” and modifiers of interchain interactions. After diffusion, they localize in defective regions of the protein matrix where ionic contacts, hydrogen bonds, and, in part, disulfide architecture have been compromised. As water evaporates and dissolved-component concentration increases during drying, the likelihood rises for additional noncovalent bonding (hydrogen and electrostatic) and for increased physical cohesion via multisite interactions with keratin domains. This increases intrafiber cohesion, reduces plastic deformation during bending, and slows progression of microdamage under repeated loading [36].

A critically important distinction of leave-in peptide formats is prolonged contact time and the absence of a rinse step, which reduces active loss and maintains the concentration gradient required for internal transfer. Competition with surfactants and coacervates—typical of rinse-off conditioners—is also minimized, as in those systems a substantial share of functional components can be fixed largely at the surface and removed during rinsing. As a result, preconditions emerge for a more pronounced contribution to mechanical stabilization of the cortex while maintaining a relatively moderate influence on weight, buildup, and film-associated surface stiffness [36].

The performance of such products is closely tied to matrix parameters: pH, ionic strength, solvent type, and the presence of components that regulate evaporation. A mildly acidic environment supports controlled protonation of functional groups, improving compatibility with negatively charged regions of damaged keratin and stabilizing distribution along the hair length. Hygroscopic agents can sustain a “wet

diffusion window” and prevent excessively rapid drying that would otherwise limit active penetration. In this sense, the frequently stated need for several minutes of dwell time should be interpreted not as a marketing convention but as a reflection of the physicochemical nature of transport and subsequent self-organization of peptide systems within the fiber structure [36].

## **CHAPTER 6. ALTERNATIVE METHODS OF THERMAL RECONSTRUCTION AND STRAIGHTENING**

It is also worth considering approaches that combine chemical exposure with thermal input to alter hair shape and structure and that are positioned as “reconstruction” or “botox” treatments.

### **Glyoxylic Acid and Derivatives**

Glyoxylic acid, belonging to the class of aldehydic acids, has become widely used in recent years in straightening technologies as an option positioned by the industry as a more acceptable substitute for formaldehyde-associated systems. The chemical specificity of the molecule is defined by the simultaneous presence of carboxyl and aldehyde functions, which sets a dual reactivity profile: the acidic fragment regulates protonation of protein centers and fiber swelling, while the carbonyl group serves as a key participant in condensation reactions under thermal activation.

Under high-temperature exposure (flat-iron heat treatment), the aldehyde fragment of glyoxylic acid reacts with primary amine groups of keratin, including side chains of lysine and arginine, forming imine linkages in the manner of Schiff bases. In parallel, pathways involving formation of hemiacetal/hemi-thioacetal structures through hydroxyl and thiol centers of the protein are possible, expanding the spectrum of covalent fixation and increasing the “rigidity” of the resulting network. Collectively, these new bonds act as additional crosslinks that stabilize the relative positioning of keratin domains and help lock the fiber geometry in a straightened state after cooling and water removal [14].

Physicochemically, the effect presents as an increase in the apparent density of surface layers, reduced roughness, and greater specular reflection, which is subjectively perceived as shine and smoothness. This result is partly explained by the fact that heat-induced fixation reduces cuticle micromobility and decreases the number of surface defects that scatter light. An additional contribution comes from formation of a film-forming layer composed of reaction products and accompanying formulation components, which temporarily lowers the coefficient of friction and facilitates fiber-to-fiber sliding.

At the same time, the chemical “efficiency” of glyoxylic systems is tightly linked to rigid process conditions. A strongly acidic environment (approximately pH 1.0–2.0) combined with a temperature range of 180–230 °C creates conditions for competing degradation pathways: acid-catalyzed

hydrolysis of selected protein regions, thermal denaturation, and disruption of the cuticle lipid phase. Such changes are not always immediately apparent from appearance, because surface leveling can mask internal accumulation of microdamage and a gradual rise in brittleness.

The ambivalence of exposure becomes especially clear with repeated procedure cycles. SEM data indicate that with multiple applications, signs of progressive cuticle erosion and localized chipping of scales may be detected despite the persistence of visual surface “polishing.” Mechanical testing in these contexts often documents reduced tensile strength and altered deformation behavior, which is attributed to restructuring of native  $\alpha$ -keratin architecture and a shift in the ratio of ordered and amorphous regions within the protein matrix.

A notable feature of imine bonds is their potential dynamic character. Stability of Schiff bases depends on the microenvironment, degree of dehydration, and acidity, as well as on stabilizing interactions within the protein matrix. Under elevated humidity and subsequent washing cycles, a portion of these bonds may undergo reversible transformations. On one hand, this explains gradual loss of the straightening effect; on the other, it supports the prolonged presence of modified regions that alter the local mechanical response of the fiber to bending and stretching. This creates preconditions for nonuniform stiffness distribution along the hair length: zones with a higher degree of modification become less tolerant to cyclic loads.

The lipid component of the cuticle is vulnerable to the combined action of acid and temperature. Destruction or extraction of surface lipids increases hydrophilicity and intensifies tribological losses, which may accelerate abrasive wear during combing. A paradoxical consequence can therefore arise: short-term smoothness is achieved at the cost of increased probability of delayed breakage, especially if subsequent lipid and cationic reconditioning support is insufficient. In this context, long-lasting “cosmetic” shine is not a reliable indicator of preserved internal strength.

From a risk-control standpoint, the regime parameters are of primary importance: system acidity, thermal load, and procedure frequency. The lower the pH and the higher the temperature, the greater the share of irreversible damage associated with protein denaturation and lipid-barrier degradation, even when a pronounced smoothing effect is present. For this reason, objective evaluation of appropriateness should rely not only on visual markers but also on instrumental indicators—cuticle morphology by microscopy, porosity and moisture-sorption dynamics, and changes in tensile strength and elastic modulus relative to baseline.

### Enzymatic Crosslinking (Transglutaminase)

Transglutaminase (TGase) is considered one of the most promising “green chemistry” tools for targeted modification

of keratin fiber. Unlike aggressive chemical crosslinkers, the enzymatic approach relies on high chemoselectivity and reactions proceeding in mild aqueous environments at moderate temperatures, which reduces the risk of uncontrolled hydrolysis and thermal degradation of the protein matrix. The biochemical essence of the process is catalysis of isopeptide bond formation between the  $\gamma$ -carboxamide group of glutamine residues and the  $\epsilon$ -amino group of lysine residues, producing an additional covalent “framework” within the protein substrate.

The TGase mechanism is stage-dependent. First, an intermediate acyl-enzyme complex forms at a glutamine site; next, the acyl fragment is transferred to an amine acceptor—most commonly the  $\epsilon$ -amino group of lysine. The resulting  $\epsilon$ -( $\gamma$ -glutamyl)lysine linkage exhibits high hydrolytic stability and is largely not subject to reversible transformations under pH and ionic-strength conditions typical of hair care. From a technological perspective, this implies the possibility of a long-lived structural modification that is not reducible to surface adsorption or weak electrostatic interactions.

Combining TGase with hydrolyzed keratin or individual amino acids broadens the spectrum of available “building blocks” for reconstruction. Hydrolysates serve as sources of peptide fragments containing glutamine and lysine motifs that can participate in enzymatic crosslinking. With appropriate selection of hydrolysate molecular weight, conditions are created for diffusion into porous cuticle zones and, in part, into the cortical region; after that, the enzymatic reaction converts reversibly retained fragments into covalently fixed elements. In practical terms, an effect of “stitching” repairing agents to the keratin matrix is produced, increasing retention and reducing wash-off during subsequent shampoo use.

The forming biopolymer network is functionally dual. On the one hand, cohesion of damaged regions increases, micromobility of structural domains decreases, and accumulation of plastic deformation under cyclic bending is reduced. On the other hand, covalent fixation of peptide fragments increases resistance to abrasive cuticle wear because the rate of “erasure” of surface layers is lowered and tribological characteristics are partially normalized. This effect is fundamentally different from conditioner film formation: it involves creation of an internally integrated protein composite in which the modifier becomes part of the matrix rather than an external coating.

The effectiveness of enzymatic crosslinking is governed by availability of reactive groups and by diffusion constraints. In hair, the number of exposed glutamine and lysine fragments depends on damage degree, cuticle state, and prior chemical history (oxidation, alkaline treatment, thermal loading). pH is also important: excessive acidity lowers the nucleophilicity of lysine amines, while overly alkaline media can impair stability of protein components and alter the charge architecture of the surface. Consequently, formulation design

requires buffering, ionic-strength control, and selection of accompanying humectant components that support substrate transport and enzyme activity.

From the standpoint of safety and sustainability, the TGase approach benefits from the absence of volatile toxic reagents and reduced reliance on extreme temperatures. At the same time, biotechnological implementation requires standardization of enzyme activity, exclusion of undesirable side substrates, and reproducibility of crosslinking degree, because excessive covalent “over-stitching” may increase fiber stiffness and worsen sensory properties. Accordingly, the optimal strategy is formation of a controlled, moderately dense network that improves strength and active retention without loss of elasticity and natural hair mobility.

### CHAPTER 7. METHODOLOGY FOR OBJECTIVE ASSESSMENT OF EFFICACY

Scientific validation of reconstruction methods is not possible without instrumental analysis. Understanding these methods makes it possible to critically evaluate manufacturer claims.

#### Scanning Electron Microscopy (SEM)

Scanning electron microscopy (SEM) is used to visualize hair microroughness in detail and to assess surface-structure morphology at the cuticle level. The method captures the spatial organization of scales, their apposition pattern, the prominence of edge defects, and signs of surface degradation, providing a clear depiction of barrier-layer integrity and hair-shaft topography.

Damaged hair typically exhibits lifted and fragmented cuticle scales with chips and microcracks—often described as a “pinecone effect.” In SEM images, such changes are accompanied by signs of surface erosion: heterogeneous microrelief, thinning of cuticular plates, disrupted overlap, and localized zones of material loss. Collectively, these features reflect reduced protective function of the cuticle and increased vulnerability to subsequent mechanical and chemical exposures.

In reconstructed hair, by contrast, tight scale apposition, a smoother and optically “calmer” surface, and visual signs of protective film formation are observed. Morphologically, this is expressed as reduced edge lifting, smoothing of micron-scale irregularities, and fewer open defects, indirectly indicating restoration of the surface barrier and higher friction resistance. In this context, SEM is particularly informative for quality control of cuticle “sealing” and coating uniformity along the hair length, including identification of areas of incomplete reconstruction and zones with uneven film adhesion.

At the same time, interpretation must account for SEM methodological limitations: visualized features relate primarily to the surface and do not directly describe internal mechanical characteristics of the cortex. Therefore,

morphological “smoothness” and dense scale apposition do not guarantee recovery of internal strength, because cortical microdefects, altered bonding among keratin fibrils, and degradation of interfibrillar matrix can persist despite an externally favorable picture. For this reason, SEM provides a reliable assessment of surface architectonics and cuticle integrity, but it does not supply information about deep structural soundness and tensile resistance [5].

For a comprehensive conclusion on reconstruction, SEM is best complemented with methods targeting internal parameters and functional properties: tensile and bending mechanical tests, spectroscopic approaches for chemical-change analysis, and microscopy methods capable of characterizing subsurface layers. Such a combined study design separates effects of surface “sealing” from true restoration of strength characteristics, minimizing the risk of overestimating outcomes based solely on topographic criteria.

Special attention should be given to the influence of sample preparation on the final morphological picture. Dehydration, conductive coating application, and vacuum conditions can enhance microdefect contrast or, conversely, partially mask thin film structures. Correct interpretation therefore relies on standardized preparation protocols, comparable imaging settings, and use of quantitative morphometric metrics (e.g., fraction of lifted scales, chip density per unit area, roughness parameters), which improves reproducibility and scientific validity of conclusions.

#### Dynamometric Testing (Tensile Strength)

The most validated approach for quantitative assessment of hair mechanical integrity is uniaxial tensile testing to failure, in which a stress-strain curve is recorded. The resulting relationship reflects sequential behavior regimes of the keratin shaft: an initial elastic response, subsequent nonlinear deformation, transition to plastic change, and final rupture. For this reason, the method is considered the “gold standard” in strength research: it converts qualitative observations of brittleness into reproducible parameters suitable for inter-laboratory comparison and statistical interpretation.

In the elastic region of the curve, the key metric is Young’s modulus (elastic modulus), which reflects hair stiffness and its ability to resist reversible deformation. A decrease in this parameter is associated with compromised structural integrity of the keratin matrix and weakening of intrashaft bonds, most notably disulfide bridges that stabilize the protein scaffold. As rupture approaches, the breaking load becomes informative—the force required to initiate and complete shaft failure—reflecting integrated material strength while accounting for defect distribution and heterogeneity along the fiber length.

Experimental data show that bleaching leads to a pronounced reduction in elastic modulus, commonly within

20–50%, consistent with concepts of chemically induced keratin damage and degradation of bonds that determine deformation resistance. Use of dimaleate- and gluconamide-based bond builders has been associated in a number of studies with restoration of modulus to 80–95% of native levels; in some cases, values even exceed baseline, which is attributed to additional polymerization and formation of a reinforcing network within the hair matrix [23].

Correct interpretation of mechanical metrics requires consideration that hair is a hierarchically organized biopolymer composite with pronounced anisotropy and viscoelastic behavior. Modulus values and breaking load are strongly influenced by test conditions: humidity and temperature, strain rate, prior loading history, accuracy of diameter measurement, gripping method, and gauge length. In particular, higher humidity typically lowers stiffness due to water's plasticizing effect and changes in intermolecular interactions, whereas higher strain rate can produce an apparent stiffness increase due to viscoelastic contribution. Standardization of protocols and comparability of test parameters are therefore critical for reliable conclusions regarding the effects of chemical procedures and reconstructive systems.

Additional scientific value is gained by extending mechanical analysis beyond single rupture: cyclic loading, creep tests, and stress-relaxation assays more fully describe structural degradation and restorative effects, separating surface contributions from internal matrix modifications. Within an evidence-based approach, it is preferable to present not only mean values but also distributions, confidence intervals, and variability estimates across tresses, because damage degree and response to reconstruction are often heterogeneous along length and between individual fibers. Such a design increases sensitivity to real strength changes and reduces the risk of methodological distortion when interpreting effects of bond builders and other reconstructive interventions.

### Differential Scanning Calorimetry (DSC)

Thermoanalytical approaches that register temperature transitions are used to assess hair thermal stability and the state of ordered (crystalline) domains of  $\alpha$ -keratin. Within this analysis, the denaturation (melting) temperature of crystalline regions is measured and treated as an integral marker of supramolecular fiber organization integrity. Changes in peak position and shape reflect the degree of destabilization of the protein scaffold and the pattern of interaction redistribution between filaments and the interfibrillar matrix.

The key interpretive principle is the link between thermal stability, packing density, and the number of intact disulfide bridges: the higher the preserved S–S fraction and the more compact the matrix packing, the higher the denaturation temperature ( $T_d$ ). Weakening of covalent crosslinking and

matrix loosening during chemical damage lower the energetic barrier for transition from ordered to disordered state, which manifests as a shift of  $T_d$  toward lower temperatures.

Experimental results show that damaged hair typically exhibits a reduced  $T_d$  (approximately from  $\sim 150^\circ\text{C}$  to  $\sim 130^\circ\text{C}$ ), consistent with partial loss of crystallinity and decreased stability of  $\alpha$ -keratin domains. With effective reconstruction, a back shift of the denaturation peak toward higher temperatures is recorded, interpreted as evidence of restored ordering and increased thermal stability of the crystalline structure. A diagnostically important aspect is not only peak position but also its width/asymmetry: broadening often reflects structural heterogeneity and coexistence of domains with different damage degrees, whereas a more “compact” peak corresponds to greater uniformity of supramolecular organization [19].

Because hair is a multicomponent composite with moisture-dependent behavior, validity of thermoanalytical conclusions depends on strict control of sample preparation. Water content strongly affects thermal transitions and can mask subtle differences in the denaturation region; therefore, standardization of sample conditioning, heating regimes, and sample mass is methodologically critical. Environmental parameters and chemical-treatment history also matter: residual reagents, oxidation products, and adsorbed polymer films can alter the heat-capacity profile and shift peaks in ways not always tied to true crystallinity restoration.

Thermoanalysis should be treated as a tool that characterizes primarily internal ordering and thermal stability of the protein scaffold rather than purely surface conditioning effects. In research protocols, the strongest evidence comes from comparing thermal data with mechanical testing and microstructural methods: a coordinated increase in  $T_d$  together with improved elastic moduli and signs of cuticle integrity restoration forms a more stringent argument in favor of true reconstruction. Such a multimodal approach reduces the risk of a “false-positive” interpretation in which external film reinforcement or altered water balance creates an appearance of improvement without genuine restoration of  $\alpha$ -keratin crystalline domains.

### Spectroscopy (FTIR and Raman)

Spectroscopic methods oriented toward functional-group recognition are used for chemical verification of hair damage and reconstruction at the keratin-matrix level. The analytical value of these approaches lies in the ability to distinguish characteristic absorption/scattering bands corresponding to specific chemical fragments and thereby move from morphological observation to quantitatively comparable molecular markers. In hair research, special attention is given to sulfur-containing cysteine centers, because they form disulfide bridges that provide structural “crosslinking” of the protein scaffold.

A particularly informative task is quantitative assessment of the S–S (disulfide) to SO<sub>3</sub>H (cysteic acid) signal ratio, where cysteic acid represents an end product of deep oxidative transformation of thiol and disulfide groups. An increased SO<sub>3</sub>H contribution is interpreted as a chemical “trace” of irreversible oxidative damage, whereas relative preservation of the S–S signal reflects maintenance of the covalent scaffold and potentially higher mechanical integrity of the hair shaft. Spectral parameters thus not only document damage but also help differentiate its dominant mechanism—primarily oxidative, or mixed with participation of hydrolytic and radical pathways.

### CHAPTER 8. CLINICAL AND ECONOMIC ASPECTS OF IMPLEMENTATION

Integration of deep-reconstruction systems reshapes the business model of salon services.

#### Market Statistics and Dynamics

The global salon-services market, valued at USD 247 billion as of 2024, is characterized by steady expansion; within this landscape, the most dynamic trajectory is observed in professional hair care, for which a compound annual growth rate (CAGR) of 7.8% is reported. Against this backdrop, the bond-builder category is consolidating as one of the fastest-growing subsegments: growth is driven not only by increased frequency of chemical procedures, but also by a structural shift in demand toward solutions that reduce the risk of cumulative fiber damage. Forecast estimates suggest an increase in total market volume to USD 447 billion by 2032.

The observed dynamics reflect a transformation of consumer preferences and value criteria for the service. The key differentiator becomes not simply the fact of color change, but manageability of procedural consequences and reproducible preservation of hair-quality parameters—strength, surface smoothness, elasticity, and visual uniformity. As a result, willingness emerges to pay a premium markup for a technologically grounded “guarantee” of reduced damage during coloring and lightening, as well as for outcome predictability under conditions of high variability in baseline hair state and prior exposure history.

For salon economics, the rapidly growing bond-builder category functions as a tool for premiumization and diversification of the product-service mix. Reconstruction protocols become either a standalone service or a mandatory element of coloring, enabling an increase in average check without a proportional increase in labor intensity. An additional growth driver is standardization of service scenarios (adding to the mixture, a post-procedure step, a course of restorative visits), which simplifies staff training, improves reproducibility of results, and reduces the probability of complaints directly associated with breakage and deterioration of tactile hair properties after chemical procedures.

Segment expansion is also reinforced by risk-management logic. Given high costs of client acquisition and retention, priority shifts toward technologies that lower the probability of pronounced damage and, consequently, reduce salon reputational losses. At the same time, demand strengthens for evidentiary support of manufacturer claims: formulas are sought whose efficacy is confirmed by objectively measurable metrics (mechanical parameters, thermal stability, chemical markers of oxidation), because such indicators can substantiate premium positioning and translate a marketing promise into a verifiable technological characteristic of the service.

#### Procedure Economics

The practice of implementing add-ons directly introduced into the dye composition, as well as dedicated reconstructive care services, forms a stable mechanism for increasing the salon’s average check by 15–30% with low operational load. A critically important factor is the minimal increment in stylist labor: a substantial share of such products is integrated into the standard technological protocol without a need to extend processing time, allowing revenue growth without reducing throughput and without reorganizing the schedule. The economic effect is amplified by scalability: the same application logic is reproducible across different coloring types and different levels of damage, thereby reducing service variability and increasing predictability of the financial outcome.

Profitability of such procedures is often assessed at 20–30% and higher, which noticeably exceeds the margin of a classic haircut. This is explained by the cost structure: the variable portion of costs is determined predominantly by product consumption, whereas the most expensive components of the service—time and specialist qualification—practically do not increase. At the same time, premiumization via technological accompaniment of coloring shifts value perception from the plane of a “cosmetic effect” to the plane of “damage-risk management,” enabling maintenance of a higher price even under competitive pressure.

Improvement of hair quality after chemical procedures has a direct impact on client retention rate, which is treated as one of the key metrics of salon-business sustainability. Reduced breakage, improved tactile characteristics, and visual uniformity of the hair canvas decrease the likelihood of negative experience and subsequent complaints; this, in turn, reduces churn and increases the probability of repeat visits. In practical terms, this translates into higher return frequency, expansion of the range of purchased services, and strengthened trust in the stylist as a source of safe coloring technologies.

From a managerial standpoint, retention converts directly into growth of customer lifetime value (LTV) and increased efficiency of marketing expenditures: at a comparable acquisition level, even a moderate improvement in retention

rate can substantially raise total profitability of the client portfolio. A further advantage is associated with formation of predictable demand: clients oriented toward preserving hair quality more often choose service cycles (supportive care visits, scheduled color corrections), which stabilizes utilization and reduces revenue sensitivity to seasonality. As a result, reconstructive add-ons and standalone care services become not only an instrument for average-check growth but also an element of a strategic model of sustainable salon development.

### CONCLUSION

The trichological and cosmetic-chemistry paradigm for assessing hair-shaft integrity has shifted from predominantly empirical product selection toward controlled molecular engineering. The body of experimental and applied data indicates that maintaining hair quality under chemical exposure requires a systemic strategy that includes three functionally mandatory links, each grounded in clearly definable biochemical premises.

At the preclinical and technological levels, pre-procedure detoxification is substantiated, because removal of metal catalysts—primarily copper and iron (Cu, Fe)—using selective chelators such as EDDS and gluconates represents a critical condition for preventing uncontrolled free-radical generation and, consequently, for reducing protein-mass loss. During the chemical processing itself, the key mechanism is intra-procedure bond building: introducing dimaleate-, gluconamide-, copolymer-, and biomimetic peptide-based additives into the reactive mixture makes it possible to functionally “intercept” a destructive scenario by shifting part of the reactive activity from bond breakage toward bond formation, thereby supporting the mechanical integrity of the cortex.

After exposure is completed, post-procedure biomimetics is required, directed toward normalization of surface physicochemical parameters—above all pH and lipid architecture involving 18-MEA—implemented through acidic sealers and lipid complexes that form a more stable barrier protection against exogenous factors. Omission of any of these links predictably reduces overall effectiveness. Further industry development is increasingly associated with personalization of chemical “cocktails” based on prior diagnosis of the molecular state of hair.

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