

able Alternatives to Quaternary Ammonium Compounds”

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1. Introduction

The global hair care market is evolving towards greener and high-performance solutions in response to consumer demand for sustainability and safety. Traditional conditioning agents used in hair care products, notably quaternary ammonium compounds (QACs) like behentrimonium chlorides and polyquaterniums and silicone based quats have long delivered effective detangling, softening and anti-static properties. However, their environmental and safety profile is getting more attention. QAC residues persist in wastewater biosolids and have been detected in sediment and sludge due to their strong sorption and slow biodegradability under anaerobic conditions [1]. These cationic surfactants can bioaccumulate and exhibit toxicity to aquatic organisms (fish, daphnids, algae) and may disrupt wastewater treatment microbial communities [2]. Consequently, regulatory authorities and consumers are putting pressure on the industry to reduce its reliance on these persistent chemicals in favor of biodegradable and eco-friendly alternatives.

At the same time, there is a clear market trend toward sustainable innovation in hair conditioning. Consumers, especially Generations Y and Z, show a preference for natural or biotechnology-derived products. Ingredients obtained through fermentation, upcycling of agri-food by-products and other green processes are viewed favorably. They align with the "clean beauty" movement, reducing environmental impact and avoiding petrochemicals or animal-derived ingredients. Another key trend is the demand for inclusive hair care solutions that are effective on different hair types and ethnicities. There is a significant market gap for high-performance conditioners suitable for curly and coily hair (types 3 and 4), which tend to be drier, more brittle, and prone to frizz and breakage. Over half of women in markets such as the US and France have naturally curly or wavy hair, but traditional conditioning products (often optimized for straight Caucasian hair) may not adequately meet the needs of Afro hair, which has a very rich texture. This has stimulated interest in novel active ingredients that can offer professional-grade conditioning for all hair textures while being 100% derived from renewable resources. In this context, oligopeptide-based conditioners have emerged as promising eco-friendly alternatives to QACs. Hydrolyzed proteins and peptides from plant or microbial sources can impart conditioning effects by bonding to the hair shaft, smoothing cuticles, and even penetrating to strengthen the cortex. Previous studies have shown that certain hydrolyzed protein treatments improve the mechanical properties of damaged hair, increasing tensile strength and elasticity while reducing breakage [3]. These materials are often biodegradable and non-toxic, making them attractive for sustainable formulations.

However, not all protein hydrolysates perform equally well: their performance depends on molecular weight, amino acid composition and affinity with hair keratin [4]. Designing a peptide-based active ingredient that can match or exceed the conditioning efficacy of QACs requires careful optimization of these parameters.

In this paper, we present the development and evaluation of an innovative oligopeptide-based hair conditioning active with keratin-like properties, obtained through fermentation and extraction from by-products of the agri-food industry. This novel active ingredient is composed of bioactive plant peptides and yeast-derived postbiotic peptides and has been engineered to have a high cationic charge at the natural acidic pH of hair and strong substantivity to the hair fiber. We hypothesized that these attributes would allow the oligopeptide to function as an effective sustainable alternative to conventional quats, providing detangling, anti-frizz and strengthening benefits comparable to or superior than benchmark synthetic conditioners. To verify this, a comprehensive characterization and performance assessment was conducted. The following sections detail the development process and selection criteria for the peptide active ingredient and present the results of ex vivo and in vivo tests on different hair types. Key performance indicators include combing force reduction, improvement in hair strength, cuticle smoothing (via SEM imaging), thermal properties (DSC analysis) and sensory outcomes. The results are discussed in the context of formulating greener hair care products that meet the needs of a diverse and sustainability-conscious consumer base.

2. Materials and Methods

2.1. Active ingredient development

The development process of the new oligopeptide began with the fermentation of agri-food by-products to generate bioactive peptides, followed by selective extraction and purification. Vegetable proteins from selected plant sources were hydrolyzed and their peptides were combined with postbiotic peptides obtained from yeast fermentation. The selection of peptide fractions was guided by target physicochemical criteria: primarily molecular weight (MW) in the low kilodalton range and basic amino acid content (arginine and lysine) which confer a high cationic charge at pH ~5. These natural alkaline amino acid residues have pK_b values that ensure they remain protonated in the slightly acidic conditions of hair care formulations, conferring a positive charge to the peptides. This positive charge promotes strong electrostatic adsorption to the negatively charged sites on damaged hair, similar to the functioning of quaternary ammonium groups, thereby providing conditioning benefits such as static reduction and cuticle alignment.

2.2 Formulation and application for testing

For the ex vivo tests, each active ingredient was applied to hair tresses in a simple model formulation. The formulation was a basic aqueous leave-in or rinse-off conditioner with the active ingredient dosed at the same concentration (3.0% active matter). This controlled approach isolates the effect of the active ingredient itself. The human hair strand samples were standardized in terms of size (typically 2 g weight, ~20 cm length) and were selected from virgin dark brown Caucasian hair or chemically treated/damaged hair, depending on the tests to be performed. Additional tresses of textured hair types were included for some evaluations: wavy/curly Caucasian hair (Type 2/3) and frizzy Afro hair (Type 4b), to assess performance across different ethnic hair types. Prior to treatment, all strands were washed with a neutral shampoo and dried. Treatments were applied and left on for a fixed time, then rinsed if applicable and dried under controlled conditions.

For the in vivo tests, a panel of human volunteers evaluated the new oligopeptide in a prototype hair care regimen versus a placebo regimen. Twenty female subjects with different hair types (straight, curly and kinky) tested a series of products (shampoo, mask, serum, leave-in

conditioner) containing either the new ingredient under investigation or a placebo without active ingredient, in a one-time use protocol. Sensory tests also compared a product containing the synthetic quat against the new oligopeptide product in half-head trials. Panelists provided feedback on attributes like ease of combing, softness, frizz, shine and overall feel immediately after use.

2.3 Analytical and performance testing methods

2.3.1 Combability and detangling

The ease of combing was measured using a dynamometer-based combing test. The Imada ZTS 550N dynamometer was mounted on a tensile tester to record the friction force as a comb passed through a strand of hair. Each treated or control tress was subjected to a fixed number of combing cycles, typically 10–50 strokes, under consistent tension. In one method, strand were fixed at the top and a comb was attached to the load cell, which moved along the length of the strand at a constant speed. The average combing force (N) over the strokes was calculated for each sample. Lower forces indicate better detangling/conditioning. In addition, a cyclic combing fatigue test was conducted to evaluate breakage resistance: the hair bundles were repeatedly combed until fiber breakage occurred, while recording the force resisted by the tress with each stroke. A higher number of strokes endured or a higher force sustained without breaking indicates greater strength and resilience to combing.

2.3.2 Scanning electron microscopy (SEM)

Hair surface morphology was examined using Scanning electron microscopy (SEM) to visualize the condition of the cuticle and surface deposits after treatment. Two specific SEM observations were made: the surface of “knotted hair” was evaluated, in particular the hair fibers were deliberately knotted tightly and then untangled to induce cuticle damage similar to tangling stress. In addition, the hair tips, which normally tend to be the most damaged (split ends, chipped cuticles), were analyzed. The treated hair tips were compared to evaluate the effectiveness of each conditioner in sealing and protecting the ends.

2.3.3 Differential scanning calorimetry (DSC)

Thermal analysis was used to investigate changes in the internal structure of hair. Small bundles of hair (5–10 mg) were analyzed by DSC to measure the denaturation temperature (T_d) of hair keratin. An increase in T_d or enthalpy may indicate an improvement in internal cohesion, while a lower T_d suggests damage. DSC analyses were performed from 30 °C to 250 °C at a fixed heating rate under nitrogen. In particular, the differences between hair damaged by bleaching and hair treated with the peptide compared to the control were evaluated as an indicator of cortex strengthening.

2.3.4 Tensile strength test

Single-fiber tensile tests were carried out on hair fibers to quantify changes in mechanical strength and elongation. Using a miniature tensile tester (Diastron MTT), individual capillary fibers with a diameter of ~50-80 µm from treated and untreated groups were stretched at a constant rate until breakage. From the stress-strain curves, metrics including the ultimate tensile strength (MPa) and extension at break (%) were recorded. For repetitive grooming resistance, a multi-fiber cyclic test was also performed: whole tresses underwent repeated combing under tension, and the cumulative damage was inferred from whether fibers broke during the test. This method, while not a standard tensile measurement, simulates real-life combing stress and was used to complement the single-fiber tensile data.

2.3.5 Hair gloss and color

Gloss was objectively measured using a calibrated digital imaging system. A Mambo[©] handheld gloss meter (Bossa Nova Technologies) was used on hair samples. This device uses an integrative sphere geometry to measure reflected light intensity from the hair, providing a brightness value. Additionally, a colorimetric analysis was done with a spectro-colorimeter to track changes in the lightness component as another indicator of shine. Images of the shine of the strands were also captured under standardized lighting with a high-resolution camera to visually confirm the instrumental data.

2.3.6 Evaluation of frizz and flyaway hair

The tendency of hair to become frizzy in humid conditions was evaluated using a frizz analysis imaging system (Bolero Lite, Bossa Nova). Treated and untreated hair strands were placed in a humidity-controlled chamber for a predetermined period of time. The Bolero system generated a 3D model of each strand and quantified the “frizz volume” or the number of fly-away fibers by comparing the contour of the strand to its solid core. A decrease in the spread of the hair contour or a reduction in the number of protruding fibers indicates effective frizz control. For each treatment, the percentage reduction in frizz was calculated compared to the control. Evaluations were also carried out by a panel: volunteers in high-humidity environments compared the level of frizz on hair treated with the peptide conditioner to that of a standard conditioner, assessing its appearance.

2.3.7 In vivo sensory evaluation

A trained panel and consumer volunteers assessed various characteristics of their hair after treatment. Detangling and ease of combing were evaluated on a qualitative scale immediately after washing and conditioning. Tactile characteristics (smoothness, softness, silkiness) and appearance (shine, volume, frizz control) were assessed once the hair was dry and styled.

3. Results

3.1. Characterization of peptidic activity

It has been confirmed that the peptide complex under investigation carries a significant positive charge under acidic conditions and has an average molecular weight in the low oligomer range (estimated <5 kDa, with a distribution of short peptides). Potentiometric titration indicated a high cationic charge density, attributable to the arginine and lysine content, which predicts a strong electrostatic bond with hair. In the formulation, the active ingredient was compatible and did not destabilize typical conditioners emulsions. No significant odor or color was imparted, and the final formulations remained neutral in appearance. These favorable characteristics of the formulation are important for practical use, indicating optimized organoleptic properties and minimal impact on product stability, despite the active ingredient being 100% natural.

3.2 Ex vivo performance testing

Table 1 summarizes the main results of ex vivo testing comparing the new oligopeptide with a placebo and a synthetic quaternary benchmark. All results are reported as a percentage improvement of the oligopeptide treatment relative to the indicated comparator. Positive percentages indicate an improvement in a beneficial attribute, while negative percentages indicate a reduction in an undesirable attribute such as combing force or frizz.

Table 1. Performance of the innovative oligopeptide in ex vivo tests, compared to placebo and a synthetic quaternary ammonium conditioner. The oligopeptide was tested at an active concentration of 3% in a simple conditioner base; the synthetic quat was tested at an equivalent active concentration. Improvements are expressed as a percentage.

Performance Measure	vs. Placebo (No Treatment)	vs. Synthetic Quat
Grooming force reduction (detangling ease) – change in combing force (↓)	-54%	-25%
Resistance to combing strokes (breakage prevention) – change in strokes endured (↑)	+130%	+72%
Fiber tensile strength (single-fiber force at break) (↑)	+71%	+5%
Gloss / luminosity (instrumental shine) (↑)	+13%	+8%
Frizz reduction (50% RH humidity chamber) (↓)	-44%	-20%

↓ denotes a reduction in a negative attribute; ↑ denotes an increase in a positive attribute.

As shown in Table 1, the oligopeptide demonstrated excellent conditioning performance. Combability improved significantly: hair treated with the peptide required over 50% less force to be combed than untreated hair, outperforming the quaternary, which achieved a reduction in force of approximately 30% compared to untreated hair. In practical terms, strands treated with the oligopeptide showed very smooth combability, with the dynamometer recording significantly lower resistance. These lower combing forces suggest excellent detangling efficacy. Hair strength and resistance to breakage were also improved. In the cyclic combing stress test, strands treated with the oligopeptide withstood more than twice as many comb strokes as the placebo before fiber breakage occurred, representing a 130% improvement. This result was significantly higher than the improvement observed with the quaternary, which increased resistance to strokes by approximately 72% compared to the placebo. This indicates that peptide treatment confers superior resistance to mechanical stress, probably by strengthening the hair structure or forming a protective lubricating film. Single-fiber tensile measurements confirmed this trend: on average, the maximum load at fiber breakage was approximately 70% higher for fibers treated with the oligopeptide than for untreated fibers. In contrast, fibers treated with the quaternary showed only a marginal improvement in tensile strength (within approximately 5-10% compared to untreated fibers). With regard to the assessment of shine and brilliance of the strands, the microcamera images and Mambo gloss readings showed a notable increase in shine for hair treated with the oligopeptide. The strands treated with the peptide reflected light more brightly, appearing visibly shinier than the placebo, which appeared dull and lifeless in comparison. Quantitatively, the oligopeptide yielded about a 13% higher luminosity reading than untreated hair. Although the quat also improved shine by about 5-8% compared to untreated hair, the oligopeptide performed better, achieving slightly higher shine on average.

One of the most noticeable benefits observed was a reduction in frizz. In a high-humidity chamber test (50% relative humidity), hair treated with the oligopeptide showed 44% less frizz than the untreated control. Treatment with quaternaries also reduced frizz, but to a lesser extent (~30% reduction compared to the control). These results demonstrate that the oligopeptide active ingredient confers hair with humidity resistance similar to, or better than, conventional anti-frizz agents, keeping hair more compact and aligned in humid conditions.

After evaluation by SEM, the oligopeptide showed clear improvements in hair surface condition. Figure 1 shows SEM micrographs of the hair shaft surfaces from Caucasian hair strands that were knotted and then gently combed to create tangling damage. Untreated hair (placebo) shows visibly damaged cuticle scales: many scales are raised or broken due to mechanical stress, creating a rough texture. Quat-treated hair shows some improvement, as

the cationic conditioner has slightly smoothed the surface, but some cuticle edges remain partially raised and some damage is still evident. In contrast, hair treated with the active oligopeptide shows intact, flat cuticle cells with significantly reduced lifting. Figure 2 shows SEM images of the hair tips: the tips treated with the oligopeptide are more cohesive and have fewer split ends than the placebo, indicating repair or sealing of split ends, while the tips treated with the quaternary, although better than the untreated ones, still have some split ends. This visual evidence supports the conclusion that oligopeptide is able to effectively protect and repair the cuticle layer, contributing to both combability and shine.

SEM ANALYSIS ON PURPOSELY TREATED KNOTTED HAIR

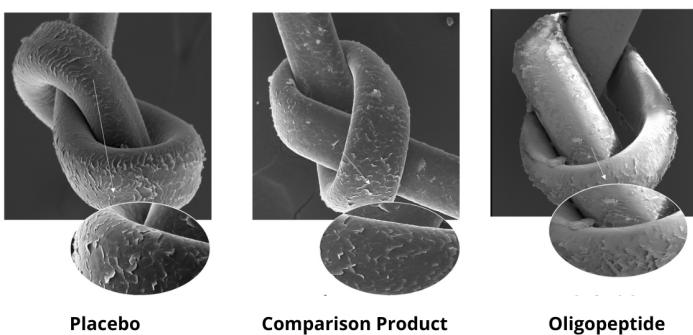


Figure 1. Scanning electron microscope (SEM) images of hair fiber surfaces after treatment (top view of the cuticle layer). Left: untreated hair tip (placebo) shows lifted, irregular cuticle scales and a rough texture, especially after the combing knot stress. Center: the tips of hair treated with Quat have slightly smoother cuticles than the control, but some raised edges are still visible. Right: the tips of hair treated with oligopeptide exhibit well-aligned cuticle scales with a smooth and uniform appearance. The oligopeptide treatment appears to coat and seal the cuticles, resulting in reduced surface damage even after stress. Scale bars: 50 μm .

SEM ANALYSIS ON PURPOSELY TREATED HAIR TIPS

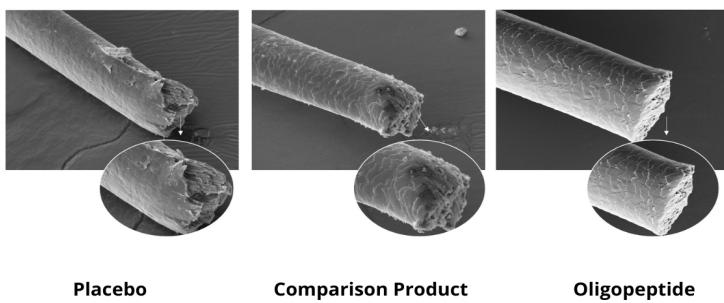


Figure 2. Scanning electron microscope (SEM) images of hair fiber tips (ends of strands) subjected to different treatments. Left: untreated hair tip (placebo) – shows frayed strand and the beginning of split ends formation. Center: hair tip treated with Quat – appearance is moderately improved, with slight recomposition of split ends, but some separations remain

visible. Right: hair tip treated with oligopeptide— the end of the fiber is consolidated and appears sealed, with a significant reduction in split ends. Scale bars: 50 µm.

3.3 In vivo sensory evaluation

Tests conducted on a panel of human volunteers confirmed the instrumental results. In controlled half-head comparisons, the conditioner with the new oligopeptide was consistently preferred by users over a placebo conditioner. All 20 panel participants reported that the side treated with the oligopeptide was easier to detangle and comb when wet and that greater shine was evident in the hair after drying. Characteristics such as softness, smoothness and combability were highly appreciated: all participants with straight hair gave positive feedback regarding detangling, shine and overall feel. For those with curly and frizzy hair, the positive opinion was unanimous (100%): the side treated with oligopeptide showed better definition and softness of curls, an anti-frizz effect and greater resistance (less breakage during combing).

A comparison between the oligopeptide and a leading quat-based conditioner in a blind test showed that volunteers found both products similar in terms of softness, but noticed a slight increase in volume and elasticity on hair treated with the peptide. It is important to note that no participants reported build-up, greasiness or heaviness with the peptide-based product; in fact, continued use over multiple washes did not result in any loss of conditioning efficacy or build-up, addressing a common issue with quats that can lead to dullness over time. Overall, the *in vivo* evaluations confirmed the excellent consumer-perceived performance of the new oligopeptide, in line with salon quality standards.

3.4 Differential scanning calorimetry (DSC)

DSC analysis provided insight into the internal effects on hair keratin. Untreated bleached hair showed a DSC endotherm (denaturation peak) around 150 °C, significantly lower than that of virgin hair. Hair treated with the oligopeptide showed a slight increase in denaturation temperature (by ~2°C) and enthalpy compared to untreated bleached hair, suggesting a partial restoration of protein network integrity. In contrast, hair treated with quat showed a negligible change in the DSC profile of bleached hair. Although a 2 °C increase does not completely restore bleached hair to its virgin state, it is a significant improvement given that no reducing agents or cross-linking agents were used, unlike typical bond repair chemicals. The result supports the reinforcing action at the cortex level of the oligopeptide, in line with the results relating to tensile strength and breakage.

4. Discussion

The results above confirm that the oligopeptide tested is a highly effective and sustainable active ingredient for hair conditioning, with efficacy equal to or exceeding traditional quaternary ammonium compounds. The oligopeptide complex has been shown to offer multiple conditioning benefits on a wide range of hair types. In this section, the implications of these results, the likely mechanisms of action of the peptide complex and its relevance to current green formulation trends will be discussed.

4.1 Mechanism of conditioning efficacy

The conditioning performance of the oligopeptide complex can be attributed to its unique composition of cationic oligopeptides. Like conventional cationic surfactants, these peptides carry positive charges that allow them to strongly adsorb onto negatively charged sites on the hair cuticle. However, unlike small-molecule quats, peptides have a larger molecular structure with multiple contact points to interact with the keratin substrate [4]. This likely leads to a more durable coating on the hair. SEM images confirmed that the peptide forms a

cohesive film along the cuticle, suggesting that multiple peptides can bind or arrange themselves to cover the surface. This film reduces friction between the fibers, thus facilitating combing and preventing moisture penetration. The reduction of the electrostatic effect is also expected from the neutralization of the negative charge by cationic peptides, fulfilling the classic role of antistatic agents.

In addition to surface effects, the small size and amino acid composition of peptides suggest that some may penetrate the cuticle and outer cortex. Previous research has shown that low molecular weight hydrolyzed keratins can infiltrate the hair fiber and improve its mechanical properties [4]. In our study, the significant improvements in tensile strength and breakage resistance during combing indicate a reinforcing action on the cortex. One hypothesis is that the oligopeptide complex diffuses into the outer cortex of the fiber, filling microcracks or damaged sites. The DSC results (slight increase in denaturation temperature) support this inner repair mechanism. This kind of dual action—formation of an external film and internal reinforcement—is a significant advantage of the peptide-based active ingredient, which distinguishes it from typical quaternaries that act mainly on the surface.

4.2 Impact on different hair types

A particularly important result is the efficacy of the oligopeptide on curly and frizzy hair. According to Andre Walker's classification, type 3 and 4 hair has a fundamentally different morphology, with an elliptical cross-section and irregular cuticle distribution, making it more prone to dryness, tangling and breakage. In particular, Afro hair has lower tensile strength and breaks with less force than Caucasian hair [3]. The superior performance of the oligopeptide in reducing breakage and combing force is therefore particularly relevant for these hair types. The strong detangling effect of the active ingredient directly addresses the primary need of consumers with curly hair, namely to achieve easier combing with less breakage. In addition, the frizz control provided by peptides is valuable for maintaining curl definition in humid conditions. Traditional conditioners are often insufficient for type 4 hair, sometimes leaving residue or failing to provide lasting hydration. In contrast, the biomimetic nature of the oligopeptide complex allows it to integrate better with the hair's natural proteins, producing superior cosmetic results on these textures. By validating its effectiveness on Afro and curly hair, this active ingredient supports a more inclusive approach to hair care, in line with industry trends aimed at meeting the needs of underserved demographic groups. It opens up new possibilities for "texture-specific" formulations, where a single naturally-derived active ingredient can adapt to the needs of consumers with very curly and less curly hair, filling a gap in the market.

4.3 Sustainability and implications for formulation

The introduction of the oligopeptide complex is an example of the trend toward green innovation in the cosmetics industry: replacing petrochemical or environmentally persistent ingredients with natural, biodegradable alternatives without compromising performance. The peptides contained in the complex under review are derived from renewable biomass, which means that production has a lower carbon footprint and adds value to what would otherwise be disposed of. The fermentation processes used to produce postbiotic peptides are generally considered sustainable and can be designed to minimize waste. Furthermore, the oligopeptide is easily biodegradable, which contrasts with many QACs that, as discussed, can persist in ecosystems and contribute to pollution and even antimicrobial resistance in microbes.

From a formulator's perspective, the oligopeptide offers versatility: it is water-soluble and works in different product formats (rinse-off conditioners, masks, leave-in sprays, serums).

The active ingredient's efficacy in both leave-on and rinse-off scenarios is noteworthy: even brief contact in a 3% rinse-off conditioner was sufficient to deposit the peptides and achieve results, while higher leave-in doses can intensify the benefits. Since it is essentially a mild aqueous protein solution, it can be incorporated without the surfactant phases or emulsifier required by quaternaries. Furthermore, no adverse interactions or stability issues have been observed with other common cosmetic ingredients. The absence of buildup after repeated use is a significant advantage for consumers, as it ensures that hair maintains its volume and natural appearance over time. This means that formulators may not need to add clarifying agents or limit the concentration of use as strictly as with heavy quaternaries or silicones.

4.4 Comparison to existing natural keratin treatments

There are other protein-based active ingredients for hair on the market, such as hydrolyzed wheat proteins, collagen and silk peptides. Many of these serve primarily as moisturizers or film formers and often lack a strong cationic charge, so their substantivity to hair is limited. The oligopeptide complex under investigation differs by combining biotechnologically derived peptides with a targeted design for cationic conditioning. Essentially, it is a bio-based cationic polymer, but composed of peptides rather than synthetic monomers. The closest analogues are emerging "vegetable keratins," blends of plant amino acids or peptides meant to mimic human hair keratin. Our results suggest that by optimizing the characteristics of the peptides (size, charge, hydrophobicity), it is possible to match the performance of engineered synthetic polymers. In fact, the oligopeptide achieved comparable or better results than a reference treatment for bond formation. A study by Barba et al. showed that treatments with wool-derived keratin peptides improved hair strength and properties of bleached hair [5], which is in line with the results obtained with a plant-based peptide system. This demonstrates the potential of next-generation natural active ingredients for hair care, which go beyond the traditional film-forming role of proteins to offer functional results such as strengthening, almost on par with professional chemical treatments.

4.5 Future directions

The success of the oligopeptide complex invites further exploration into peptide-based hair care products. Future research could identify specific peptide sequences that are primarily responsible for the conditioning effects, potentially leading to even more optimized blends or even the recombinant production of ideal peptides. Another avenue is to combine the oligopeptide active ingredient with other green ingredients to create synergistic effects: for example, pairing it with a natural alternative to silicone could ensure both high shine and a strong conditioning effect with completely natural ingredients. Furthermore, while the current active ingredient is designed to ensure stability after rinsing, exploring its use in protection against hot irons or as a pre-treatment for chemical treatments could broaden its applications. In terms of hair types, although it has demonstrated broad utility, further customization, with slight modifications in the peptide composition, could allow for the creation of variants targeted, for example, at protecting colored hair or improving curl retention for perm hairstyles.

From a sustainability perspective, widespread adoption of such bioactives could significantly reduce the environmental impact of personal care products. If quaternaries were gradually replaced, issues such as aquatic toxicity and sludge contamination by conditioning agents would be mitigated. It is important to note that positive consumer acceptance means that the commercialization of such an ingredient can align with the clean beauty narratives without asking consumers to compromise on performance, a critical factor in real-world acceptance.

5. Conclusion

We have developed and evaluated an innovative oligopeptide-based hair conditioning active ingredient derived from fermented agri-food by-products. This peptide complex was designed as a sustainable alternative to quaternary ammonium conditioners and our results demonstrate that it effectively fulfills this role. In extensive ex vivo tests, the peptide active ingredient exhibited superior detangling properties, significant anti-breakage benefits and increased shine and anti-frizz performance compared to conventional reference products. High-resolution SEM imaging confirmed that the new oligopeptide creates a smooth protective film on the hair fibers and helps repair lifted cuticles and split ends, explaining its dual ability to improve cosmetic and mechanical properties. Importantly, these benefits translated to in vivo improvements in both Caucasian and highly textured Afro hair, indicating broad efficacy and addressing a variety of hair care needs. Panel participants universally noted easier combing, improved softness and reduced frizz, with the peptide-treated hair often outperforming a leading synthetic conditioner in blind comparisons.

This innovative oligopeptide is an example of how green chemistry and biotechnology can meet the performance standards of professional-quality products. By leveraging naturally derived peptides that mimic and integrate with hair's structure, it provides conditioning functionality that rivals traditional quats while being inherently more eco-friendly and biodegradable. This work highlights the potential of bioactive peptides in ushering in a new generation of sustainable hair care formulations, where consumers no longer have to compromise between high performance and environmental responsibility. In summary, this keratin-like oligopeptide represents a next-generation of sustainable hair conditioning active ingredients that offers a viable path for formulators to replace petrochemical quaternary compounds, aligning hair care innovation with global trends of sustainability and inclusivity.

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