Novel natural polymer coacervates: Innovative retinol encapsulation for advanced skin-care formulation design

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Abstract

This cross-sectional study explores the development of a new skin care formulation containing retinol, from its encapsulation to its integration into cosmetic matrices. Fungal chitosan (FC), a positively charged polysaccharide derived from fungal sources, and gum arabic (GA) were combined through electrostatic interactions to develop novel vegan complex coacervates of retinol (RET). The physical and chemical characteristics of FCGA-RET particles were analyzed using thermogravimetric analysis, rheological measurements, and morphological examinations. FCGA-RET coacervates of around 50 µm with irregular shapes were obtained with good encapsulation efficiency and yield (73.7% and 83%, respectively). Encapsulation of retinol was shown to increase its thermal stability to 200°C. Liquid coacervates were examined through rheological measurements, highlighting their thixotropic behavior and their ability to withstand high shear stress. Finally, retinol particles were successfully integrated into the oil-in-water emulsion and positively impacted texture and rheological properties without disturbing overall stability. This study emphasizes the potential of novel natural polymers to revolutionize the design of advanced skincare formulations.

Keywords: Complex coacervation; encapsulation; retinol; bio-based polymers; skin-care formulation

1. Introduction.

Retinol, the most biologically active form of vitamin A, has long been recognized for its potential benefits in skin care. This lipophilic compound is known for its ability to thicken the epidermis, stimulate cell and tissue production, and decrease the appearance of wrinkles [1,2]. However, the use of retinol in skin care formulations has been limited due to its low solubility and susceptibility to heat, light, acids, and oxidation [2,3]. Encapsulation techniques have been used increasingly to address these limitations by improving stability and efficacy in skin care formulations [4]. Microencapsulation is a technique consisting of a core (solid, liquid, or gas) entrapped within a polymeric wall that can be permeable, semi-permeable, or impermeable. Microencapsulation involves entrapping a core (solid or liquid) within a polymeric wall that can be permeable or impermeable. Consequently, the active component (core) is shielded from the surrounding environment. Depending on the encapsulation method, properties such as release rate, bioavailability, and stability can be improved. Several studies report the use of microencapsulation techniques for the protection of vitamin A and its derivatives, such as spray drying [5,6], solid lipid nanoparticles (SLN) [4], spray cooling [7] or nanocomplexation [8,9], but rarely delve into the future use of particles in emulsions.

Complex coacervation is a physicochemical technique of microencapsulation involving two oppositely charged polysaccharides that are assembled under specific conditions (pH, ionic strength, temperature, etc.) through electrostatic interactions, resulting in the formation of a coacervate phase that encapsulates the active compound [10]. One of the most studied coacervation systems is the gelatin/gum Arabic system [3]. Junyaprasert *et al.* [11] encapsulated vitamin A palmitate using this system and achieved an encapsulation efficiency of up to 83.4 % by using formaldehyde as a crosslinking agent. However, due to its allergenic and carcinogenic properties, formaldehyde is not suitable for cosmetic purposes according to the Cosmetic Products Regulation No 1123/2009 [12]. Furthermore, since gelatin is derived from animal

sources, it has become imperative to explore alternative options to develop stable and effective systems.

Gum Arabic (GA), derived from *Acacia Senegal*, is a negatively charged polysaccharide known for its high solubility and emulsifying properties [13,14]. Chitosan, on the other hand, is a positively charged polysaccharide obtained by the deacetylation of chitin found in the walls of fungal cells or the shell of crustaceans and possesses various beneficial characteristics such as biocompatibility, antimicrobial activity, film formation ability, and antioxidant properties [15]. In addition to its animal equivalent, fungal chitosan (FC) offers several advantages, including being allergy-friendly and vegan-friendly, having lower molecular weight, being free of heavy metals, and having higher degrees of deacetylation. Reducing the reliance on animal sources makes it a more environmentally friendly option for the design of future skin care formulations [16]. Currently, only a few works have studied the fungal chitosan/gum Arabic system [17,18] and the impact on cosmetic formulations has not been investigated yet. Furthermore, to the best of our knowledge, such a system has never been studied for the encapsulation of retinol.

This cross-sectional study explores the development of a new skincare formulation containing retinol, from its encapsulation to its integration into cosmetic matrices. Thus, innovative non-animal, bio-based complex coacervates of retinol were developed by combining two biobased polymers, fungal chitosan (FC), a positively charged polysaccharide derived from fungal sources, and gum arabic (GA) through electrostatic interactions. Retinol (RET) was dissolved in sweet almond oil (SAO), and the effectiveness of the method was evaluated on the basis of the encapsulation efficiency and yield. Furthermore, the physical and chemical characteristics of FCGA-retinol coacervates were analyzed using thermogravimetric analysis, rheological measurements, and morphological examinations. Then, these coacervates were introduced into direct emulsions for comparison with emulsions containing non-encapsulated retinol under real conditions to assess their impact on texture and stability.

2. Materials and Methods.

2.1. Materials

Fungal chitosan (FC) with degree of deacetylation: 80.9 ± 0.1% determined by conductimetric dosing and average molecular weight: 39 ± 1 kDa was acquired from Kraeber & Co GmbH (Ellerbek, Germany) and Arabic *Senegal* (GA) (average molecular weight: 393 ± 23 kDa was gifted by Alland & Robert (France). Intrinsic viscosity measurements were used to determine the mean molecular weights for both polymers, with Mark-Houwink-Sakurada parameters reported in the literature by Kasaai *et al. (*2007) [19] for chitosan and by Gómez-Díaz *et al.* (2008) [20] and Idris *et al.* (1998) [21] for gum arabic. Glycerol and sweet almond oil (SAO) were obtained from Aromazone (France), xanthan gum from Rhodia (France), glyceryl stearate from Symrise (Germany), and the preservative mixture consisting of benzyl alcohol, dehydroacetic acid, and aqua from Arxada AG (Switzerland). All-trans-retinol (RET) (≥ 95%), hydrochloric acid (HCl), and glacial acetic acid were purchased from Fisher Scientific (USA). Absolute ethanol (EtOH) was purchased from Brabant (France).

2.2. Methods

2.2.1. Preparation of Biopolymer Stock Solutions

Biopolymer stock solutions were prepared by dissolving FC in acetic acid (1% v/v) and GA in deionized water under magnetic stirring for 4 hours at room temperature. Biopolymer solutions were kept overnight at 4°C to ensure complete polymer hydration. The concentrations of the biopolymer solutions were 5% w/w, and 10% w/w respectively.

2.2.2. Preparation of retinol complex coacervates (FCGA-RET)

The FCGA-RET coacervates were prepared at ratio FC:GA 1:4 w/w and pH 4.8 as follows:

1) Retinol was dissolved in sweet almond oil at 2 % w/w with an ultrasonic bath (120W) for 2 min,

2) The oil phase was emulsified in a solution of GA 5 % w/w using a VMI Turbotest (Rayneri, VMI Mixing) equipped with a defloculator operating at 1000 rpm for 10 min,
3) The resulting emulsion was stirred using a T25 digital Ultra-Turrax device (IKA, Freiburg, Germany) at 8000 rpm for 5 min,
4) The FC solution (5 % w/w) was gradually added to the emulsion under magnetic stirring,
5) After 10 min, the entire FCGA-RET solution was diluted and continued magnetic stirring for another 10 min,
6) Finally, pH adjustment to reach optimal levels (4.8), followed by maintaining magnetic stirring for 30 more minutes before allowing the solution to rest undisturbed for 48 h at room temperature,
7) After 48 h, the polymer mixture was filtered through Whatman no. 42 filter paper using a Büchner funnel. Subsequently, liquid coacervates were placed in Petri dishes to freeze-dry for one night (-96°C) to obtain a powder by grinding the frozen coacervates.

The yield of the coacervates formed is defined as the ratio between the total mass of recovered particles (FCGA-RET) and the theoretical mass of solid materials contained in the initial solution (i.e., FC, GA and SAO+RET) (Eq. 1).

$$Yield\ (\%) = \frac{\mathrm{m_{FCGA-RET}}}{\mathrm{m_{FC}} + \mathrm{m_{GA}} + \mathrm{m_{SAO+RET}}} \times 100 \qquad (\mathbf{1})$$

2.2.3. Formulation of retinol emulsions

The retinol emulsions were prepared using a previous direct emulsion (O/W) developed in the laboratory, chosen for its long-term storage stability, and made with natural ingredients. Two formulations were prepared: one with non-encapsulated retinol (OW-RET) and another with FCGA-RET coacervates (OW-FCGA-RET), to study the impact of the coacervates on the emulsion. The composition of OW-RET and OW-FCGA-RET is detailed in **Table I**. A mixture of glyceryl stearate citrate and water was heated to 78°C while mechanically stirred with a defloculator until the surfactant completely dissolved. The oil phase, consisting of sweet almond

oil (and non-encapsulated retinol for OW-RET), was also heated to 78°C and then incorporated into the surfactant solution under continuous stirring (700 rpm) for a duration of 2 minutes. The rotor-stator was then used to form the emulsion at a speed of 9500 rpm for 2 minutes. Subsequently, the emulsion was cooled to 35°C while being continuously stirred using a defloculator. FCGA-RET coacervates (for the OW-FCGA-RET emulsion) were introduced and mixed under continuous stirring for an additional 5 minutes at 700 rpm. Subsequently, xanthan gum was mixed with glycerin and incorporated into the emulsion for 10 minutes under continuous stirring at 700 rpm. Finally, the preservative was added to the emulsion and mixed for an additional duration of 2 minutes. The final emulsions were left at room temperature for one day and then transferred to appropriate containers for storage and further testing. The stability of the emulsions was evaluated by monitoring changes in microstructure, particle size distribution, and rheological properties for 14 days at 40°C.

Table I Detailed composition of the emulsions with nonencapsulated (OW-RET) and encapsulated (OW-FCGA-RET) retinol.

Ingredients (INCI)	Supplier	Fonction	%
Aqua	N.A.	Solvent	QSP 100
Glycerin	AromaZone	Humectant	3,0
Xanthan Gum	Rhodia	Texture agent	0,4
Glyceryl stearate citrate	Symrise	Surfactant	4,0
Prunus Amygdalus Dulcis Oil	AromaZone	Emollient	15,0
Benzyl alcohol, dehydroacetic acid, aqua	Arxada AG	Preservative	1,0
Retinol or FCGA-RET	Fisher Scientific	Antioxidant	0,01 / 1

2.2.4. Active loading and encapsulation efficiency

To evaluate the encapsulation efficiency (EE) and active loading (AL) of FCGA-TOCO, 100 mg of sample were weighed in a plastic tube with 10 mL of EtOH (by triplicate). The solution was placed in an ultrasonic bath (VWR Ultrasonicator) for 10 min at room temperature to extract the encapsulated retinol. The solution was then filtered using a 0.45 µm pore-sized filter in cellulose

acetate. A standard calibration curve (R^2 = 0.999) was used, with the retinol concentration determined by calculating the area under the UV detection peak after separation by LC-UV.

Retinol concentration in coacervates was measured using an Agilent 1200 (Agilent Technologies, Waldbronn, Germany) equipped with a C18 XDB 5 µm 6.6 x 150 mm column and a UV-vis detector Agilent Infinity 1260 VL+. The compound was eluted in a mobile phase milliQ water/MeOH at ratio 5/95 in isocratic mode at a flow rate of 1 mL/min. The column temperature was maintained at 40 °C and the detection wavelength was 325 nm. The elution time of retinol was 3.1 min. Encapsulation efficiency (EE) was calculated as the relationship between the experimental concentration and the theoretical concentration of retinol in the coacervates (Eq. 2):

$$\mathrm{EE}\ (\%) = \frac{[\mathrm{retinol}]_{\mathrm{exp}}}{[\mathrm{retinol}]_{\mathrm{ini}}} \times 100 \qquad (2)$$

2.2.5. Optical microscopy observations

The emulsions and FCGA-RET microstructure were examined using an optical microscope (ECLIPSE Ni-U, Nikon) equipped with a camera under bright light. The images obtained were analyzed using Nikon software (NIS Element Viewer).

2.2.6. Particle Size Distribution

The particle size distribution of FCGA-RET and emulsions was analyzed using static light scattering with a SALD-7500 nano laser diffraction particle size analyzer from Shimadzu Co., Ltd., Japan, which is equipped with a violet semiconductor laser (405 nm) and a reverse Fourier optical system. Before measurement, samples were diluted in deionized water to achieve an absorption parameter of 0.2. During the measurements, the samples were stirred in the batch cell to ensure homogeneity. For each product, three samples were collected and analyzed, and the measurements were performed in triplicate for each sample. Data analysis was performed using Wind SALD II software.

2.2.7. Rheological Measurements

The rheological properties of the liquid coacervates and emulsions were determined by continuous and oscillatory measurements, using a hybrid DHR-2 rheometer (TA Instruments, USA) using a plate aluminum geometry with a diameter of 40 mm at 20 °C. Once loaded, the samples were left at rest for 60 s prior to measurement. The flow properties were determined by continuous ramp tests, recording the viscosity value as the shear rate increased from 0.001 to 1000 s^{-1} (logarithmic mode) for 300 s. Oscillatory measurements were conducted at a constant frequency of 1 Hz with increasing strain from 0,01% to 200%, to determine the linear viscoelastic region (LVER). The frequency sweep ramp was performed from 0,01 to 100 Hz at a fixed strain comprised in the linear viscoelastic region of the samples (1%). The storage (G') and loss (G'') moduli were recorded to characterize the viscoelastic properties of the emulsions. Measurements were carried out in duplicate. Finally, the thixotropic properties of the FCGA-RET liquid coacervates were evaluated by stepwise changes in shear rate at 0.01 s^{-1} and 1000 s^{-1}. Each shear rate was maintained for 2 min in a total time frame of 10 min.

2.2.8. Thermal Gravimetric Analysis (TGA) and Moisture Content

The thermal characteristics of the FCGA-RET coacervates were assessed using a Setsys TGA 1200 device by SETARAM, in an air atmosphere with a temperature ranging from 25°C to 600°C at 10°C/min. Moisture content was determined by measuring weight loss at a temperature of 150 °C.

2.2.9. Texture Analysis of Emulsions

The consistency of OW-RET and OW-FCGA-RET emulsions was analyzed using a TA.XT Plus texture analyzer (Stable Micro Systems, Cardiff, UK). Compression tests were conducted at room temperature. A 1 mL volume of sample was placed on the apparatus base and compressed by a cylindrical P/35 probe (35 mm diameter, aluminum) at a constant speed of 1mm/s before returning to its starting position. For each test, the curve force = f(time) was recorded and several

parameters were collected: the minimal and maximal forces (g) and the positive and negative areas (g/s).

2.2.10. Storage Stability of Emulsions

OW-RET and OW-FCGA-RET emulsions were stored in closed containers at 40°C for 14 days. Their stability was assessed by particle size analysis, optical microscopy observations, and frequency sweep tests.

2.2.11. Statistical Analysis

All analyses were carried out at least in duplicate. The results are displayed as mean ± standard deviation (SD).

3. Results.

3.1. Production and Characterization of Coacervates

FCGA-RET coacervates were produced by complex coacervation using a mixture of FC and GA in a 1:4 (w/w) ratio at pH 4.8. The core, which consists of a solution of 2%w retinol in SAO, was introduced at a ratio of FCGA: core 1:1 (w/w). The core, containing a 2%w solution of retinol in SAO, was added at an FCGA to core ratio of 1:1 (w/w). Process parameters were selected based on previous research findings. The particles were then characterized before and after the coacervation process, with their properties detailed in **Table II**.

Table II Characteristics of retinol coacervates (FCGA-RET) prepared by complex coacervation.

Yield (%)	Active loading (%)	Encapsulation efficiency (%)	Moisture content (%)
83	0.88 ± 0.01	73.7 ± 0.8	2.9 ± 0.2

After the process, 83% of the FCGA-RET solid coacervates were recovered by freeze-drying and contained 0.88% RET and had a moisture content of 2.9%. The encapsulation efficiency,

reflecting the amount of effectively encapsulated RET compared to the initial amount introduced, was 73.7%.

3.1.1. Morphology and particle size of coacervates

Figure 1 Observation of the gum arabic-retinol (GA-RET) emulsion and fungal chitosan-gum arabic (FCGA) coacervates by optical microscopy and their corresponding particle size distribution (in volume).**Figure 1** and **Table III** present the evolution of the morphology and particle size of particles before and after the coacervation process.

Table III Particle size of the gum arabic-retinol (GA-RET) emulsion and fungal chitosan-gum arabic (FCGA) coacervates (in volume).

Name	Mean Value (µm)	D10 (µm)	D50 (µm)	D90 (µm)
GA-RET	8.5 ± 1.1	2.5 ± 1.2	10.8 ± 0.9	23.0 ± 0.7
FCGA-RET	48.3 ± 1.7	17.9 ± 0.3	52.6 ± 1.4	132.4 ± 4.8

After emulsifying the oil phase (2%w retinol in SAO) in the GA solution, two droplet populations with a mean diameter of 8.5 µm were observed. Subsequently, optical microscopy revealed that coacervates formed irregular shapes around the oil droplets during the complex coacervation process. The FCGA-RET coacervates exhibited a polydisperse distribution with an average diameter of 48.3 µm.

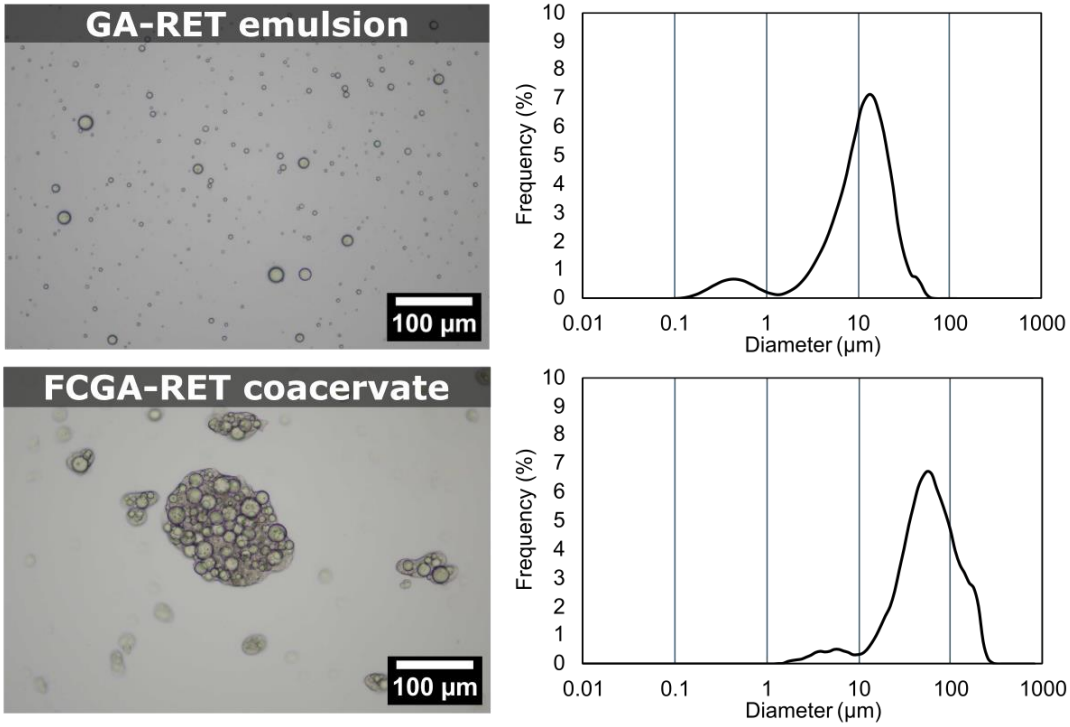

Figure 1 Observation of the gum arabic-retinol (GA-RET) emulsion and fungal chitosan-gum arabic (FCGA) coacervates by optical microscopy and their corresponding particle size distribution (in volume).

3.1.2. Rheology Measurements

The rheological properties of liquid FCGA-RET coacervates were assessed through continuous and oscillatory measurements. **Figure 2** shows the variations in flow behavior (a), thixotropic response (b), and oscillatory dynamics (c, d) of the generated coacervates. They exhibited shear thinning behavior with increasing shear rates of up to 1000 s^{-1}. At shear rates greater than 100 s^{-1}, a drop-in viscosity was observed, indicating structural breakdown occurring under these conditions. However, as illustrated in **Figure 2b,** FCGA-RET were subjected to alternating high and low shear rate cycles and were able to recover their original structure. This suggests that the alteration in structure witnessed at high shear rates is reversible, implying an easy reforming of electrostatic interactions within FCGA-RET coacervates.

Figure 2c shows the linear viscoelastic region (LVER) at 1 Hz, indicating the range of strain where oscillations are sufficiently weak to avoid impacting the sample's structure and thus

reflecting its ability to deform. The LVER remains linear for deformations below 7%, with G" surpassing G', signifying that coacervates essentially behave like a viscoelastic liquid.

Frequency sweep tests were conducted to evaluate the behavior of FCGA-RET coacervates according to the stress time. **Figure 2d** represents the evolution of modulus G' and G" depending on the angular frequency. At lower frequencies, G" exceeds G', indicating a liquid viscoelastic behavior in the coacervates. As the frequency is increased (to 0.15 rad/s), the curves for G' and G" intersect, with G' surpassing G", signifying a shift towards a more solid viscoelastic nature in the coacervates. At the point of intersection between the two curves, the opposite of the frequency is related to the material's relaxation time, corresponding to 42 s for FCGA-RET coacervates.

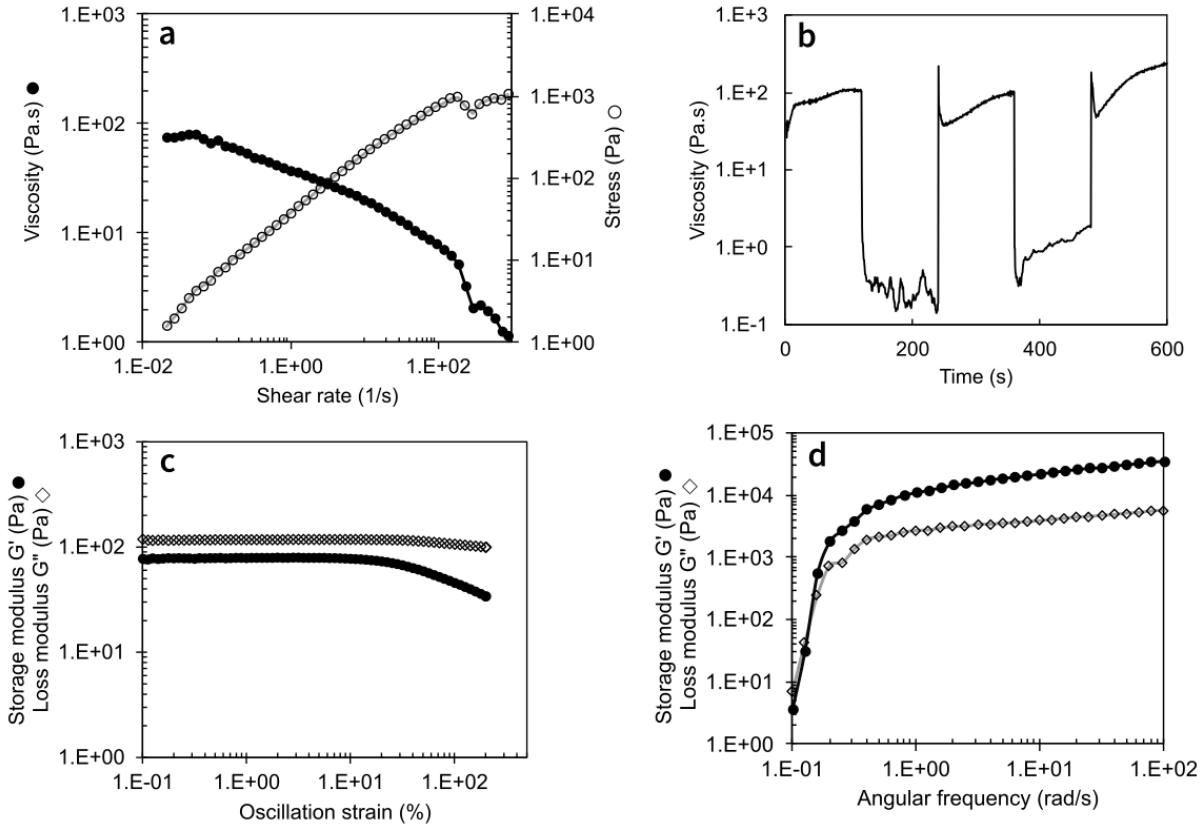

Figure 2 Analysis of the rheology of the retinol coacervates (FCGA-RET): flow test (a), evaluation of the thixotropy properties (b), deformation test (c), and frequency sweep test (d).

3.1.3. Thermogravimetric Analysis (TGA) and Moisture Content

The thermo-oxidative stability of FCGA-RET coacervates and pure RET was evaluated by performing TGA analysis in an air atmosphere from 25 to 600°C. The moisture content was determined by measuring the mass loss at 150 °C. The corresponding thermograms are presented in **Figure 3**.

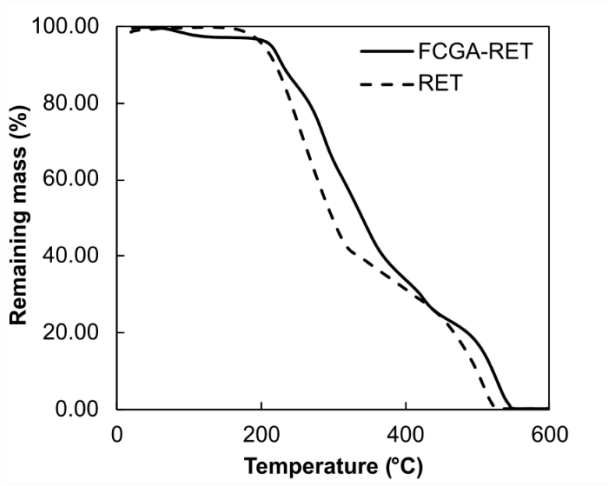

Figure 3 Thermal degradation profile of retinol (RET) and retinol coacervates (FCGA-RET)

Retinol demonstrated greater stability when enclosed within FCGA coacervates, with the initial degradation occurring at a higher temperature of 200°C compared to 160°C in its unencapsulated form. Furthermore, at 320°C, only 43% of RET was degraded as opposed to 67% for FCGA-RET. These findings suggest that encapsulation effectively enhances the resistance of RET to both high temperatures and oxidation within FCGA coacervates.

3.2. Characterization of Retinol Emulsions

Two direct emulsions (O/W) with non-encapsulated retinol (OW-RET) and with retinol coacervates (OW-FCGA-RET) were prepared. After 24 hours at room temperature, particle size distributions, microstructure, and rheological properties were evaluated.

3.2.1. Microstructural Characterization of Emulsions

The granulometry of the emulsions was determined by SLS to assess the impact of the addition of coacervates on their distribution and microstructure. The results presented in **Figure 4** showed that both emulsions have a multimodal distribution with a mean diameter of 3.6 µm for OW-RET and 6.4 µm for OW-FCGA-RET the latter having a higher number of large particles in the range of 10-100 µm. This population of particles may be due to the initial droplet of RET/SAO incorporated in coacervates and to the size of the coacervates themselves.

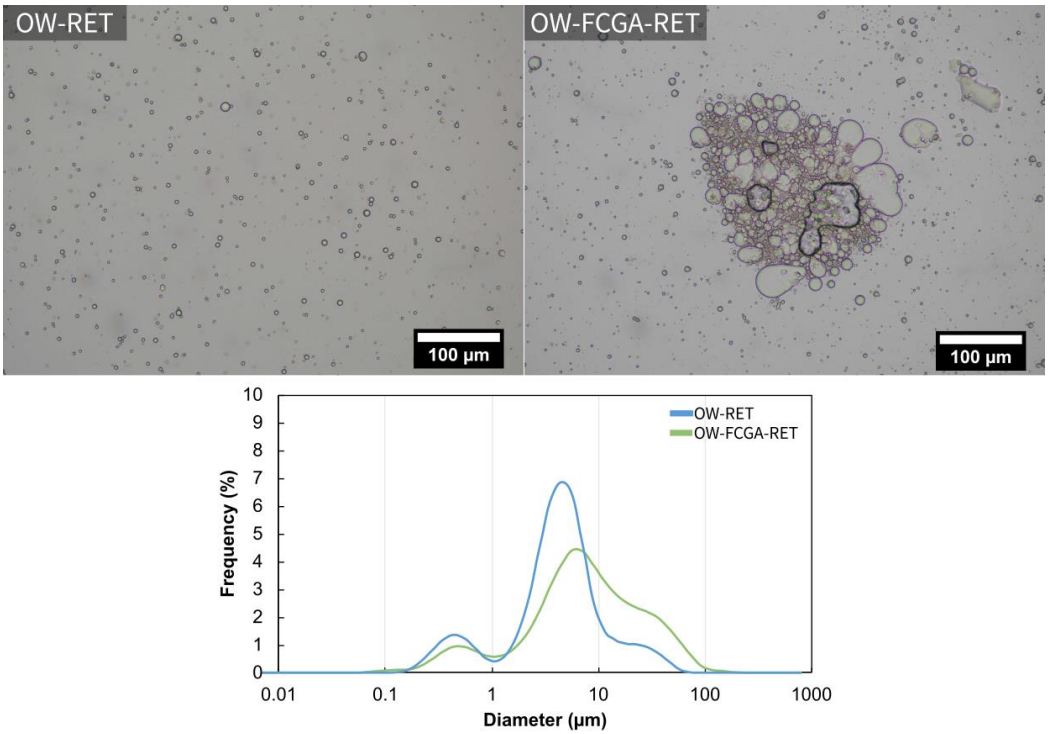

Figure 4 Optical microscopy observations and particle size distributions of nonencapsulated (OW-RET) and encapsulated (OW-FCGA-RET) retinol emulsions

3.2.2. Macrostructural Characterization of Emulsions

The rheological properties of the emulsions were determined by rheology measurements and the results are shown in **Figure 5**. The emulsions exhibited a reduction in viscosity under shear stress, with a notably higher viscosity (tenfold increase) observed when coacervates were introduced. Furthermore, the presence of FCGA-RET coacervates affected LVER, leading to a

decrease in critical strain from 1.7% to 0.7%. Under low oscillation strain conditions, the emulsions displayed solid viscoelastic properties until they reached a critical crossover point that decreased from 131% to 19%, after which they transitioned to liquid viscoelastic behavior. Overall moduli were significantly higher for OW-FCGA-RET emulsions because of stronger interactions in the media between the coacervates and the compounds of the formulation.

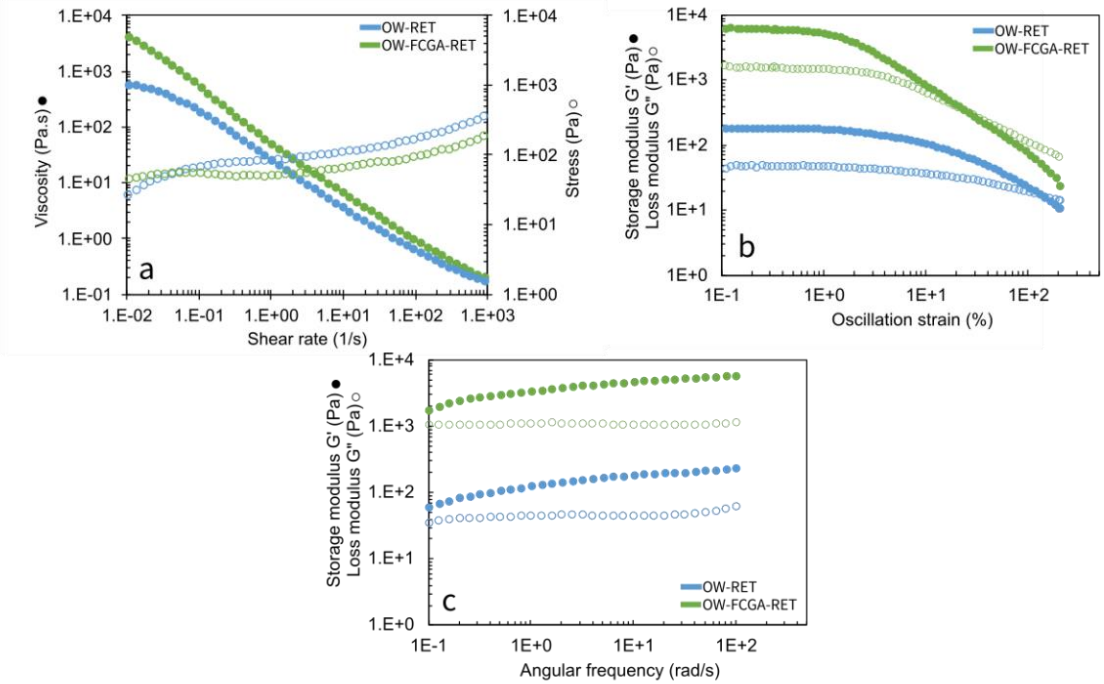

Figure 5 Rheological properties of nonencapsulated (OW-RET) and encapsulated (OW-FCGA-RET) retinol emulsions: flow test (a), deformation test (b), and frequency sweep (c).

Texture analysis was performed by conducting compression tests on emulsions to assess their consistency, cohesiveness, stickiness, and firmness. The introduction of FCGA-RET coacervates in the formulation led to a significant increase in the consistency, firmness, and stickiness of the emulsions, aligning with previously identified rheological properties. The cohesiveness, corresponding to the work of the probe (g/sec) to return to its initial position, was not significantly affected by the presence of coacervates.

3.2.3. Storage Stability of Emulsions

The formulations OW-RET and OW-FCGA-RET were placed in sealed containers and kept at 40°C for 14 days. To evaluate the stability of the emulsions, frequency sweep (**Figure 6**) and particle size analysis (**Figure 7**) were carried out. Despite the observation of a homogeneous appearance of the emulsions, microstructural changes were observed:

The OW-RET emulsions were found to be stable with only slight variations in moduli and particle size. A minor decrease in the storage and loss modulus was observed, correlated with the increase in the larger droplet population with D[90] growing from 13.1 µm to 18.5 µm after 14 days at 40°C. However, in the case of the OW-FCGA-RET emulsions, the microstructure was found to fluctuate during storage with a decrease in storage and loss modulus after 7 days at 40°C followed by an increase after 14 days. An increase in the population of particles around 40 µm was observed over time due to oil droplet aggregation around coacervates that was observed by optical microscopy (not shown). Consequently, it appears that coacervates present in the emulsion alter its microstructure as they interact with oil droplets; this interaction leads to the formation of larger aggregates over time.

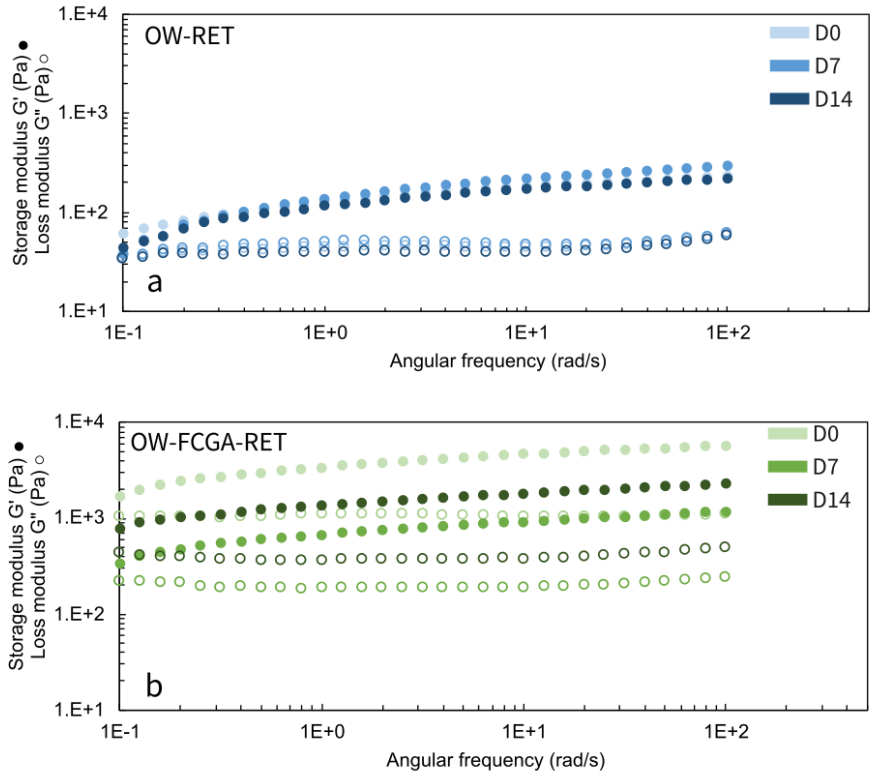

Figure 6 Frequency sweep of (a) non-encapsulated (OW-RET) and (b) encapsulated (OW-FCGA-RET) retinol emulsions over 14 days at 40°C

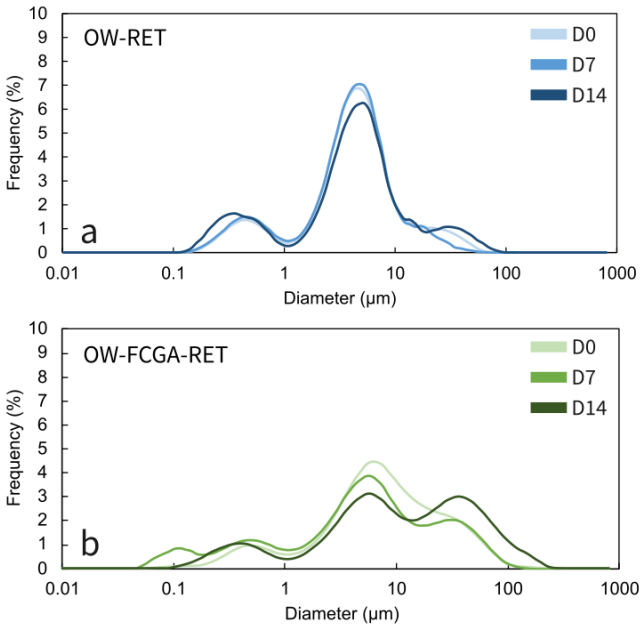

Figure 7 Particle size distribution of (a) non-encapsulated (OW-RET) and (b) encapsulated (OW-FCGA-RET) retinol emulsions over 14 days at 40°C. Results are displayed as volume diameters.

4. Discussion.

This cross-sectional study represents the first attempt to apply the complex coacervation technique to encapsulate retinol, using a combination of two natural polysaccharides: gum arabic and fungal chitosan. The FC-GA coacervates demonstrated strong efficacy in retinol encapsulation in coacervates sized approximately 50 µm, showing high encapsulation efficiency (73.7%) and yield (83%). While Kim et al. reported a range of 63 to 76.3% and Jiang et al. achieved a maximum of 82.22% encapsulation efficiency using chitosan derived from animals and ethanol as a solvent, these particles may not be appropriate for cosmetic applications [8,9]. These results suggest that encapsulation could be improved by changing the solvent to facilitate the dissolution of retinol and its emulsification. Thermal analysis of FCGA-RET particles showed that they were stable up to around 200°C with superior temperature resistance compared to non-encapsulated retinol, rendering it appropriate for processes involving high temperatures.

The FCGA-RET liquid coacervates demonstrated shear thinning and thixotropic characteristics that easily returned to their initial state upon removal of applied force. This property makes them suitable for formulation processes as a result of their ability to withstand shear. This phenomenon has been observed in multiple studies based on complex coacervates [22,23].

The incorporation of these coacervates into cosmetic formulations was successful and led to an improvement in texture properties. Although some alterations in particle size occurred over time due to interactions between coacervates and droplets, rheological properties suggest that the emulsion remains stable with a storage modulus significantly higher than the loss modulus (G' >> G") [24]. Furthermore, variability in the particle size and rheological measurements could be explained by the amount of aggregate introduced during analysis.

5. Conclusion.

This study emphasizes the potential of novel natural polymer coacervates, specifically a combination of fungal chitosan and gum arabic, in revolutionizing the design of advanced skincare formulations. The encapsulation of retinol using these innovative complex coacervates showed promising results, particularly in terms of enhancing the texture properties and stability of the emulsion over time. Furthermore, the use of natural polymers, such as fungal chitosan and gum arabic, in coacervate formation aligns with the growing trend of sustainable and eco-friendly practices in the cosmetics industry.

By leveraging these natural biopolymers, we address consumer's expectations for stable and effective delivery of active ingredients, while also meeting the demand for environmentally friendly beauty solutions.

6. Acknowledgments.

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7. Conflict of Interest Statement.

NONE.

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