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Physico-chemical properties of modern cosmetics for styling and their effect on hair structure

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Abstract

The article is dedicated to the physico-chemical properties of modern cosmetics for styling and their effect on hair structure under conditions of repeated thermal, chemical, and mechanical exposure. The relevance of the topic is determined by the growing use of multifunctional styling products that alter not only the visible state of the hair fiber but its interfacial chemistry, frictional behavior, porosity, and internal cohesion. The novelty lies in the interpretation of styling cosmetics not as isolated finishing products but as active systems of surface deposition, molecular penetration, and self-assembly acting within an already damaged biological substrate. The work describes the structural organization of the hair fiber, the transformation of its surface after degradation, and the operational mechanisms through which polymers, proteins, surfactants, and bioinspired ingredients modify fiber behavior. Special attention is paid to the interdependence between damage state, adsorption regime, and conditioning efficiency. The goal is to explain how modern styling formulations reshape hair structure at different functional levels. Analytical review and conceptual comparison of recent international studies were used. The conclusion outlines the transition from restorative claims to controlled structural compensation. The article will be useful for cosmetology researchers, formulation developers, and beauty practice specialists.

Keywords: hair fiber, styling cosmetics, cuticle, film formation, adsorption, porosity, biopolymers, hair damage

Introduction

The contemporary market of hair styling products has moved far beyond simple fixation and decorative control. Modern formulations combine conditioning polymers, film-forming agents, low-molecular protein fragments, surfactants, lipids, and bioinspired compounds that interact with the hair shaft at several structural levels at once. This expansion of functional complexity has increased practical efficiency, yet it has made scientific interpretation more difficult. The visible result of styling no longer depends only on the applied product. It depends on the prior state of the cuticle, on the degree of lipid loss, on the porosity of the cortex, and on the balance between interfacial deposition and internal penetration. Because the hair fiber is a damaged keratin composite rather than a regenerating tissue, any cosmetic effect develops through physicochemical compensation. That point gives the topic its current relevance.

A further reason for relevance lies in the mismatch between consumer language and material behavior. Products are frequently presented as repairing, restructuring, or restoring agents, whereas published evidence more often describes selective coating, charge neutralization, lubrication, moisture redistribution, and temporary reinforcement. The discrepancy is not trivial. It affects formulation strategy, interpretation of laboratory tests, and professional practice in salons, where product choice is usually guided by sensory outcomes rather than by the structural condition of the fiber.

The aim of the study is to establish the physicochemical mechanisms that determine the interaction between modern styling cosmetics and structurally damaged hair fiber, and to identify the factors governing their functional efficiency under repeated exposure conditions.

To reach this purpose, three research objectives were formulated. The first objective is to identify the structural zones of the hair fiber and determine which of them govern the response to styling formulations under chemical, thermal, and mechanical stress. The second objective is to clarify the mechanisms through which modern cosmetic ingredients adsorb, assemble, penetrate, and redistribute along damaged hair surfaces. The third objective is to evaluate how these mechanisms affect observable and measurable outcomes such as friction, combing behavior, porosity, roughness, and temporary mechanical stabilization.

The hypothesis of the study states that the efficiency of modern styling cosmetics is determined not by the nominal presence of active ingredients as such, but by the correspondence between their molecular and interfacial properties and the pre-existing damage architecture of the hair fiber. Under this assumption, surface charge, porosity, molecular size, and film-forming behavior govern cosmetic performance more strongly than general product category labels.

The novelty of the study lies in the integration of physicochemical, structural, and formulation-based perspectives into a unified operational framework explaining how styling cosmetics function on damaged hair as a dynamic and heterogeneous substrate. The scientific significance of the study lies in bridging the gap between material science approaches to hair structure and applied cosmetology practices, enabling a more accurate interpretation of cosmetic performance beyond marketing-based claims.

Methods and materials

The literature base was assembled through a focused search in international scientific databases, primarily Scopus, Web of Science, PubMed, and publisher platforms indexing peer-reviewed cosmetic science and materials research from the last five years. The search logic combined keyword clusters connected through AND/OR operators, linking terms related to hair structure, cuticle damage, styling cosmetics, conditioning polymers, film formation, adsorption, porosity, thermal protection, keratin systems, and bio-based ingredients. At the initial stage, about forty publications were identified; after removing marginally relevant items and excluding works with weak relation to structural mechanisms of interaction, the corpus was narrowed to ten studies suitable for detailed analytical comparison.

The design of the work combined analytical review with conceptual interpretation of underlying structures and relationships. The selected studies were compared not by topic labels but by the type of process they described: interfacial adsorption, hydrophobic restoration, coacervate formation, molecular penetration, porosity modulation, heat protection, and bioinspired reinforcement. Particular attention was given to implementation detail, since the explanatory value of the literature depended not on broad claims about conditioning or repair, but on how individual systems interacted with cuticle defects, cortex cohesion, surface charge, or moisture retention under specified experimental conditions.

The assembled sources differed substantially in scope and analytical focus. Some examined the hierarchical architecture of the hair fiber and the chemical consequences of weathering; others concentrated on formulation behavior, self-assembly of polymers and surfactants, or the response of damaged hair to specific biopolymers, liposomal carriers, cellulose derivatives, and thermoresponsive keratin systems. Across this heterogeneous body of work, recurring patterns were identified: damage increased surface reactivity; deposition efficiency depended on charge and molecular size; film continuity altered friction and optical response; deeper penetration improved local cohesion but remained temporary; bio-based systems expanded functional options but introduced variability in reproducibility and performance stability (Patil & Netravali, 2022).

Comparison of the selected studies revealed a persistent gap. The individual components of the phenomenon are often described separately - hair damage, ingredient chemistry, adsorption, film formation, penetration, or sensory outcome - while their interdependence remains insufficiently clarified. This made it necessary to reinterpret the published evidence as a connected operational process in which the altered state of the fiber governs the pathway and limit of cosmetic action.

Results

The observable behavior of modern styling cosmetics emerges from a continuous interaction between the intrinsic structure of the hair fiber and the external deposition of chemically diverse agents that reorganize its surface and partially penetrate its internal matrix. Hair does not respond as an inert substrate. It behaves as a hierarchical composite system in which the cortex provides mechanical resistance while the cuticle governs interfacial phenomena such as friction, adhesion, and optical reflection. The protein fraction constitutes approximately 65–95% of the fiber mass, with the cortex alone accounting for nearly 90%, which explains why even minor chemical modifications at the molecular level propagate into macroscopic changes in stiffness and elasticity (Fernandes et al., 2023). At the same time, the outer lipid layer formed by 18-methyleicosanoic acid establishes a hydrophobic barrier that regulates surface energy and sliding behavior. Once this layer is disrupted, the system shifts toward a hydrophilic and negatively charged state, fundamentally altering how cosmetic agents interact with the fiber (Fernandes et al., 2023). The systematization of approaches is presented below (Table 1).

Table 1. Mechanisms of interaction between styling cosmetics and hair fiber structure (compiled by the author based on Fernandes et al., 2023; Luengo et al., 2023; Carvalho et al., 2024)

Mechanism type	**Functional layer of hair**	**Operational process**	**Resulting structural effect**
Electrostatic adsorption	Cuticle surface	Charge neutralization and selective deposition	Reduction of static electricity and fiber repulsion
Hydrophobic interaction	Lipid layer remnants	Alignment of non-polar chains with residual lipids	Restoration of surface lubrication
Film formation	Cuticle defects	Polymer deposition and surface coating	Smoothing of surface irregularities
Molecular penetration	Cortex	Diffusion of low-molecular compounds	Partial reinforcement of internal cohesion
Self-assembly (coacervation)	Interface (cuticle-solution)	Formation of polymer-surfactant aggregates	Localized delivery of conditioning agents

Styling cosmetics operate within this altered state by reorganizing the interfacial layer through controlled deposition and self-assembly. The process is not random; it follows a balance between electrostatic attraction, hydrophobic affinity, and diffusion kinetics. Charged polymers and surfactants form structured aggregates in aqueous formulations, which separate during rinsing into coacervate phases that selectively deposit on the hair surface. These coacervates act as carriers, concentrating conditioning agents exactly where structural damage has increased surface charge density (Luengo et al., 2023). The resulting film is not uniform. It reflects local variations in damage, porosity, and chemical composition of the fiber. The systematization of approaches is presented below (Figure 1).

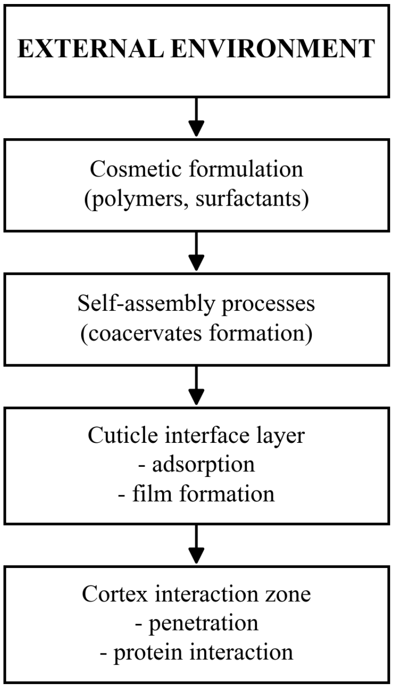

Figure 1. Multilevel interaction architecture of styling cosmetics with hair fiber (compiled by the author based on Luengo et al., 2023; Fernandes et al., 2023; Bui et al., 2025)

Film formation constitutes one of the dominant mechanisms governing styling performance. High-molecular-weight polymers, including silicones and cellulose derivatives, create continuous layers that fill microdefects in the cuticle and reduce inter-fiber friction. Experimental observations show that such films directly modify tactile properties by decreasing friction coefficients and suppressing static charge accumulation. In cellulose-based formulations designed for hair modelling, microscopic analysis demonstrates uniform surface coverage combined with measurable improvements in structural stability under mechanical stress (Carvalho et al., 2024). The effect is primarily interfacial. Penetration remains limited due to molecular size.

A different mechanism emerges when low-molecular-weight or structurally adaptive agents are used. Hydrolyzed proteins and keratin-derived systems can diffuse into the cortex, where they interact with native keratin through hydrogen bonding and partial restoration of crosslink density. Their influence depends strongly on molecular size, typically within the 1–10 kDa range, which allows penetration without complete washout during rinsing (Fernandes et al., 2023). Thermoresponsive keratin systems modified with organosilicon compounds demonstrate this dual behavior: they form protective films at elevated temperatures while simultaneously interacting with internal protein structures. Such systems have been shown to restore hydrophobicity and reduce surface roughness after thermal exposure, while maintaining mechanical integrity under repeated styling cycles (Li et al., 2026).

The modulation of porosity plays a central role in determining the efficiency of these mechanisms. Increased porosity enhances the uptake of conditioning agents but reduces structural cohesion.

Under consumer-relevant conditions combining chemical and thermal stress, measurable increases in porosity correlate with reductions in tensile resistance and increased brittleness (Gasparin et al., 2025). The fiber becomes more accessible yet less stable. Conditioning systems must therefore balance penetration with structural reinforcement.

Self-assembly processes further refine the behavior of modern formulations. Polymer-surfactant interactions generate complex architectures that adapt to the physicochemical state of the substrate. In practice, this means that identical formulations behave differently depending on the degree of hair damage. The adsorption spectrum ranges from purely charge-driven interactions, where cationic groups bind to negatively charged sites, to hydrophobically driven processes dominated by non-polar segments aligning with residual lipid domains (Luengo et al., 2023). Intermediate regimes are common. Small variations in pH or ionic strength shift the dominant mechanism, altering deposition thickness and durability.

Quantitative performance indicators reveal how these mechanisms translate into measurable effects. In systems based on hyaluronic acid, reduction in wet combing force reaches 85% at a molecular weight of 8 kDa, decreasing to 79.5% at 90 kDa and 49.2% at 130 kDa, before rising again to 54.2% at 800 kDa due to changes in rheological behavior and film formation (Fernandes et al., 2023). Such non-linear dependence illustrates that performance is governed not only by chemical composition but by the interplay between molecular size, diffusion, and viscoelastic properties of the deposited layer.

Bioinspired and biopolymer-based systems introduce an additional layer of complexity by combining structural mimicry with functional adaptation. Spider silk-inspired biopolymers generate highly cohesive films that enhance color retention and reduce moisture loss, indicating a strong capacity to maintain structural integrity under environmental stress (Press et al., 2025). Liposome-based delivery systems encapsulating keratin demonstrate targeted penetration into damaged regions, reducing protein oxidation and restoring surface smoothness through localized deposition (Bui et al., 2025). These approaches shift the focus from passive coating to active interaction with the fiber architecture.

Natural-derived surfactants and conditioning agents further illustrate how molecular design influences adsorption efficiency. Biosurfactant systems derived from renewable sources exhibit adsorption capacities reaching 3679 $\mu g \cdot g^{-1}$ under optimized conditions, closely matching conventional petrochemical analogues while maintaining improved environmental profiles (Fernandes et al., 2023). At the same time, amino lipid surfactants reduce combing force by 97.81%, indicating that chain length and amphiphilic structure directly control lubrication efficiency and inter-fiber interactions (Fernandes et al., 2023). These values are not incidental. They reflect precise tuning of molecular architecture to match the physicochemical state of damaged hair.

The structural consequences of these interactions accumulate over repeated applications. Bleached hair used as a standardized substrate reveals that conditioning agents do not restore original architecture but instead create a stabilized modified state characterized by reduced roughness, partial rehydration, and altered optical properties (Martins et al., 2024). The fiber does not revert to its initial configuration. It transitions into a new equilibrium defined by the presence of external films and internal molecular substitutions. The systematization of approaches is presented below (Figure 2).

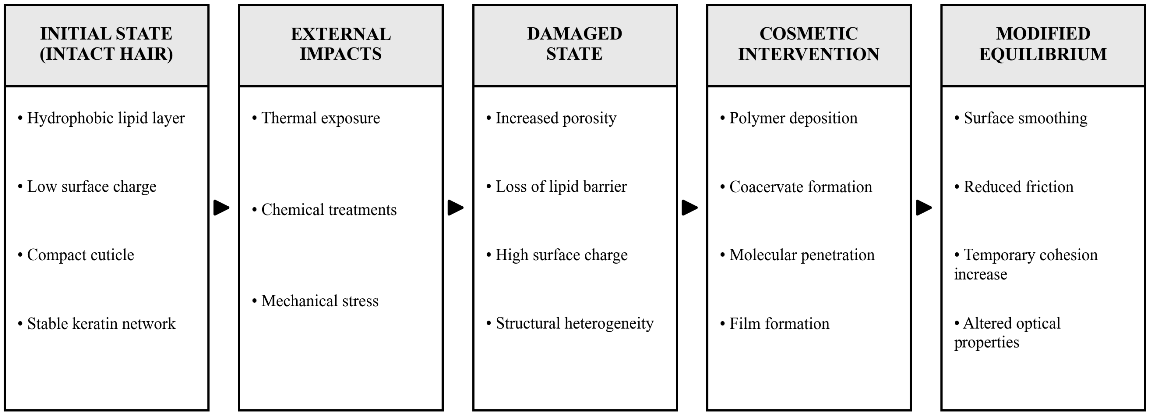

Figure 2. Transition of hair fiber from native state to cosmetically modified equilibrium (compiled by the author based on Fernandes et al., 2023; Martins et al., 2024; Press et al., 2025)

Several limitations should be acknowledged. The analysis relies on heterogeneous experimental designs, with variations in hair type, treatment protocols, and measurement techniques restricting direct comparison of numerical values. Differences in environmental conditions and formulation composition further complicate interpretation. Despite these constraints, consistent patterns emerge across datasets.

Modern styling cosmetics do not repair hair in a biological sense. They reorganize its surface and partially compensate for structural loss. The fiber remains damaged. Its behavior is modified. The obtained results demonstrate that the efficiency of styling cosmetics is directly dependent on the correspondence between formulation properties and the physicochemical state of the fiber, thereby confirming the systemic nature of cosmetic-substrate interaction.

1. Discussion

The observed behavior of modern styling cosmetics does not align with a model of direct restoration of hair structure. Instead, the system evolves through continuous surface reconfiguration, where the fiber operates as an adaptive interface rather than a static substrate. What becomes visible as smoothness or gloss emerges from a redistribution of interfacial energy rather than from any reconstruction of internal architecture. The cuticle layer, already partially degraded, functions as the primary operational zone. Its geometry changes. Its chemistry shifts. The interaction field expands.

This shift begins with the transformation of surface polarity. Once the lipid barrier is disrupted, the fiber no longer maintains its initial hydrophobic regime. It transitions into a charged, hydrophilic interface with increased affinity for external molecules. The mechanism is not simply adsorption; it is a selective capture process governed by electrostatic gradients and local heterogeneity. Regions of higher damage accumulate more conditioning agents. Less altered areas remain comparatively inactive. The system becomes spatially uneven. This unevenness is functional.

Deposition processes respond to this heterogeneity through dynamic assembly. Polymer-surfactant complexes reorganize during application and especially during rinsing, where phase separation generates localized aggregates capable of attaching to the fiber surface. These structures do not distribute randomly. They follow the electrochemical map created by prior damage. The resulting film is discontinuous at the microscale, even when macroscopically perceived as uniform. Continuity is an illusion. Performance still emerges.

A different behavior appears when molecular size allows partial penetration. Low-molecular-weight peptides and modified keratin fragments do not remain confined to the surface. They enter the cortex, interacting with internal protein structures. The mechanism here shifts from surface smoothing to internal reinforcement. Hydrogen bonding networks reorganize. Local cohesion increases. Yet this process remains incomplete and temporary. The underlying disulfide network is not re-established. Structural fatigue persists.

Film-forming systems operate through another layer of control. High-molecular-weight polymers generate continuous coatings that alter friction and optical response. These films reduce scattering by flattening cuticle irregularities and redistribute mechanical stress during grooming. Their effectiveness depends on compatibility with the substrate. Hydrophobic polymers prefer less damaged regions. Charged polymers target disrupted zones. The result is a composite coating formed through multiple overlapping interactions. No single mechanism dominates.

At the same time, the interaction between chemical modification and mechanical stress introduces feedback into the system. Damage increases adsorption capacity, while adsorption reduces friction and delays further damage propagation. This loop stabilizes the fiber under repeated styling conditions but does not eliminate degradation. Instead, it slows its progression. The system operates in a managed state rather than a recovered one.

The introduction of bio-based ingredients modifies not only composition but also interaction pathways. Natural polymers and biosurfactants exhibit broader structural variability, which affects their assembly and deposition behavior. Their performance depends strongly on formulation conditions. Small changes in pH or ionic strength alter aggregation patterns and, consequently, film formation. Stability becomes less predictable. The system gains adaptability but loses uniformity.

This variability reflects a deeper structural difference. Conventional petrochemical ingredients are designed for reproducibility. Bio-based compounds are often mixtures with inherent heterogeneity. Their interaction with hair fibers cannot be fully standardized. In practice, this leads to fluctuating performance across different hair types and environmental conditions. The formulation becomes a probabilistic system rather than a deterministic one.

Previous studies converge around the idea that conditioning effects originate at the interface, yet they diverge in how this interface is conceptualized. Some models prioritize electrostatic attraction as the dominant mechanism, especially for damaged hair with high charge density. Others emphasize hydrophobic interactions and film formation. A third group focuses on self-assembly and coacervate dynamics. These perspectives describe different operational regimes of the same system. None is sufficient in isolation.

The absence of a unified framework reflects the complexity of the substrate. Hair is not chemically uniform, and its condition evolves along the fiber length and over time. Experimental models often simplify this variability, using standardized tresses or controlled treatments. Such simplifications enable measurement but reduce ecological validity. Real usage conditions introduce additional variables - humidity, UV exposure, mechanical stress - that alter system behavior in ways not fully captured in laboratory studies.

Several limitations should be acknowledged. The analysis relies on previously published data obtained under heterogeneous experimental conditions. Differences in hair origin, degree of damage, and treatment protocols restrict direct comparison. Many studies isolate specific ingredients or mechanisms, while real formulations involve multi-component systems with interacting effects. Temporal dynamics remain insufficiently explored, particularly the cumulative impact of repeated application and removal cycles. These gaps constrain the interpretation of long-term behavior.

The system formed by styling cosmetics does not recreate the original fiber. It reorganizes its surface and partially stabilizes its structure through external inputs. Internal damage remains embedded. The fiber continues to evolve under use.

2. Conclusion

The completed analysis confirms the first research objective by showing that the response of hair to styling cosmetics is concentrated in two structurally unequal yet functionally connected zones. The cuticle governs interfacial events, including adsorption, lubrication, electrostatic neutralization, and optical smoothing. The cortex determines the limits of internal stabilization, since low-molecular compounds may penetrate and reinforce cohesion only where the damaged structure allows diffusion. The hair fiber, for that reason, behaves not as a homogeneous strand but as a layered substrate with uneven reactivity along its surface and depth.

The second research objective was fulfilled through clarification of the principal mechanisms of cosmetic action. Modern styling formulations act through selective deposition, coacervate-assisted delivery, hydrophobic alignment, polymeric film formation, and partial molecular penetration. Their behavior changes with the physicochemical condition of the fiber. A disrupted lipid barrier increases hydrophilicity and charge density; porosity expands access for active compounds but weakens structural resistance; variations in pH, ionic strength, and molecular size reshape the balance between surface coating and internal interaction. Cosmetic efficiency, in this model, develops from mechanism-substrate correspondence rather than from product category alone.

The third research objective was addressed by linking these mechanisms with measurable outcomes. Reduced combing force, lower friction, temporary restoration of hydrophobicity, improved gloss, moderated roughness, and partial mechanical stabilization were shown to arise from controlled reorganization of the damaged interface. Yet the same comparison established a boundary that carries practical and analytical significance: modern styling cosmetics do not biologically restore hair. They create compensatory surface and near-surface structures that delay further deterioration and improve functional behavior under use conditions.

The proposed hypothesis was supported. Cosmetic performance depends primarily on the degree to which molecular architecture, interfacial behavior, and diffusion capacity match the damage profile of the fiber. This explains why identical formulations act differently on intact, bleached, porous, textured, or repeatedly heated hair. It explains as well why the language of repair often exceeds the actual material process.

The analytical contribution of the article lies in treating styling cosmetics as multilevel physicochemical systems operating within an already transformed keratin substrate. Such an interpretation provides a more precise basis for future formulation design, laboratory evaluation, and professional selection of products in beauty practice. The practical significance of the study lies in providing a scientifically grounded basis for the selection and formulation of styling products according to specific hair damage profiles, which can improve both product development strategies and professional application in cosmetology practice.

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