IFSCC 2025 full paper (IFSCC2025-1301)

Efficacy of a blend esters plant-based oils and avocado oil on the mechanical properties of bleached coily hair

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1. Introduction

The global hair care market continues to expand, driven by increasing consumer demand for products that are both effective and environmentally sustainable. This trend has accelerated research and development in plant-based active ingredients, which offer multifunctional benefits while aligning with the growing preference for naturally derived formulations [1]. In recent years, there has been particular emphasis on addressing the specific needs of different hair types, especially highly textured or coily hair, which presents unique structural and physiological characteristics [2].

Understanding hair fiber diversity is essential for the development of targeted and effective cosmetic treatments. Hair varies significantly in its macroscopic features, such as curvature, diameter, stiffness, and shine, as well as in microscopic and biochemical properties, including keratin structure, lipid content, tensile strength, and porosity [3,4]. These variations influence the behavior of the hair under mechanical and chemical stress and affect how it responds to cosmetic products. Coily hair, in particular, is more susceptible to damage due to its tighter curl pattern and increased fragility, requiring specialized care and protective ingredients.

In response to these needs, the cosmetic industry has increasingly turned to vegetable oils and their derivatives as sustainable alternatives to synthetic compounds. These oils not only serve as emollients but also contribute to lipid replenishment, fiber protection, and improved sensory attributes [5,6]. Among them, esters derived from plant oils have garnered interest for their ability to mimic the functionality of silicones while maintaining a high naturality index, offering performance benefits without compromising environmental responsibility.

In this context, the present study aimed to evaluate the effects of a blend of plant-based esters and avocado oil, applied in a leave-in formulation, on the mechanical properties of bleached coily and straight hair.

2. Materials and Methods

2.1 Vegetable Oils

A blend of vegetable oil esters was developed, an active ingredient composed of ethyl esters and triacylglycerols from sunflower oil (*Helianthus annuus)*, crambe oil (*Crambe* *abyssinica*) and avocado oil (*Persea gratissima*). This blend is composed of hydrophobic alkyl esters that interact through dipole-dipole and hydrogen bonding with the varying electron densities of the hair's peptide bonds, facilitating the homogeneous dispersion of plant-based oils in the right amount according to the hair's specific needs and being a sustainable and biodegradable molecule (Chemyunion, Sorocaba, BR). The avocado oil, also studied individually, were obtained through supercritical CO_2 extraction, a method that allows the separation of lipid compounds without the use of chemical solvents, making it a more sustainable technique that better preserves the oil's nutrients (University of São Paulo, BR).

2.2 Hair

Standardized hair tresses (15 cm in length) with coily (African origin) and straight (Caucasian origin) textures, both dark brown in color, were obtained from DeMeo Brothers, Inc. (USA). For pre-treatment, all tresses were washed with a shampoo containing 8.1% Sodium Lauryl Ether Sulfate and were allowed to dry naturally for 24 hours at room temperature.

To simulate chemical damage, four of the five African hair tresses and five Caucasian hair were subjected to a bleaching procedure. Following this step, the tresses were assigned to five experimental groups according to the treatment protocol, as described in Table 1.

Table 1. Hair tresses

Hair Tress Code	Hair Type	Condition
G1	Coily	Virgin (untreated control)
S1	Straight	
G2	Coily	Bleached (no treatment – bleached control)
S2	Straight	
G3	Coily	Bleached + treated with vehicle formulation
S3	Straight	
G4	Coily	Bleached + treated with 2% blend of plant-based esters
S4	Straight	
G5	Coily	Bleached + treated with 2% avocado oil
S5	Straight	

2.3 Bleaching procedure

Hair tresses assigned to groups G2, G3, G4, G5 and S1, S2, S3, S4 and S5 were subjected to chemical bleaching to simulate damage. The bleaching mixture was prepared in a 1:2 ratio of bleaching powder to 12% hydrogen peroxide solution (40 vol.) and applied evenly to the hair. Each tress was wrapped in aluminum foil and incubated in an oven at 30 °C and 50% relative humidity (R.H.) for 30 minutes. After each treatment, the tresses were rinsed with water and dried using a hairdryer at medium temperature. This bleaching procedure was repeated three times for all hair tresses.

For the straight hair tresses, a total of five bleaching cycles were performed: three treatments in the oven under the same controlled conditions (30 °C and 50% R.H.), followed by two additional treatments conducted outside the oven at room temperature (25 °C and 50% R.H.), each lasting 30 minutes. After the final bleaching cycle, all hair tresses were washed with anti-residue shampoo containing 8.1% Sodium Lauryl Ether Sulfate and left to dry naturally for 24 hours.

2.4 Application of formulation

The treatment protocol involved the application of a standardized amount of neutral shampoo equivalent to 50% of the hair tress weight. The shampoo was applied to wet hair, gently massaged for one minute, and then rinsed with water. For groups G1,G2, S1 and S2 the hair was subsequently dried using a hairdryer at medium temperature.

For groups G3, G4, G5, S3, S4 and S5 following towel drying, a leave-in treatment was applied in an amount corresponding to 30% of the hair tress weight. The product was left on the hair for 30 minutes before being rinsed and dried with a hairdryer. This treatment cycle was repeated three times; however, in the final application, the leave-in was not rinsed out, simulating typical consumer use conditions.

2.5 Mechanical Testing Protocol

Hair samples were equilibrated at 22 ± 2 °C and 50 ± 5% relative humidity for at least 24 hours prior to and during testing. Cross-sectional area and mean diameter were measured using the FDAS-770 system equipped with a Dimensional Analysis System (Dia-Stron Ltd., UK). This equipment employs a laser scanning micrometer, enabling precise, non-contact dimensional measurements through automated fiber rotation and translation. Five measurement points were taken along each individual fiber.

The mechanical properties, including elastic modulus, break extension, and break stress, were assessed using the Automated Miniature Tensile Tester MTT686 (Dia-Stron Ltd., UK). The UvWin software was used to calculate these parameters, with tensile strength (break stress) determined by correlating the applied load to the cross-sectional area at the point of fiber breakage [7].

3. Results

The analysis of cross-sectional area showed significant differences between hair types, as shown in Figure 1. Coily hair tresses (G1–G5) exhibited significantly larger cross-sectional areas compared to straight hair tresses (S1–S5) (p < 0.0001). However, within each hair type, no statistically significant differences were observed among the treatment groups (p > 0.05). These results indicate that the treatments, including bleaching and application of the vehicle, blend of esters, or avocado oil, did not alter the cross-sectional structure of the hair fibers.

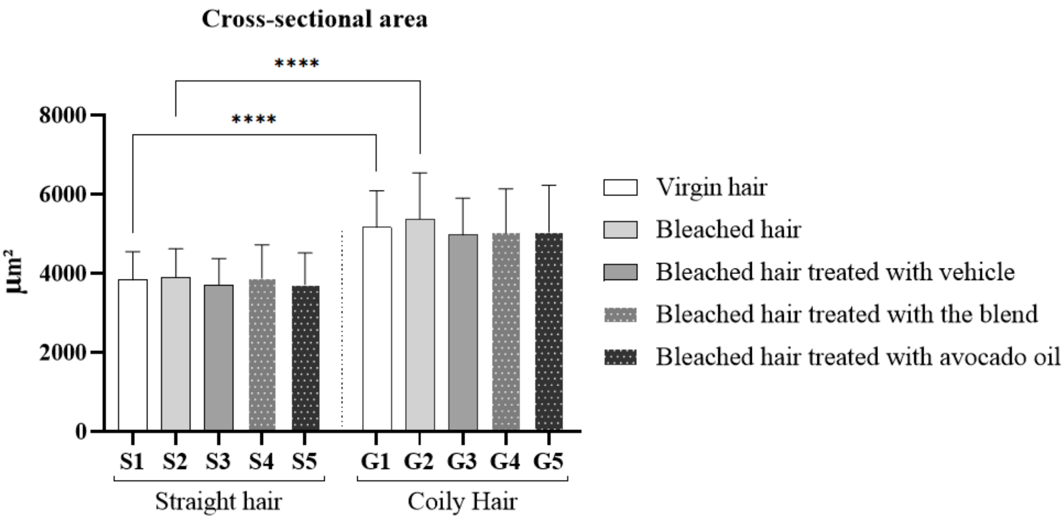

Figure 1. Cross-sectional area (μm²) of straight (S1–S5) and coily (G1–G5) hair tresses under different treatment conditions. ****p < 0.0001.

Regarding fiber diameter, coily hair showed a significantly larger mean diameter than straight hair ($p < 0.0001$). However, within each hair type, no statistically significant differences were observed among the treatment groups ($p > 0.05$) (Figure 2). This indicates that neither the bleaching process nor the treatments affected the average fiber diameter in either straight or coily hair.

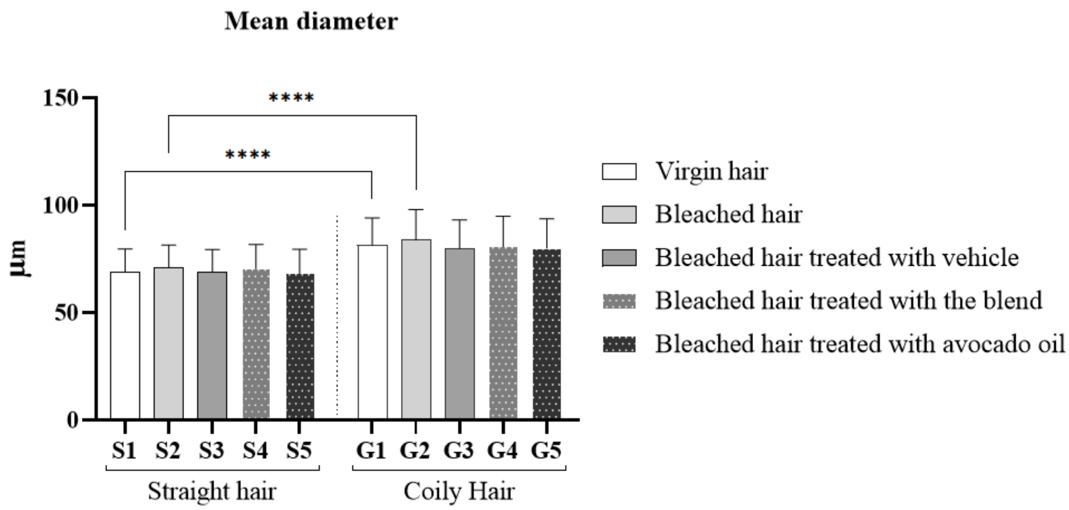

Figure 2. Mean diameter (µm) of straight (S1–S5) and coily (G1–G5) hair tresses under different treatment conditions. ****$p < 0.0001$.

The break stress analysis showed significant differences across treatments and hair types (Figure 3). In straight hair, all groups (S2–S5) exhibited significantly lower break stress compared to the virgin control (S1) ($p < 0.0001$). Among them, S2 and S3 (bleached and vehicle-treated) showed the lowest values. Despite the significant reduction, treatment with the blend of esters (S4) and avocado oil (S5) resulted in higher break stress compared to S2 and S3, indicating partial recovery of mechanical resistance. In coily hair, break stress was significantly reduced in G2 and G5 when compared to the virgin control G1 ($p < 0.0001$ and $p < 0.01$, respectively). Treatment with the vehicle (G3) and the blend of esters (G4) led to a significant increase compared to the bleached group G2 ($p < 0.05$ and $p < 0.001$), while the avocado oil-treated group (G5) showed no significant difference from G2 ($p > 0.05$). These results indicate that bleaching reduces the mechanical strength of both hair types, while treatments with the blend of ester improve break stress, particularly for coily hair.

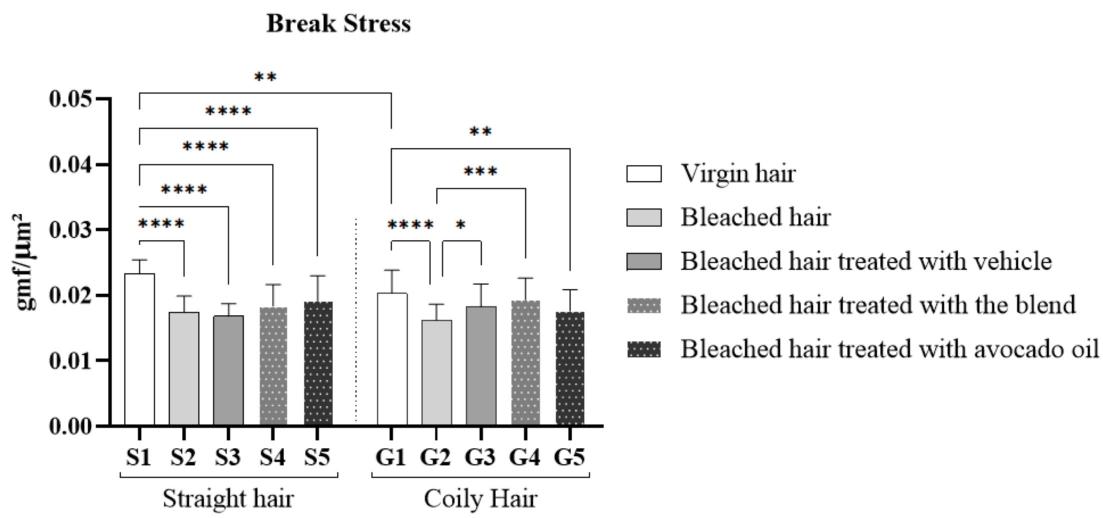

Figure 3. Break stress (gmf/μm²) of straight (S1–S5) and coily (G1–G5) hair tresses under different treatment conditions. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$ and ****$p < 0.0001$.

Regarding the break extension results, S2 to S4 groups showed significantly higher break extension compared to the virgin control (S1) (****$p < 0.0001$). This increase in extensibility was maintained regardless of the treatment applied, with no significant differences among these groups. On the other hand, S5 showed a significant difference compared to the bleached group S2 ($p < 0.0001$), indicating that the treatment with avocado oil was able to reduce the excessive increase in break extension typically observed after bleaching. Notably, the mean value of S5 (42.34 ± 7.63%) was closer to the virgin hair group S1 (48.89 ± 4.92%), with a non-significant difference between the two groups.

In contrast, coily hair did not show significant variation in break extension between the groups (G1–G5), suggesting that bleaching and the tested treatments did not alter the strain behavior of this hair type. Despite the stability within the coily hair groups, overall extensibility was consistently higher in straight hair (****$p < 0.0001$), highlighting intrinsic structural differences between the two hair types (Figure 4).

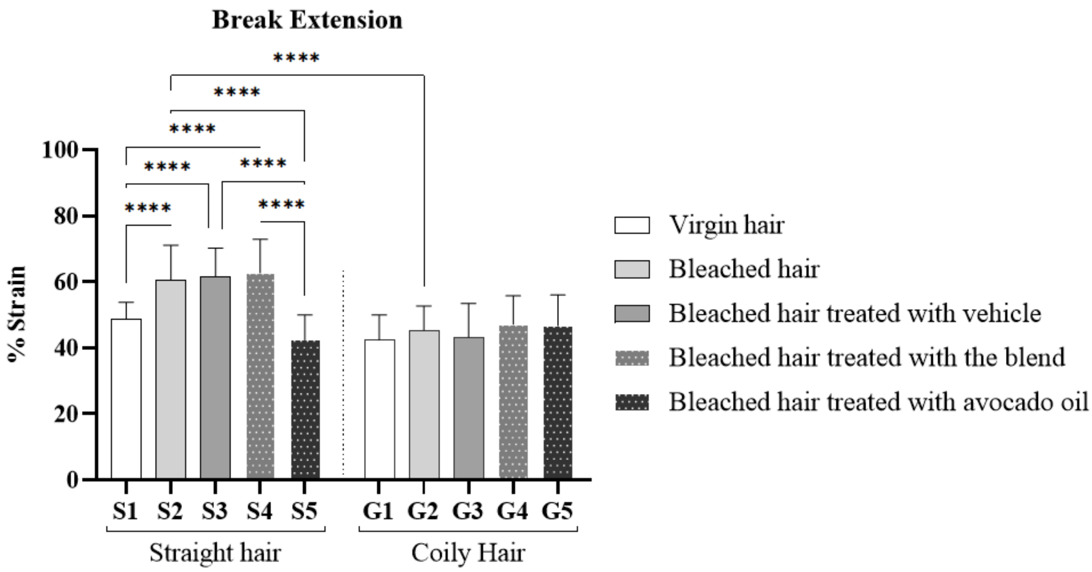

Figure 4. Break extension (% strain) of straight (S1–S5) and coily (G1–G5) hair tresses under different treatment conditions. ****$p < 0.0001$.

Elastic modulus values for straight and coily hair are presented in Figure 5. In straight hair, the bleaching process increased the elastic modulus in all groups, being significant for the S3 and S4 groups ($p < 0.0001$). When comparing the treatments, only the S5 presented a significant reduction compared to the S3 ($p < 0.05$) and the mean values were closer to the virgin hair than the other groups (S1: $3.33 \times 10^9 \pm 0.46 \times 10^9$ and S5: $3.62 \times 10^9 \pm 0.60 \times 10^9$). In contrast, coily hair groups did not show statistically significant differences among treatments ($p > 0.05$), and their elastic modulus values remained consistently lower than those observed in straight hair. Once again, the difference between both hair types is observed in the elastic modulus, with coily hair presenting a lower elastic modulus in both virgin and bleached conditions.

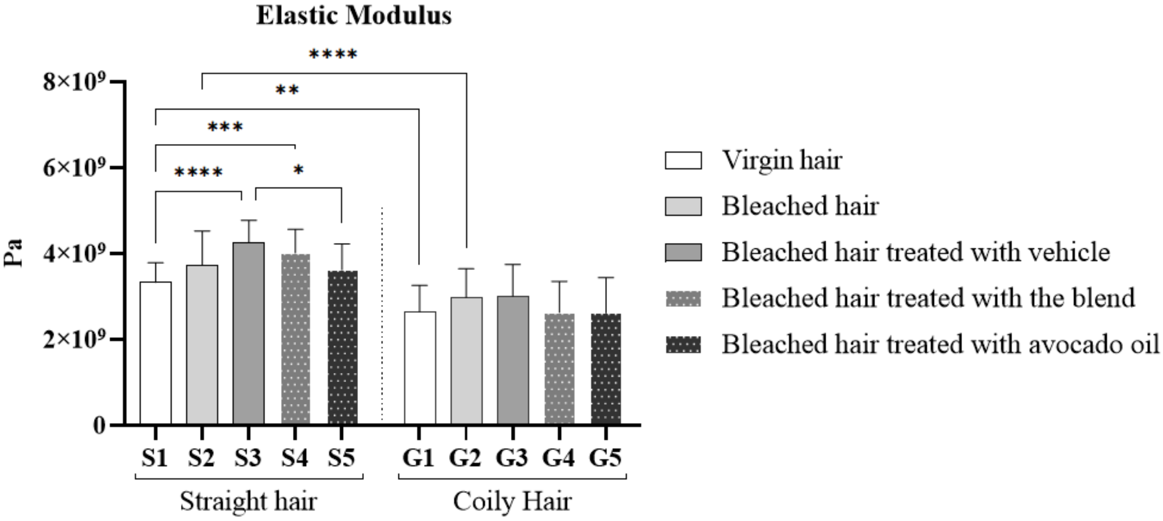

Figure 5. Elastic modulus (Pa) of straight (S1–S5) and coily (G1–G5) hair tresses under different treatment conditions. *p < 0.05, **p < 0.01, ***p < 0.001 and ****p < 0.0001.

4. Discussion

Hair exhibits mechanical properties that vary according to its microscopic and macroscopic characteristics, such as fiber diameter, shape, presence of curvatures, and the organization of the cuticle layers. These features directly influence the fiber behavior under mechanical stresses such as tension, bending, and twisting [8]. Coily hair has an arched mechanical structure, which gives it distinct mechanical behavior. This structural conformation makes it more prone to breakage, primarily due to the limited distribution of natural oil along the fiber, which contributes to increased dryness [9]. An example elucidated through the study that illustrates these factors can be observed in the cross-sectional area analysis and mean diameter of the fiber, which showed that coily hair tresses have larger sectional area than straight hair, indicating that coily hair is structurally thicker.

In contrast, straight hair allows for a more uniform distribution of natural oil along the fiber, which reduces the need for lipid replenishment and contributes to greater resistance to breakage. In general, coily hair fibers are believed to have lower strength compared to straight hair fibers, and therefore require greater lipid restoration within their structure [10,11]. In this context, the use of vegetable oils and their esters can attend the specific needs of coily hair. Based on these considerations, vegetable oils stand out due to their rich composition as restorative agents, with film-forming and moisture-retention properties that help reconstitute the external lipid layer and improve the mechanical integrity of the fibers [12].

The study of oils plays a crucial role in analyzing the mechanical properties of hair, taking into account the specific needs of each hair type. The results indicate that the oils promoted an improvement in breakage resistance, especially in coily hair, highlighting that the ester blend acts as a potent restorer of the hair's mechanical integrity, particularly after aggressive treatments like bleaching. The ester blend contains a combination of unsaturated and monounsaturated fatty acids, which favor deep penetration into the hair fiber, promoting the recovery of breakage resistance [13]. These factors are crucial for the recovery of coily hair, which, due to its more porous and curved structure, tends to suffer more severe damage. On the other hand, avocado oil did not show a significant effect on coily hair but demonstrated greater efficacy on straight hair, reinforcing the idea that the penetration capacity varies according to the oil's structure and the condition of the hair cuticle [14]. This finding supports the importance of understanding the structural characteristics of each hair type to select more effective treatments, such as the ester blend for coily hair, which may offer more substantial restorative benefits due to its rich chemical composition

Thus, the study of oils or ester blends requires an understanding of their physicochemical properties, particularly regarding their ability to penetrate the hair fiber or form protective films on its surface, as well as how they interact with different hair types. This can be elucidated, for example, in relation to hair proteins, which contain peptide bonds, also known as amide bonds, primarily in the cuticle region. These bonds exhibit an electronic shift in the nitrogen, carbon, and oxygen atoms, leading to the formation of different electronic densities in these atoms. The blend of vegetable oil esters with its hydrophobic alkyl esters, interacts through dipole-dipole interactions and hydrogen bonding with the varying electronic densities of the hair's peptide bonds, resulting in the homogeneous dispersion of plant-based oils onto the hair. These behaviors vary according to the molecular composition of the oil and the structural condition of the hair, especially when comparing healthy and chemically treated tresses, contributing to the development of formulations that improve the mechanical properties of the hair fiber [15,16].

These factors drive the need and importance of research that evaluates cosmetic ingredients for different hair types, given that they present mechanical and chemical differences across hair classifications, resulting in specific care requirements. This has led the cosmetics industry to introduce innovations to meet this demand through studies of underexplored ingredients, as well as products with high levels of naturality and sustainability.

According to these results, the studies showed that the blend of esters improved the mechanical resistance of the hair fibers, demonstrating its potential to enhance strength and performance, especially in damaged coily hair fibers. Additionally, the evaluation of elasticity parameters revealed that avocado oil contributed to maintaining the extensibility of the hair fibers within a physiologically normal range, potentially preserving structural integrity and preventing over-elastic behavior often associated with chemically damaged hair. This reinforces the relevance of selecting oils not only based on penetration capacity but also on their ability to support the mechanical balance of the fiber, ensuring adequate flexibility without compromising strength.

5. Conclusion

There are differences in the mechanical properties between coily and straight hair.
The blend of esters was effective in improving the mechanical properties of damaged coily due to increased flexibility of mechanical resistance. However, avocado oil was effective in improving the mechanical properties of damaged straight hair, due to increased flexibility, and extensibility. Thus, the blend of esters demonstrated superior performance, especially in restoring mechanical resistance, and showed even more promising results for coily hair. Finally, the blend of esters offers a sustainable and innovative solution for hair care formulations aimed at meeting consumer demands.

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