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Role of Lipids in Water Permeation of Different Curl Pattern Hair Types

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Abstract

Background: Dark-base hair fibers with Curl Pattern (CP) types 2 and 3 from Asian and European populations, respectively, are very similar, although each presents different behaviors regarding water diffusion and cosmetic treatments, including in relation to dyeing. This study aims to identify the key drivers of water diffusion in hair, particularly the role of lipids in the diffusion processes. Methods: Virgin, externally delipidized, and internally delipidized CP2 and CP3 hair strands were subjected to Dynamic Vapor Sorption (DVS) and ATR-FTIR investigations. In addition, external and internal lipid extracts were quantified and analyzed via thin-layer chromatography–flame ionization detection (TLC/FID). Results: The results obtained indicate that CP2 hairs present lower water regain at all humidity steps and a different diffusion behavior depending on the humidity. Lower diffusion was obtained at low humidity and higher diffusion at high humidity. TLC/FID analyses indicate that CP2 fibers present a significantly higher amount of external lipids (1.4% vs. 0.4%) and internal lipids (3.2% vs. 2.6%) as compared with the CP3 fibers. Conclusions: The higher amount of internal lipids is mainly due to the greater amount of polar lipids (ceramides). Lipid extraction tends to modify the water content, leading to a more hydrated and less permeable lipid-depleted fiber. The similar water properties of the two types of lipid fiber support the fundamental role of lipids, even when present in small quantities, in the differentiation of hair types. This study highlights a potential link between the lipid composition of CP3 and CP2 hair fibers and their differences in behaviors regarding water diffusion, which could also explain varying responses to cosmetic treatments.

Keywords: hair; lipids; moisture; diffusion

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1. Introduction

The hair shaft is a complex biological material composed of three concentric layers. The cuticle, the outermost layer, consists of flat cells that overlap the core of the fibers [1]. This arrangement forms a protective barrier, reinforced by a network of lipids, representing only 1 to 9% of the hair mass but playing a key role in maintaining hydrophobicity at the surface

of the hair and resulting in its protection [2]. The cortex, which contains most of the mass of the fiber, comprises elongated keratin inserted in a protein matrix, and plays an essential role in ensuring fiber strength and flexibility [3]. Finally, the medulla, which is not always present, is located in the innermost part of the hair. Other studies have previously confirmed the detection of lipids in this region [4,5]; in fact, lipid levels were found to be between 3 and 20 times higher in the medulla than in the surrounding cortex [6,7]. To date, studies of hair lipids have been performed primarily by comparing hairs derived from different ethnic groups or by exposing hair to external factors [8,9]. Lipids are characterized as exogenous or endogenous, depending on whether they originate from sebaceous glands or hair matrix cells, respectively. Exogenous lipids consist of free fatty acids (FFAs), triglycerides, cholesterol (CH), wax esters and squalene. Endogenous hair lipids comprise FFAs, CH, ceramides, glycosylceramides, cholesterol sulfate and 18-methyleicosanoic acid. Endogenous lipids, including sterols, FFA, CS and CER, constitute 2.5% of the total hair fiber, while exogenous lipids, such as SQ and sterol esters, account for less than 1% [10].

The importance of lipids within hair fibers has become apparent [9], even though lipids comprise less than 9% of the fiber dry weight [11]. Some studies [2,12] conducted to identify the effects of lipids on the properties of fibers have found that lipids play a key role in maintaining adequate water permeability and the hydrophobic character of the fiber surface. These effects were primarily related to the lipid amounts and the order within the cuticle region. It is difficult to discern differences in the structural/functional contributions of the different kinds of lipids. External lipid extraction partially decreases the hydrophobicity and induces a reduction in the water content of the fiber, probably due to a disordering of the remaining surface lipids, whereas internal lipid extraction increases the internal fiber's polarity by increasing the water content [2,10].

Changes in the lipid quantity or composition could modulate the dynamics of water in the fiber and thereby generate regions with distinct resistance [13]. However, unlike skin, the removal of lipids did not have such a high impact on water exchanges kinetics. Lipids randomly distributed in the fiber seem not to have a major role in "barrier function" [14]. Therefore, the role of lipids in the fiber and their relationship to diffusion behavior is unclear.

Virgin human hair accounts for an important portion of the phenotypic variation among the different human hair types. Historically, three different types of ethnic hair were categorized (African, Caucasian and Asian), but a new classification of hair, independent of presupposed ethnicity, was proposed in the 2000s based on morphological parameters of curls, starting from Curl Pattern (CP) 1 for straight hair and proceeding to CP8 for tighter coils [15]. The study of hair properties has largely addressed the fraction of protein within the fibers, which cannot explain the physical differences previously demonstrated [16]. CP5+ is the hair type which differs most significantly from others, having less tensile strength [17,18], exhibiting lower moisturization [18], less radial swelling when flushing with water [19] and higher water diffusion or permeability [9] compared with CP3 or CP2 hair fibers. It was then assumed there may be possible lipid differentiation among human populations, and to that end, CP5+ hair was demonstrated to have more lipids and be highly disordered, relating to higher permeability [20].

CP2 and CP3, respectively, Asian and Caucasian population, hair fibers are very similar; however, their different morphologies and chemical compositions can account for their different behavior in front cosmetic treatments, e.g., bleach and hair lightening. Treatments with hair styling agents were studied to produce different effects depending on the lipid amount in hair [21]. Different fluorescent dyes were applied to various hair fiber types, and it was clearly demonstrated that the incorporation of dyes into the CP2 (Asian population) hair fibers was more difficult than performing the same process with those of the CP3 (Caucasian) population [22]. CP2 hair fiber has a greater diameter

with circular geometry and cylindric shape, and more and wider cuticular layers than CP3 [19,23]. Asian population hair fibers were reported to have a lower amount of lipids, albeit exhibiting significantly richer polarity, lower moisture content and similar or lower water diffusion [9,20]. However, the large differences in behavior found for these two types of fibers regarding cosmetic treatments are difficult to explain with the current knowledge and understanding of these fibers, as it is believed to be related to the chemical composition of their lipids and the structures they form inside the fiber. It has been shown that the cuticle of Asian hair is resistant to damage caused by straightening treatments, whereas the cuticle and cortex of Caucasian hair were relatively susceptible to stress imposed by coloring treatments [24].

This work is therefore an in-depth study of the lipid presence and function in CP3 (Caucasian) and CP2 (Asian) fibers. The study aims to identify the key drivers of water diffusion in different hair types, particularly the impact of lipids. Virgin, externally delipidized and internally delipidized CP3 and CP2 hair strands were subjected to water sorption gravimetric and spectroscopic analyses, respectively, via DVS and ATR-FTIR investigations. During the extraction procedure, sebaceous lipids and free structural lipids from the exterior and interior of the fiber were removed (covalently bound lipids were not removed). It is therefore possible to discern differences in the structural/functional contributions of measured fiber properties by analyzing either sebum lipids or free structural lipids of CP3 and CP2 hairs. In addition, external and internal lipid extracts were quantified and analyzed via TLC/FID. The amount and chemical character of the lipids extracted could be related to the diffusion properties of water found for the two types of hair fibers. This study therefore aims to explore the possible relationship between the lipid structure of hair fibers of two different ethnic groups, i.e., CP3 and CP2, by analyzing their different behavior in the diffusion of water, the results of which could have implications for cosmetic treatments.

2. Materials and Methods

2.1. Hair

Hair was obtained from three different CP3 (Caucasian) subjects and three different CP2 (Asian) subjects. These hair samples were collected following research studies. Six batches of ten 1-gram hair strands (three for each hair type: CP3—hair fibers of Caucasian origin; CP2—hair fibers of Asian origin) provided by L'Oréal were washed in a hair/surfactant solution (ratio 1:30) with 3 % diluted commercial UltraDoux shampoo followed by a water rinse and drying under ambient temperature conditions.

2.2. Hair Morphology

Some fibers from each batch are embedded in resin to realize cross sections of 10 µm thickness with a LEICA microtome. Microscopic observations are then performed using an OLYMPUS BX63 bright-field optic microscope. The observations are performed at a magnification of $\times$20 and $\times$40. The cross section diameters and ellipticity and the size of the medulla are measured through image analysis.

2.3. Lipid Extractions

The extracted lipids are categorized as exogenous and endogenous depending on whether they originate from sebaceous glands or hair matrix cells, respectively, and their varying compositions support the use of different extraction protocols [2,20,25].

Extractions of external and internal lipids were performed using different organic solvents. The external surface lipids of the washed hair samples were removed using Soxhlet extraction with n-hexane (hair/solvent ratio 1:120) for 4 h [9]. Internal lipids

were removed via extraction with different solvent mixtures of chloroform/methanol (2:1 v/v, 1:1 v/v and 1:2 v/v) for 2 h for every mixture and 100% methanol overnight at room temperature in a stirring system using the same hair sample (hair/solvent ratio 1:75 w/v) [2,9]. The different extracts were then combined, concentrated and dissolved in 25 mL chloroform/methanol (2:1) before analysis.

2.4. Lipid Analyses: TLC/FID

Lipid analyses of the different extracts were performed using thin-layer chromatography coupled to an automated flame ionization detector (TLC/FID), Iatroscan MK-5 analyzer (Iatron, Tokyo, Japan). The lipid extracts were directly spotted onto silica gel-coated Chromarods (type S-III) using a precision Hamilton 2 µL syringe coupled to an SES 3202/IS-02 sample spotter (NiederOLm, Germany). Determination of the lipid content was performed using an optimized TLC/FID protocol [2,9] using a methodology where rods (in a set of 10) were developed in the following mobile phases: (i) chloroform/methanol/water (57:12:0.6, $v/v/v$) for a distance of 2.5 cm twice, (ii) n-hexane/ethyl ether/formic acid (50:20:0.3, $v/v/v$) to 8 cm and (iii) n-hexane/benzene (35:35, v/v) to 10 cm; finally, a total scan (100%) was performed to quantify the most polar lipids using calibration curves.

2.5. Moisture Content

Moisture content was studied on non-extracted and extracted hairs according to the difference in weight as measured before and after drying fibers in an oven. Samples of around 100 to 150 mg were maintained in a conditioned room (23 $\pm$ 2 °C and 50 $\pm$ 5% RH) for at least 24 h before being weighed and subsequently dried in an oven at 105 °C for 24 h. After the sample was cooled in a desiccator under a P_2O_5 atmosphere, it was weighed again, and the moisture content was calculated as a percentage in duplicate.

2.6. Dynamic Vapor Sorption (DVS)

The water absorption/desorption kinetics of the hair were evaluated using a TA Instruments Q5000SA Sorption Analyzer (New Castle, DE, USA), which consists of a highly sensitive microbalance and a chamber to control relative humidity. DVS is a thermogravimetric technique that evaluates how much and how quickly a sample absorbs a solvent. Evaluation of moisture kinetics uptake and loss is a good strategy for obtaining more detailed information about the structural integrity and organization of a given sample. An absorption/desorption isotherm describes the process.

The sample is exposed to different relative vapor pressure values during the experiment, and the overtime weight changes are registered. The isotherm shows the absorbed vapor quantity in the function of the relative vapor pressure, expressed as relative humidity (RH). Utilizing this technique, the water diffusion coefficients are obtained.

During the tests, the weight of the analyzed hair samples was 10.0 $\pm$ 0.5 mg. The experiments were performed with a gas flow of 200 mL/min, at 25 °C and using the following methodology (described elsewhere) [9,20]. The isotherms can be divided into two phases: the adsorption isotherm for increasing relative humidity stages and the desorption isotherm for decreasing relative humidity stages.

Mathematical models describe sorption isotherms, the Guggenheim–Anderson–de Boer (GAB) model being the most widely used [26]. The GAB model provides a physical description of the sorption processes. In our case, with the moisture content at the end of each stage, the TA Instruments software program adjusted the GAB model to the experimental data.

In addition to the adsorption/desorption isotherms, the kinetics of the sorption process can be evaluated. The method applied by Vickerstaff [27] to study dye diffusion into fibers was adjusted to obtain the diffusion coefficient of water expressed from a derived

Fick's equation for moisture diffusion. The rate of adsorption/desorption of water can be calculated, obtaining the diffusion coefficients [20].

The DVS of the different samples therefore indicates differences in the humidity content, the binding energies of water to different components of the fiber (GAB model), and the water diffusion or velocity to exchange water with the environment (Da), which is of special relevance in this study because of the important role of lipids in water diffusion.

2.7. IR Spectroscopy (ATR-FTIR)

A Nicolet Avatar 360 FTIR spectrophotometer (Madison, WI, USA) was used, equipped with an attenuated total reflection (ATR) accessory and a diamond crystal (with ZnSe lens) with a 42° angle of incidence in horizontal orientation. Before analysis, the hair is placed towards the diamond crystal. To ensure reproducible contact between the sample and the glass, a pressure of 10,000 psi is applied to the samples. This allowed us to analyze the first 5 µm of the hair fiber, which corresponds to the cuticle layer.

All the analyzed spectra represent an average of 64 scans with a resolution of 2 cm^{-1}, and the wavenumber range used is 4200–650 cm^{-1}. The maximum positions have been determined with the help of OMNIC software version 8.1.210 (ThermoFisher, Sci., Waltham, MA, USA).

2.8. Statistical Analysis

Statistical analyses were performed with the StatGraphics software platform (version 5.0). Differences were tested for statistical significance using nonparametric tests (Kruskal–Wallis). Significance was tested at the 0.05 or 0.10 level of probability (p).

3. Results and Discussion

Lipids, particularly those present in the cuticle, are also considered part of the intercellular complex of hair. Fatty acids appear to be bonded by thio-ester linkages to the proteins of the outermost part of the cuticle. In recent decades, considerable attention has been given to structural lipids, especially covalently bound 18-MEA [28]. Previously, lipids of sebaceous origin were thought to play little or no functional role in hair. However, McMullen et al. [21] have provided evidence that non-covalently bound lipids play an indispensable role in the surface properties of human hair. They not only govern the properties of hair but also influence hair treatments. Hair lipids primarily comprise free fatty acids, cholesterol esters, cholesterol, cholesterol sulfate and ceramides. These lipids are categorized as exogenous and endogenous lipids depending on whether they originate from sebaceous glands or hair matrix cells, respectively [29], and their presence is crucial for maintaining the internal water content inside the fiber. Internal hair lipids could thus promote the barrier effect and prevent external materials from fiber penetration [12,30].

First, a morphological analysis of CP2 and CP3 hairs is performed on three batches per Curl Pattern. In all cases, whether the diameter is medium, large or small, CP2 hairs are larger than CP3 (albeit no significant difference between them). It can also be noticed that CP2 hair is larger in size and exhibits a higher amount of medulla. These results must be balanced to consider the diversity within each batch of hair and each CP, which explains the high standard deviation (Table 1).

In addition, the size of the medulla has been measured according to the process described in the Material and Methods section. An analysis of the images shows that on average, CP3 hair is thinner than CP2 hair, and the surface area occupied by the medulla is more important for CP2 hair, at 3.05% of the cross section compared to CP3 hair 0.79% (Figure 1). The larger medulla of CP2 hair may be prone to containing greater amounts of

internal lipids, which corroborates the results of the internal lipids extracted for CP2 hair versus CP3 hair.

Table 1. Morphological study of CP3 and CP2 fibers.

Hair Morphology	CP3	CP2
Mean diameter (μm)	72.66 ± 18.01	88.66 ± 19.46
Big diameter (μm)	85.54 ± 26.69	100.27 ± 27.32
Small diameter (μm)	63.38 ± 16.28	81.03 ± 17.16
Medulla proportion (%)	0.79 ± 1.23	3.05 ± 2.66

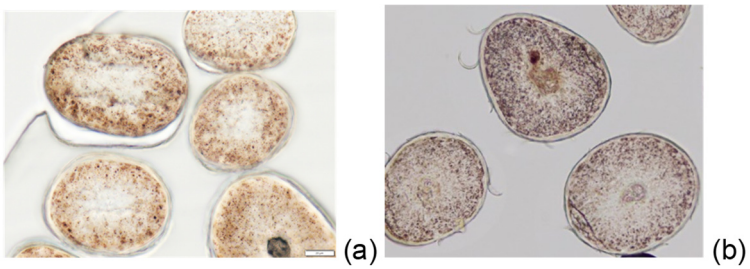


Figure 1. Optical microscopy illustration: (**a**) CP3 hair cross sections; the medulla occupies on average 0.79% of the cross section. (**b**) CP2 hair cross sections; the medulla occupies on average 3.05% of the cross section.

The analyses of the lipid extracts might provide interesting knowledge regarding the levels and types of lipids that can be obtained from the two kinds of hair fibers studied. External and internal lipids were extracted twice from three different CP3 and CP2 batches, as described in the Materials and Methods section. Lipid extracts were quantified and analyzed via TLC/FID to qualitatively and quantitatively discern the lipid differences between the different hair types. A statistical evaluation was therefore also performed (Table 2).

Table 2. Mean amount of external and internal lipid extraction from CP3 and CP2 hair fibers presented as a percentage over total amount analyzed (% ota) or percentage over total weight of fiber (% owf).

LIPIDS	CP3 External L.	CP2 External L.	CP3 Internal L.	CP2 Internal L.
	% over total amount analyzed (% ota)			
ECOL	65.47 ± 14.72	60.41 ± 18.42	6.13 ± 0.73	8.55 ± 4.20
FFA	22.07 ± 8.72	24.02 ± 18.30	56.77 ± 2.61	52.39 ± 6.11
CHOL	1.06 ± 2.59	6.63 ± 3.10	8.44 ± 3.93	6.27 ± 2.42
Cer	11.41 ± 9.96	8.94 ± 2.60	27.00 ± 5.34	32.79 ± 8.13
TOTAL	**100.00**	**100.00**	**100.00**	**100.00**
	% overweight of fiber (% owf)			
TOTAL EXTRACTED	**0.3630 ± 0.1840**	**1.3600 ± 1.2620**	**2.5850 ± 0.3860**	**3.1640 ± 0.6170**
ECOL	0.0966 ± 0.0529	0.4517 ± 0.4129	0.0896 ± 0.0184	0.1494 ± 0.0619
FFA	0.0384 ± 0.0347	0.3263 ± 0.4024	0.8378 ± 0.2030	1.089 ± 0.6083
CHOL	0.0014 ± 0.0035	0.0441 ± 0.0296	0.1242 ± 0.0618	0.1099 ± 0.297
Cer	0.0246 ± 0.0316	0.0777 ± 0.0707	0.3995 ± 0.1519	0.7049 ± 0.4727
TOTAL ANALIZED	**0.1610 ± 0.1038**	**0.8998 ± 0.8988**	**1.4511 ± 0.3554**	**2.0533 ± 1.0257**

ECOL: cholesterol esters; FFA: free fatty acids; CHOL: cholesterol; Cer: ceramides.

From the amount of total extracted lipids (% over weight of fiber), a lower amount of external lipids relative to the internal ones can be observed in Table 2. For the CP3 hair, it accounts for about 0.4% owf being similar for the different batches, whereas for the CP2

(Asian population) hair fibers, it accounts for a statistically different 1.4% owf being quite different depending on the batch. The internal lipid extraction is more similar between batches and accounts for 2.6% owf for the CP3 and 3.2% owf for the CP2 hair fibers.

Lipid profiles are very different for external and internal lipid extracts. External lipids are mainly composed of hydrophobic compounds, with cholesterol esters (60–65% ota (over total analyzed)) and free fatty acids (20–25% ota) being the most abundant compounds. However, internal lipids are mainly composed of less hydrophobic compounds, with FFA (52–58% ota) and polar lipids rich in ceramides (27–33% ota) being the most abundant. However, it is important to mention the great similarity between most lipid families in both the external and internal CP3 and CP2 hair type extracts. For the external lipid extracts, the amount found for all compounds over the total analyzed are statistically similar, which indicates a very similar proportion between lipids in the CP3 and CP2 hair extracts. However, due to the greater amount of extracted lipids from CP2 fiber, there are statistically significant differences in the amount of cholesterol ester and the amount of free fatty acids (the main lipids of the external extraction). For the internal lipid extracts, the only statistically significant differences were found for ceramides, which are present in a larger amount in the CP2 hair type extract (Figure 2).

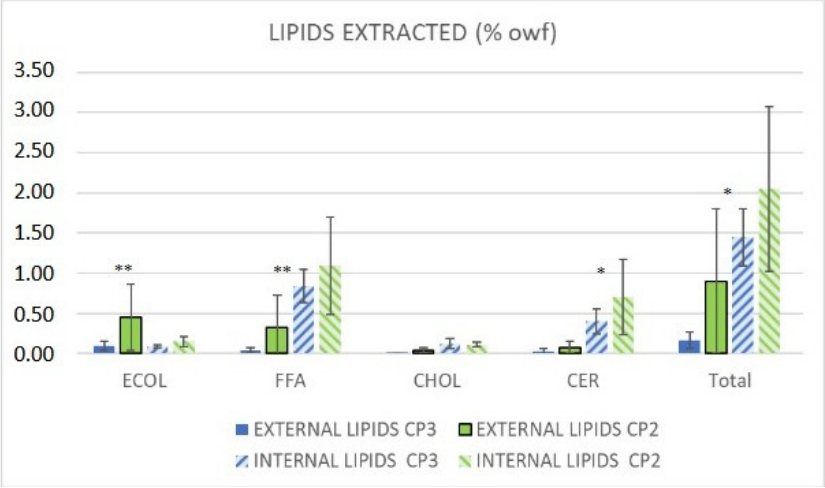


Figure 2. Representation of mean CP3 and CP2 external and internal lipids (% owf, over weight of fiber). ECOL: cholesterol esters; FFA: free fatty acids; CHOL: cholesterol; Cer: ceramides. * Significant difference between CP3 (Caucasian) and CP2 (Asian) at 90% confidence level. ** Significant difference between CP3 (Caucasian) and CP2 (Asian) at 95% confidence level.

The CP2 fibers were therefore found to have a significantly higher amount of extracted internal and, in particular, external lipids compared with the ones obtained for the CP3 hair fibers. This higher amount of external lipids was found to be mainly composed of cholesterol ester and free fatty acids, despite the similar proportion between lipids in the extract in the two hair types. The higher amount of internal lipids is mainly due to the greater amount of polar lipids (ceramides) on the CP2 (Asian population) hair fiber extracts.

In previous works [9,20], Asian hair fibers presented much higher amounts of polar lipids (ceramides) compared to Caucasian hair. Although differences in ceramide content according to ethnicity are not extensively studied in hair fibers, they are well studied in skin. Asian skin is reported to have ceramide levels similar to those of Caucasian skin, but always much higher than those of Black skin [31–33]. This is consistent with reports in the literature that ceramide levels were highest in Asians populations and lowest in Black populations [34]. Moreover, Sugino et al. [35] reported the amount of ceramides in different ethnic groups (in decreasing order): Asians > Hispanics > Caucasians

> Blacks. In addition, statistically significant differences were found between ethnicities in the ceramide/cholesterol ratio, with Asians having the highest ratio, white-skinned individuals having intermediate values and Africans having the lowest values [36]. It is therefore not surprising that, similarly to the amount of lipids present in the skin, more ceramides are found in Asian hair compared to Caucasian hair.

As discussed in the Introduction section, the role of lipids in maintaining adequate water permeability is not clearly established. Changes in the lipid quantity, quality or composition could modulate the dynamics of water in hair fiber. However, unlike skin, the removal of lipids did not have such a high impact on water exchange kinetics. The role of lipids in hair fiber is therefore studied here by evaluating the moisture content and vapor sorption behavior of virgin and both external and internal lipids extracted from CP3 and CP2 dark-base hair fibers.

Moisture results for CP3 and CP2 virgin fibers evaluated at 23 ± 2 °C and 50 ± 5% RH indicate a moisture percentage of around 11% for CP3 and 10% for CP2 hair (Table 3). Moreover, the DVS study indicates a maximum regain of about 25% for CP3 and around 23% for CP2 hair at 95% of RH, with a statistically significant difference (Figure 3). Mean values indicate lower water absorption for the CP2 samples at all humidities relative to the CP3 ones (Figure 4A), which could be related to the higher amounts of lipids found in the different external and internal extractions. The presence of a greater amount of lipids and potentially their better structuring could be the reasons for a lower amount of water absorbed in the CP2 hair fibers.

Table 3. Mean of moisture and DVS parameters of virgin, external lipid-extracted (E) and internal lipid-extracted (I) CP3 and CP2 dark-base hairs from Caucasian and Asian populations, respectively.

	Virgin CP3	**External Lipid-Extracted CP3**	**Internal Lipid-Extracted CP3**	**Virgin CP2**	**External Lipid-Extracted CP2**	**Internal Lipid-Extracted CP2**
Moisture 50% RH	10.9 ± 0.7	10.9 ± 0.9	11.0 ± 1.0	10.0 ± 1.2	10.3 ± 0.9	10.9 ± 0.7
Regain at 95% RH (%)	25.55 ± 0.52 *	24.63 ± 0.63	25.40 ± 0.33	23.10 ± 1.34 *	23.65 ± 0.37	25.07 ± 0.94 ***
Wm (%)	0.086 ± 0.003	0.078 ± 0.002 **	0.086 ± 0.001	0.081 ± 0.004	0.073 ± 0.005 ***	0.087 ± 0.002
Cg	5.40 ± 0.04 *	6.18 ± 0.27 **	5.45 ± 0.06	5.14 ± 0.14 *	6.11 ± 0.39 ***	5.25 ± 0.21
K	0.699 ± 0.005	0.722 ± 0.012 **	0.706 ± 0.009	0.689 ± 0.019	0.736 ± 0.019 ***	0.704 ± 0.006
R^2	0.999 ± 0.000	0.999 ± 0.001	0.999 ± 0.000	0.999 ± 0.000	0.999 ± 0.001	0.999 ± 0.000
D_a Absorption ($min^{-1} \times 10^{-3}$)	0.0250 ± 0.0072	0.0235 ± 0.0077	0.0222 ± 0.0068	0.0254 ± 0.0112	0.0232 ± 0.0084	0.0215 ± 0.0074
D_a Desorption ($min^{-1} \times 10^{-3}$)	0.0293 * ± 0.0001	0.0274 ± 0.0012	0.0264 ± 0.0002	0.0323 * ± 0.0039	0.0277 ± 0.0013	0.0260 ± 0.0022 ***

* Significant difference between CP3 and CP2 (virgin hairs) at 95% of confidence level. ** Significant difference between CP3 hairs (virgin and extracted hairs) at 95% of confidence level. *** Significant difference between CP2 hairs (virgin and extracted hairs) at 95% of confidence level.

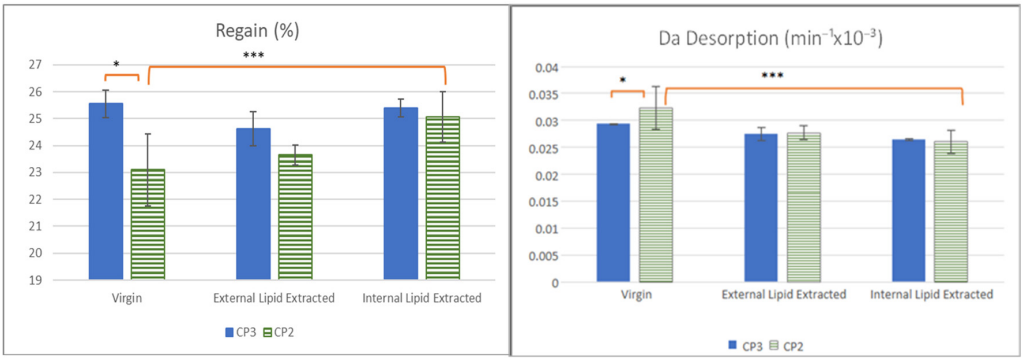


Figure 3. Mean amount of absorbed water at 95% RH and diffusion in desorption for virgin, external lipid-extracted and internal lipid-extracted CP3 and CP2 dark-base hairs. * Significant difference between CP3 and CP2 (Virgin hairs) at 95% of confidence level. *** Significant difference between CP2 hairs (Virgin and extracted hairs) at 95% of confidence level.

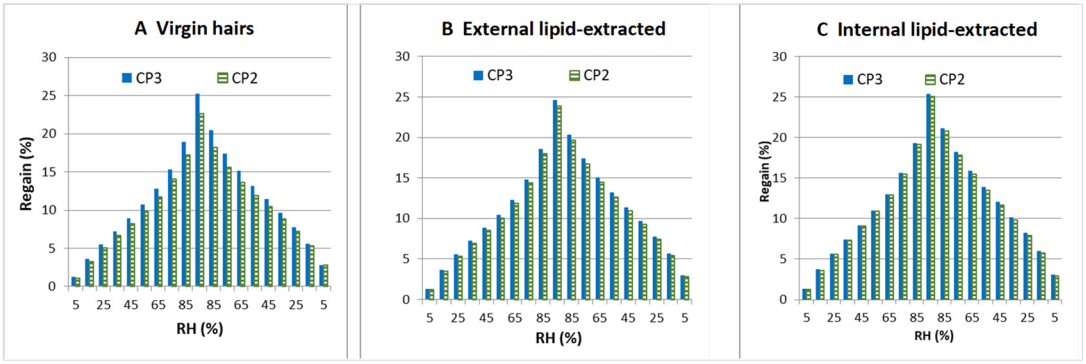


Figure 4. Amount of absorbed and desorbed water (regain) of virgin (**A**), external lipid-extracted (**B**) and internal lipid-extracted (**C**) CP3 and CP2 dark-base hairs from Caucasian and Asian populations, respectively.

A higher water content in hair overwhelmingly leads to considerably diminished sensorial properties [37] such as frizz and hair volume control. An explanation for these findings likely relies upon the ability of water to induce swelling in hair fibers, where a higher water content produces increased swelling, slight uplifting of the cuticle scales and a rougher feel. It is therefore very likely that reducing the moisture content of hair may be more desirable. A previous study [38] reported a low impact of humidity on ratings of frizziness for straight hair, while curly hair was found to be more susceptible than straight hair to perceivable changes in texture due to humidity-induced swelling [38].

It is difficult to accurately compare the rate of diffusion between CP3 and CP2 hairs. Although a higher diffusion of mean values was obtained for CP2 virgin hairs (statistically significant in the desorption process) (Table 3 and Figure 3), lower diffusion was obtained at low humidity and higher diffusion at high humidity for CP2 hairs (Figure 5). It can therefore be summarized from the DVS study of virgin fibers that the lower water regain for all the CP2 samples at all humidity levels and the different diffusion behavior were dependent on the humidity, with lower diffusion obtained at low humidity and higher diffusion at high humidity for CP2 hairs.

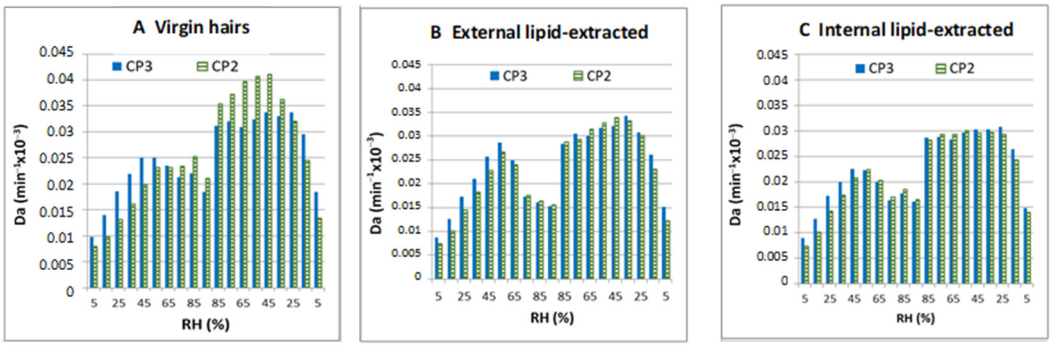


Figure 5. Apparent water diffusion coefficient (D_a) of virgin (**A**), external lipid-extracted (**B**) and internal lipid-extracted (**C**) CP3 and CP2 dark-base hairs from Caucasian and Asian populations, respectively, at the absorption and desorption process.

The effects of external and internal lipid extraction of the two kinds of fibers are detailed in Table 3 and can also be visualized in Figure 3. The observed moisture content in lipid-depleted fibers indicates that only the moisture content of CP2 fibers is increased following external and, moreover, internal lipid extraction of CP2 hairs (Table 3 and Figure 3). It seems that the lower amount of lipids in the CP2 fibers and the higher lipid disorder facilitate water penetration into the fibers leading to a higher moisture content. This is in accordance with the

more precise DVS results: the values of regain at 95% HR and the monolayer moisture content (Wm) present in the virgin hairs are always higher for the CP3 fibers than CP2 ones, with these values being statistically diminished for the external lipid-extracted fibers and increased via internal lipid extraction to reach similar values for the two totally lipid-depleted fibers (Table 3 and Figure 3). It is important to highlight the different roles of external and internal lipids in the amount of water absorbed. The extraction of the external lipids statistically decreases the amount of water, especially Wm, and increases the two energy constants Cg and K, indicating a lower water content in the monolayer and better fixation into the fiber, while the subsequent extraction of the internal lipids causes an opposite effect for the two types of fibers (Table 3).

A recent work states that most of the water that permeates the CMC creates 40 Å-sized clusters the form strong hydrogen bonds [39]. When the lipids from the CMC are partially removed, the clatharate-like cluster is naturally reduced, which could be the reason for the lower amount of absorbed water with high bonding energy of the external lipid-extracted fibers. Depending on the polar lipids and the degree of swelling in the cuticle CMC, the water forms transient microscopic "semi-ordered clatharate-like clusters" on the surface of the δ-layer arising from strengthened water hydrogen bonding, so-called hydrophobic hydration [39]. The formation of these water clusters following internal lipid depletion could be the reason for the increase in water content, mainly in the significant amount of internal lipid-extracted CP2 fibers.

In addition, the observed diffusion coefficient (Da) and Da Desorption results (Table 3, Figures 3 and 5B,C) indicate that permeability was diminished in both types of fibers after lipid extraction but more pronounced for CP2 fibers, resulting in fibers with similarly low water-diffusion properties. Contrary to the expected results, diffusion values indicate that following external and, moreover, total lipid extraction, the rate of water penetration has been slowed down. Similar results for the diminution of diffusion were obtained for delipidized hair fibers compared with other keratins [12,40]. Other authors [41] reported that the overall rate of diffusion into keratinized fibers is controlled by two factors: diffusion of water molecules through the cell membrane complex (CMC) and diffusion into the cortical cells. The latter process involves swelling of the cell, which constricts the CMC and reduces the rate of diffusion through these channels. Therefore, the increase in moisture due to lipid depletion could constrict the CMC and reduce the rate of diffusion.

Furthermore, water diffusion could be related to the amount of lipids and their order. There is a clear decrease in diffusion after lipid extraction, which could facilitate the formation of large water clusters in the place of the removed lipids. The extensive ordering of water molecules in the hydration phase of hydrophobic molecules is due to van der Waals attraction between hydrophobic C-based molecules and water O atoms [42]. Water diffusion of these water clusters from lipid-depleted fibers could be reduced because water molecules in the vicinity of a hydrophobic solute form stronger and more tethahedrally oriented hydrogen bonds than those in bulk water and their mobility is restricted [43].

Therefore, virgin CP2 hair presents clearly lower water content with higher water diffusion than CP3 hair. Lipid extraction tends to modify water content, mainly increasing after internal lipid extraction and clearly decreasing diffusion of CP2 fibers (mainly), leading to a more hydrated and less permeable lipid-depleted fiber. Critically, the differences in the water content and diffusion of the two virgin fibers disappeared after total lipid extraction, indicating that the difference in behavior when faced with water is mainly due to the content and structure of the lipid.

We performed an ATR-FTIR evaluation of the virgin fibers and both the external and internal lipid-extracted fibers for the CP3 and CP2 fibers to discern the possible differences between the different types of hair fibers due to their different compositions

and forms of structural lipid organization. The bands associated with the alkyl chain vibrations of the lipid fraction of the hair were studied, particularly the CH2 stretching bands, approximately 2920 (asymmetric) and 2850 cm^{-1} (symmetric)). For both peaks, a shift to higher wavenumbers indicated an increase in lipid disorder. The 2850 cm^{-1} peak was most susceptible to packing changes; a peak below 2850 cm^{-1} is indicative of the presence of an orthorhombic (OR) chain lipid conformation, whereas a maximum between 2850 and 2852 cm^{-1} is produced by a hexagonal (HEX) chain conformation, and a liquid crystalline (LIQ) chain conformation results in a maximum at a wavenumber higher than 2852 cm^{-1} [30,44,45]. Shifts in the asymmetric peak at 2820 cm^{-1} are more imprecise but useful for corroborating the symmetric peak at 2850 cm^{-1}. This technique can be used to determine lipid order disposition by studying the frequency and integration of the CH2 asymmetric stretching mode; it is also quite reliable for determining lipid content. Therefore, the frequency and absorbance of CH2 symmetric and asymmetric stretch peaks were determined for the six kinds of fibers by evaluating virgin, external lipid-extracted, and internal lipid-extracted fibers from CP3 and CP2 hairs. All values are expressed in Table 4, and wave numbers are presented in Figure 6.

Table 4. Average frequency and absorbance of the CH2 asymmetric and symmetric stretching vibrations of lipids present in virgin, external lipid-extracted, and internal lipid-extracted CP3 and CP2 dark-base hairs from Caucasian and Asian populations, respectively.

	CP3			CP2		
	Virgin	**External Lipids Extracted**	**Internal Lipids Extracted**	**Virgin**	**External Lipids Extracted**	**Internal Lipids Extracted**
			Absorbance a.u.			
CH_2 Asym. str.	0.130 ± 0.003	0.132 ± 0.017	0.130 ± 0.002	0.131 ± 0.044	0.114 ± 0.008	0.118 ± 0.007
CH_2 Sym. str.	0.098 ± 0.003	0.097 ± 0.020	0.116 ± 0.007	0.097 ± 0.034	0.088 ± 0.008	0.084 ± 0.010
			Frequency λ (cm^{-1})			
CH_2 Asym. str.	2925.2 ± 3.8	2928.1 ± 1.6	2929.7 ± 0.8	2923.6 ± 3.9	2928.5 ± 1.5	2929.9 ± 1.0
CH_2 Sym. str.	2852.7 ± 1.5	2854.3 ± 1.3	2854.5 ± 3.1	2852.1 ± 1.6	2857.0 ± 1.0	2855.4 ± 1.5

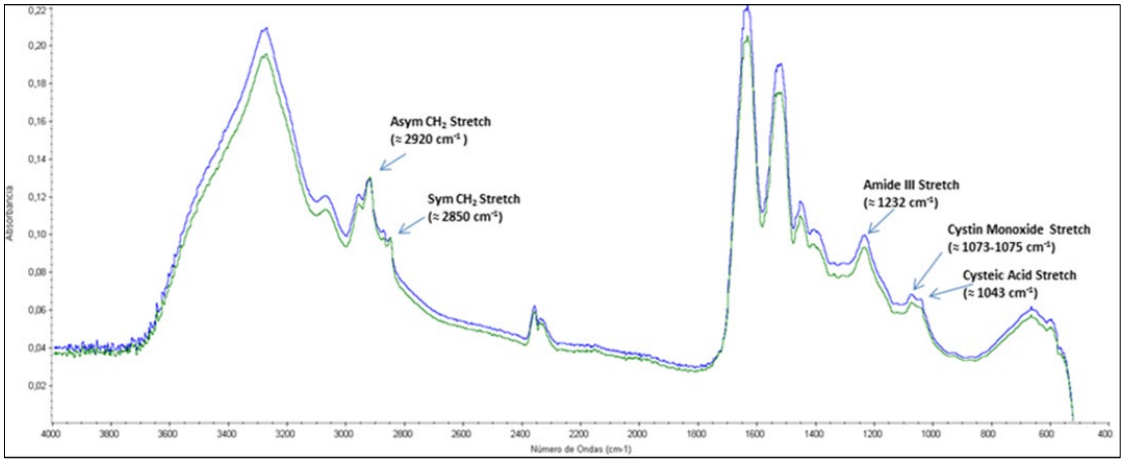


Figure 6. Examples of the ATR-FTIR spectra for Asian CP2 (green) and Caucasian CP3 (blue) hair.

The IR spectroscopic analysis of the lipid fraction of the two kinds of virgin hair showed very similar absorbance, indicating very similar quantities of lipids for the two types. However, there was a higher wavelength for the virgin CP3 fibers than for the virgin CP2 ones, indicating that the lipid structure of the CP3 fibers is more disordered, and therefore higher diffusion of water, dyes, and other actives was expected.

The previous DVS evaluation indicated this higher water diffusion for CP3 fibers only at low humidity steps. Therefore, to confirm this postulation, an IR spectroscopic analysis of the lipid fraction at different humidity levels was performed to understand the different diffusion behaviors of the two fibers in relation to humidity [46]. The results indicate that humidity strongly influences the frequency of lipid peaks mainly for CP3 fibers. An increase in humidity promotes a decrease in frequency. Therefore, it seems that lipids are better structured in a more humid environment. This change is much more marked for the CP3 hair [46]. Therefore, the higher water diffusion for CP3 hair at low humidities can be related to the severe lipid disorder under these conditions, and the lower water diffusion of CP3 hair at high humidities can be related to the much greater extent of lipid order under these conditions. The changes in the CP2 fibers follow the same tendency, while the changes due to humidity are not so marked. Clearly, the properties of CP3 hair are much more dependent on humidity than CP2 hair. Therefore, it can be concluded that ambient conditions have a great influence on the lipid and protein structures of hair, with this influence being much more acute for CP3 than for CP2 hair. To the best of our knowledge, the influence of humidity on the lipid structure of hair has not been previously studied and could be essential to understand the permeation of this fiber and its diffusion properties.

External and internal lipid fiber extracts were also evaluated in duplicate for the six types of fibers. The mean results of frequency and absorbance for the external lipid-extracted fibers indicated that for both peaks, the frequency increased significantly, which means an increase in lipid disorder, with this increase being more prominent for the CP2 hair fibers, leading to even higher frequencies than the CP3 ones. The absorbance and the quantity of lipids that were similar for the two virgin fibers mainly decreased for the CP3 fibers. The mean results of frequency and absorbance for the internal lipid-extracted fibers indicated that the frequency increased mainly for the asymmetric stretching peak, leading to higher frequencies for the CP2 fibers than for the CP3 ones. The absorbance, or the quantity of lipids that were similar, for the two virgin fibers also decreased, particularly for the CP3 fibers.

Based on all the ATR-FTIR results, it can be concluded that there are similar amounts of lipids in the virgin hairs of Caucasians and Asians, being a facile extraction of external lipids in the case of CP2 hairs. CP2 virgin hair presents a more ordered lipid bilayer and greater lipid depletion, resulting in more disordered bilayers for the two fibers, particularly for CP2 fibers. Therefore, the lipid extraction quantification and FTIR-ATR results indicate that the higher quantity of lipids extracted from the CP2 fibers was mostly due to the ease of lipid extraction rather than a much higher lipid content. In addition, the more ordered lipid structure of the CP2 fibers becomes more disordered even with external lipid extraction, resulting in greatly disordered fibers after lipid extraction.

4. Conclusions

The results obtained from the study of virgin CP3 and CP2 dark-base hairs from Caucasian and Asian populations, respectively, via DVS and ATR-FTIR indicate that CP2 hair presents lower water regain at all humidity steps, meaning there are different fiber behaviors with higher quantities of lipids, hindering external water penetration and reducing moisture. Moreover, different diffusion behaviors were observed depending on the humidity. CP2 fibers presented lower diffusion at low humidity and higher diffusion at high humidity. ATR-FTIR experiments were performed at different humidity levels to explain this result. Lipids were found to be more structured in a more humid environment, with this change being much more marked for CP3 hair.

In the lipid depletion study, the CP2 fibers presented significantly higher quantities of external lipids (1.4% owf) and internal lipids (3.2% owf) relative to the CP3 fibers (0.4%

owf and 2.6% owf, respectively). This could mean that either the virgin CP2 fibers contain more lipids or that lipids are more easily extracted from CP2 fibers. The external lipids obtained from the CP2 fibers were found to be mainly composed of cholesterol esters and free fatty acids, despite the similar proportions between lipids in the extract of the two types. The greater quantity of internal lipids is mainly due to the greater number of polar lipids (ceramides) in the CP2 extract, which could explain the better-structured bilayer with lower diffusion of CP2 fibers relative to the CP3 fibers.

The lipid extraction quantification and ATR-FTIR results indicate that the greater quantity of lipids extracted from the CP2 fibers is largely due to the ease of lipid extraction rather than a much higher lipid content. In addition, the highly ordered lipid structure of the CP2 fibers becomes more disordered even with external lipid extraction, resulting in a greatly disordered fiber after total lipid extraction. The DVS results indicate that lipid extraction tends to modify water content (decreasing and increasing after external or internal lipid extraction, respectively), clearly decreasing diffusion of CP2 fibers in particular, leading to a more hydrated and less permeable lipid-depleted fiber. The extraction of lipids with a disordered bilayer would support an increase in the water content of the fiber; however, a decrease in the speed of water penetration was found. Similar results were found for hair and wool lipid-depleted fibers. A possible explanation could be a potential swelling of the fiber due to increased water penetration and potential shrinkage of the CMC of the lipid-depleted fibers. Therefore, it can be concluded that CP2 hair has lower moisture with more and more ordered lipids than CP3 hair, with water diffusion being greatly dependent on humidity. More lipids were extracted from CP2 fibers containing a higher quantity of polar lipids. Ceramides are probably the reason for better lipid structuration. Therefore, we can conclude that the difference between CP3 and CP2 hair is not due to the 90% protein content or hair structure organization but rather the lipid fraction, even though it is present in a much smaller proportion. Cosmetic treatments for these two types of fibers must therefore consider their differences in lipid composition and water sorption behavior in order to provide appropriate effectiveness in each case.

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Abbreviations

The following abbreviations are used in this manuscript:

CP2	Curl Pattern type 2
CP3	Curl Pattern type 3
DVS	Dynamic Vapor Sorption
ATR-FTIR	Attenuated total reflectance–Fourier transform infrared
TLC/FID	Thin-layer chromatography–flame ionization detection
CP	Curl Pattern
RH	Relative humidity
GAB	Guggenheim Anderson de Boer
18-MEA	18-methyleicosanoic acid
Ota	Over total amount
Owf	Over total weight of fiber
ECOL	Cholesterol ester
FFA	Free fatty acid
CHOL	Cholesterol
Cer	Ceramides
E	External lipid-extracted
I	Internal lipid-extracted
Wm	Monolayer moisture content
Cg	Guggenheim constant
K	Energy constant
R^2	Correlation coefficient
Da	Apparent diffusion coefficient
CMC	Cell membrane complex
HEX	Hexagonal chain conformation
LIQ	Liquid crystalline chain conformation
Asym. Str.	Asymmetric stretching
Sym. Str.	Symmetric stretching

References

1. Swift, J.A. Fine details on the surface of human hair. *Int. J. Cosmet. Sci.* **1991**, *13*, 143–159. [CrossRef]
2. Coderch, L.; Oliver, M.A.; Martinez, V.; Manich, A.M.; Rubio, L.; Martí, M. Exogenous and endogenous lipids of human hair. *Skin Res. Techol.* **2017**, *23*, 479–485. [CrossRef]
3. Yu, Y.; Yang, W.; Wang, B.; Meyers, M.A. Structure and mechanical behavior of human hair. *Mater. Sci. Eng. C* **2017**, *73*, 152–163. [CrossRef]
4. Kreplak, L.; Briki, F.; Duvault, Y.; Doucet, J.; Merigoux, C.; Leroy, F.; Lévêque, J.L.; Miller, L.; Carr, G.L.; Williams, G.P.; et al. Profiling lipids across Caucasian and Afro-American hair transverse cuts, using synchrotron infrared microspectrometry. *Int. J. Cosmet. Sci.* **2001**, *23*, 369–374. [CrossRef] [PubMed]
5. Bantignies, J.-L.; Fuchs, G.; Carr, G.L.; Williams, G.P.; Lutz, D.; Marull, S. Organic reagent interaction with hair spatially characterized by infrared microspectroscopy using synchrotron radiation. *Int. J. Cosmet. Sci.* **1998**, *20*, 381–394. [CrossRef] [PubMed]
6. Oliver, M.A.; Martí, M.; Coderch, L.; Carrer, V.; Kreuzer, M.; Barba, C. Lipid loses and barrier function modifications of the brown-to white hair transition. *Skin Res. Technol.* **2019**, *25*, 517–525. [CrossRef] [PubMed]
7. Sandt, C.; Borondics, F. A new typology of human hair medullas based on lipid composition analysis by synchrotron FTIR microspectroscopy. *Analyst* **2021**, *146*, 3942–3954. [CrossRef]
8. Csuka, D.A.; Csuka, E.A.; Juhász, M.L.W.; Sharma, A.N.; Mesinkovska, N.A. A systematic review on the lipid composition of human hair. *Int. J. Dermatol.* **2023**, *62*, 404–415. [CrossRef]
9. Martí, M.; Barba, C.; Manich, A.M.; Rubio, L.; Alonso, C.; Coderch, L. The influence of hair lipids in ethnic hair properties. *Int. J. Cosmet. Sci.* **2016**, *38*, 77–84. [CrossRef]
10. Coderch, L.; Alonso, C.; García, M.T.; Pérez, L.; Martí, M. Hair lipid structure: Effect of surfactants. *Cosmetics* **2023**, *10*, 107. [CrossRef]

11. Masukawa, Y.; Narita, H.; Imokawa, G. Characterization of the lipid composition at the proximal root regions of human hair. *J. Cosmet. Sci.* **2005**, *56*, 516–517. [CrossRef]
12. Barba, C.; Martí, M.; Carilla, J.; Manich, A.M.; Coderch, L. Moisture sorption/desorption of protein fibres. *Thermochim. Acta* **2013**, *552*, 70–76. [CrossRef]
13. Ji, J.H.; Park, T.S.; Lee, H.J.; Kim, Y.D.; Pi, L.Q.; Jin, X.H.; Lee, W.S. The ethnic differences of the damage of hair and integral hair lipid after ultra violet radiation. *Ann Dermatol.* **2013**, *25*, 54–60. [CrossRef]
14. Bildstein, L.; Deniset-Besseau, A.; Pasini, I.; Mazilier, C.; Keuong, Y.W.; Dazzi, A.; Baghdalli, N. Discrete Nanoscale Distribution of Hair Lipids Fails to Provide Humidity Resistance. *Anal. Chem* **2020**, *92*, 11498–11504. [CrossRef] [PubMed]
15. Loussouarn, G.; Garcel, A.-L.; Loazano, I.; Collaidin, C.; Porter, C.; Panhard, S.; Saint-Léger, D.; de La Metterie, R. Worldwide diversity of hair curliness: A new method of assessment. *J. Dermatol.* **2007**, *46* (Suppl. 1), 2–6. [CrossRef] [PubMed]
16. Wolfram, L.J. Human hair: A unique physicochemical composite. *J. Am. Acad. Dermatol.* **2003**, *48*, 106–114. [CrossRef]
17. Kamath, Y.K.; Hornby, S.B.; Weigmann, H.D. Mechanical and fractographic behavior of negroid hair. *J. Soc. Cosmet. Chem.* **1984**, *35*, 21–43.
18. Syed, A.; Kuhajda, A.; Ayoub, H.; Ahmad, K.; Frank, E.M. African-American hair: Its physical properties and differences relative to Caucasian hair. *Cosmet. Toil.* **1995**, *110*, 39–48.
19. Franbourg, A.; Hallegot, P.; Baltenneck, F.; Toutain, C.; Leroy, F. Current research on ethnic hair. *J. Am. Acad. Dermatol.* **2003**, *48*, S115–S119. [CrossRef]
20. Barba, C.; Oliver, M.A.; Martí, M.; Kreuzer, M.; Coderch, L. Lipid distribution on ethnic hairs by Fourier transform infrared synchrotron spectroscopy. *Skin Res. Technol.* **2022**, *28*, 75–83. [CrossRef]
21. McMullen, R.L.; Laura, D.; Chen, S.; Koelmel, D.; Zhang, G.; Gillece, T. Determination of physicochemical properties of delipidized hair. *J. Cosmet. Sci.* **2013**, *64*, 355–370.
22. DeLauder, S.F.; Kidwell, D.A. The incorporation of dyes into hair as a model for drug binding. *Forensic Sci. Int.* **2000**, *107*, 93–104. [CrossRef] [PubMed]
23. Takahashi, T.; Hayashi, R.; Okamoto, M.; Inoue, S. Morphology and properties of Asian and Caucasian hair. *J. Cosmet. Sci.* **2006**, *57*, 327–338. [PubMed]
24. Lee, Y.; Kim, Y.-D.; Pi, L.; Lee, S.; Hong, H.; Lee, W. Comparison of hair shaft damage after chemical treatment in Asian, White European, and African hair. *Int. J. Dermatol.* **2014**, *53*, 1103–1110. [CrossRef] [PubMed]
25. Coderch, L.; Oliver, M.A.; Carrer, V.; Manich, A.M.; Martí, M. External lipid function in ethnic hairs. *J. Cosmet. Dermatol.* **2019**, *18*, 1912–1920. [CrossRef]
26. Timmermann, E.O. Multilayer sorption parameter: BET or GAB values? *Colloids Surf. A Phys. Eng. Asp.* **2003**, *220*, 235–260. [CrossRef]
27. Vickerstaff, T. *The Physical Chemistry of Dyeing*; Oliver and Boyd: London, UK, 1954.
28. Jones, L.N.; River, D.E. 18-Methyleicosanoic acid in the structure and formation of mammalian hair fibres. *Micron* **1997**, *28*, 469–485. [CrossRef]
29. Coderch, L.; Méndez, S.; Barba, C.; Pons, R.; Martí, M.; Parra, J.L. Lamellar rearrangement of internal lipids from human hair. *Chem. Phys. Lipids* **2008**, *155*, 1–6. [CrossRef]
30. Nishimura, K.; Nishino, I.; Inaoka, Y.; Kitada, Y.; Fukushima, M. Interrelationship between the hair lipids and the hair moisture. *Nippon Koshohin Kagakkaishi* **1989**, *13*, 134–139.
31. Rawlings, A.V. Ethnic skin types: Are there differences in skin structure and function? *Int. J. Cosmet. Sci.* **2006**, *28*, 79–93. [CrossRef]
32. Hellemans, L.; Muizzuddin, N.; Declercq, L.; Maes, D. Characterization of stratum corneum properties in human subjects from a different genetic background. *J. Investig. Dermatol.* **2005**, *124*, 371.
33. Muizzuddin, N.; Hellemans, L.; Van Overloop, L.; Corstjens, H.; Declercq, L.; Maes, D. Structural and functional differences in barrier properties of African American, Caucasian and East Asian skin. *J. Dermatol. Sci.* **2010**, *59*, 123–128. [CrossRef]
34. Richards, G.M.; Oresajo, C.O.; Halder, R.M. Structure and function of ethnic skin and hair. *Dermatol. Clin.* **2003**, *21*, 595–600. [CrossRef] [PubMed]
35. Sugino, K.; Imokawa, G.; Maibach, H.I. Ethnic difference of stratum corneum lipid in relation to stratum corneum function. *J. Investig. Dermatol.* **1993**, *100*, 587. [CrossRef]
36. Jungersted, J.M.; Høgh, J.K.; Hellgren, L.I.; Jemec, G.B.E.; Agner, T. Ethnicity and stratum corneum ceramides. *Br. J. Dermatol.* **2010**, *163*, 1169–1173. [CrossRef] [PubMed]
37. Evans, T.; Wickett, R.R. (Eds.) Chapter 10; Adsorption Properties of Hair. In *Practical Modern Hair Science*; Allured Business Media: Carol Stream, IL, USA, 2012.
38. Skedung, L.; Collier, E.S.; Harris, K.L.; Rutland, M.W.; Applebaum, M.; Greaves, A.J.; Luengo, G.S. A Curly Q: Is Frizz a Matter of Friction? *Perception* **2021**, *50*, 728–732. [CrossRef]

39. Ishihara, A.; Tsukamoto, Y.; Inoue, H.; Noda, Y.; Koizumi, S.; Joko, K. Analysis of water distribution in delipidated human hair by small-angle neutron scattering (SANS). *Int. J. Cosmet. Sci.* **2021**, *43*, 653–661. [CrossRef]
40. Barba, C.; Martí, M.; Carilla, J.; Manich, A.M.; Coderch, L. The effect of internal lipids on the water sorption kinetics of keratinized tissues. *J. Therm. Anal. Calorim.* **2016**, *123*, 2013–2020. [CrossRef]
41. Keis, K.; Huemmer, C.I.; Kamath, Y.H. Effect of oil films on moisture vapour absorption on human hair. *J. Cosmet. Sci.* **2007**, *58*, 135–145.
42. Baldwin, R.L. Dynamic hydration shell restores Kauzmann's 1959 explanation of how the hydrophobic factor drives protein folding. *Proc. Natl. Acad. Sci. USA* **2014**, *111*, 13052–13056. [CrossRef]
43. Grdadolnik, J.; Merzel, F.; Avbelj, F. Origin of hydrophobicity and enhanced water hydrogen bond strength near purely hydrophobic solutes. *Proc. Natl. Acad. Sci. USA* **2017**, *114*, 322–327. [CrossRef]
44. Mendelsohn, R.; Flach, C.R.; Moore, D.J. Determination of molecular conformation and permeation in skin via IR spectroscopy, microscopy, and imaging. *Biochim. Biophys. Acta (BBA)-Biomembr.* **2006**, *1758*, 923–933. [CrossRef]
45. Coderch, L.; Lorenzo, R.D.; Mussone, M.; Alonso, C.; Martí, M. The Role of Lipids in the Process of Hair Ageing. *Cosmetics* **2022**, *9*, 124. [CrossRef]
46. Coderch, L.; Alonso, C.; Petitjean, S.; Baghdadli, N.; Martí, M. Influence of Room Humidity and Temperature on Water Permeation and Lipid Structure of Caucasian and Asian Hair Fibers (In Preparation).

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