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Hydroxyethyl cellulose as carbohydrate polymer scaffold for surfactant-free serums with enhanced hydration and structural stability

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ABSTRACT

Conventional cosmetic serums often suffer from rapid dehydration, phase separation, and component aggregation, leading to non-uniform ingredient dispersion and limited hydration durability. In this study, hydroxyethyl cellulose (HEC) was investigated as a structural modifier to improve the physicochemical stability and moisturizing performance of surfactant-free cosmetic serums. Moisture retention tests showed that HEC-containing formulations exhibited improved hydration durability, with moisture loss limited to approximately 5% after 30 min even after 7 days of storage. Extended measurements further showed that HEC-containing systems maintained higher moisture retention over longer time scales than HEC-free formulations. Scanning electron microscopy revealed a smoother and more homogeneous dried microstructure in the presence of HEC, indicating improved structural uniformity without conventional surfactants. Thermogravimetric analysis showed altered dehydration behavior, suggesting modified water-binding environments rather than changes in intrinsic thermal stability. FT-IR spectroscopy with peak deconvolution provided strong evidence for intermolecular hydrogen bonding between the hydroxyl groups of HEC and the carbonyl groups of sodium hyaluronate, while complementary ^{1}H NMR analysis revealed peak broadening and subtle chemical shift variations, indicating changes in local proton environments and intermolecular interactions. These results support the formation of a stabilized polymeric network by HEC, which contributes to improved structural integrity and sustained hydration performance in surfactant-free serum systems.

1. Introduction

Cosmetic serums are extensively employed as high-performance skincare formulations intended to deliver concentrated bioactive ingredients and rapid hydration to the skin [1,4] Their lightweight texture and fast absorption profile make them particularly attractive compared to conventional creams or lotions, especially in intensive moisturizing and anti-aging applications [11]. Despite their widespread use and commercial success, however, many conventional serum formulations still exhibit inherent physicochemical drawbacks that limit their long-term stability and functional durability [34]. A major limitation of cosmetic serums lies in their insufficient capacity to maintain hydration on the skin over extended periods. Most formulations rely heavily on low molecular weight humectants, such as glycerol or hyaluronic acid, which are highly effective at attracting water but tend to release it rapidly due to their molecular mobility and lack of structural confinement [3]. Consequently, an initial surge in skin hydration is often followed by a rapid decline, resulting in transient moisturizing efficacy [19,23]. Furthermore, serum components frequently interact preferentially with chemically similar species according to the 'like dissolves like' principle, which can drive phase separation, microdomain formation, and aggregation of active ingredients [5,8,29,33]. Such phenomena lead to structural inhomogeneity, uneven skin coverage, and diminished functional performance [15,28]. To address these issues, surfactants are commonly incorporated to enhance compatibility and dispersion between hydrophilic and hydrophobic components within serum formulations [10,16,22,30,37,40]. Although effective in improving macroscopic homogeneity, certain classes of surfactants, particularly anionic surfactants such as Sodium Lauryl Sulfate (SLS) and Sodium Laureth Sulfate (SLES), cationic surfactants including Benzalkonium Chloride, as well as poly(ethylene glycol) (PEG)-based surfactants, are known to adversely affect skin barrier integrity. These surfactants can disrupt intercellular lipids, interact with skin proteins, and in the case of PEG-based systems, enhance the penetration of co-formulated ingredients into the skin. Such effects may increase the risk of irritation and compromise biocompatibility, particularly in

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individuals with sensitive skin, making their use problematic in leave-on cosmetic formulations [12,35,44]. This has prompted growing interest in the development of surfactant-free serum systems that rely on intrinsic molecular organization to achieve both physical stability and sustained hydration, rather than on classical emulsification mechanisms [17,42,43].

Hydroxyethyl cellulose (HEC) is a water-soluble, cellulose-derived carbohydrate polymer known for its high biocompatibility, biodegradability, and adaptability in formulation design [9,18,24,25,27,47]. Its molecular structure is rich in hydroxyl and ether functionalities, enabling extensive hydrogen bonding and dipole-dipole interactions with water molecules and other polar constituents [13,21,26,31,39,41,45]. These interactions facilitate the formation of hydrated polymer networks that can effectively immobilize water and regulate the microstructural organization of aqueous systems [7,32,36,46]. While HEC is widely utilized as a thickening agent and rheological modifier in cosmetic and pharmaceutical products, its potential function as a molecular scaffold that controls component distribution, water retention, and microstructural stability in cosmetic serums has not yet been systematically elucidated [2,6,18,20,25,38].

In this study, we propose that HEC functions not only as a viscosity modifier but also as a structural scaffold that organizes serum constituents into a hydrated polymer network [14,26,48]. By incorporating HEC into a sodium hyaluronate-based cosmetic serum, we aimed to suppress local aggregation, enhance water immobilization, and improve formulation uniformity without the use of surfactants. Using moisture retention measurements, SEM, TGA, FT-IR spectroscopy with peak deconvolution, and ^{1}H NMR spectroscopy, we examined the molecular and microstructural changes induced by HEC [13,44]. This work presents a carbohydrate polymer-based design strategy for surfactant-free cosmetic serums with improved structural stability and prolonged hydration performance.

2. Experimental

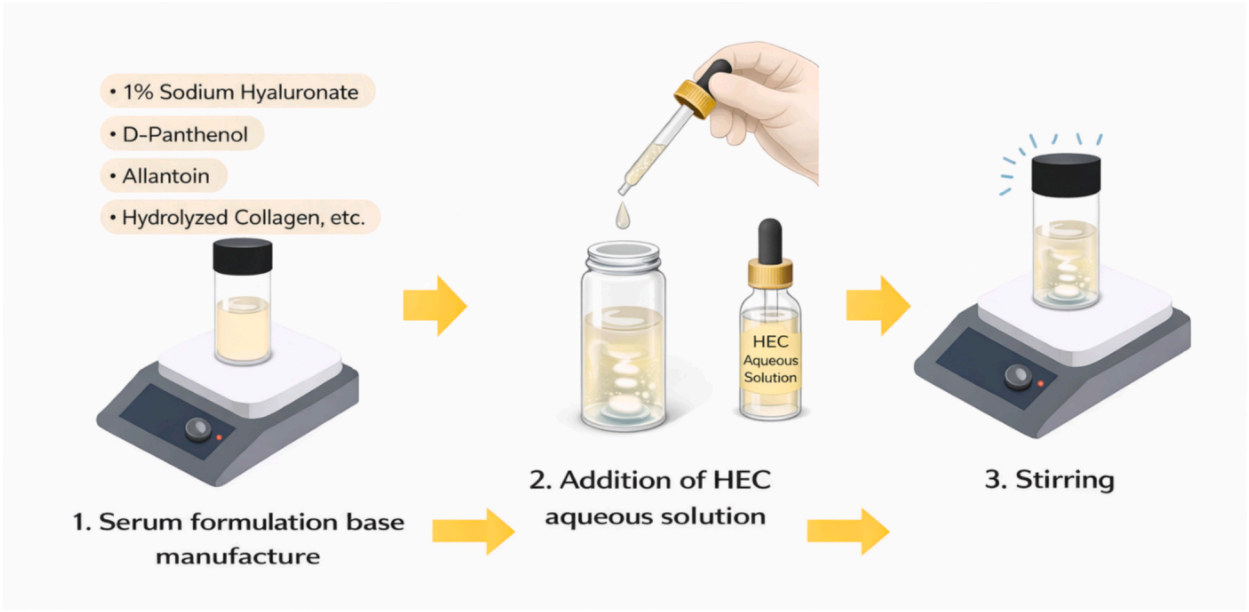
Hydroxyethyl cellulose (HEC; viscosity: ~145 mPa.s, 1% in H_2O (20 °C) and Mw: 380,000 g/mol) was obtained from Ashland and used without further purification. Sodium hyaluronate (1 wt% aqueous solution) served as the primary polymeric humectant, while hydrolyzed collagen powder was incorporated as a bio-derived moisturizing additive. Low molecular weight polyol humectants, including 1,3-butylene glycol (1,3-BG) and 1,3-propanediol, were employed to enhance hydration. Betaine (natural betaine solution) and trehalose were introduced as osmoprotective moisturizing agents. D-Panthenol was used for its skin-conditioning properties, and an allantoin solution was added to provide a soothing effect. Epidermal growth factor (EGF, sh-Oligopeptide-1, 10 ppm aqueous solution) was incorporated as a bioactive ingredient. All reagents were used as received, without additional purification or chemical modification.

The HEC-free serum base was prepared via a stepwise aqueous blending process. First, distilled water (7 g) was mixed with sodium hyaluronate (1 wt%, 3 g) in Beaker 1 under gentle stirring until complete dissolution was achieved. In parallel, distilled water (7 g) was combined with hydrolyzed collagen (0.3 g) in Beaker 2 and stirred until a homogeneous solution was obtained. The two solutions were then merged and further mixed to ensure uniformity. Subsequently, 1,3-butylene glycol (3 g), betaine (2 g), D-panthenol (2 g), and trehalose (0.7 g) were added sequentially to the combined solution, followed by continuous stirring until full homogenization. Thereafter, 1,3-propanediol (1 g) and allantoin (0.6 g) were introduced, and the mixture was stirred until a transparent and uniform serum base was formed. Finally, epidermal growth factor (EGF, 10 ppm, 0.3 g) was added, and the formulation was gently mixed to obtain the final HEC-free serum. As illustrated in Scheme 1, HEC-containing serums were prepared by introducing a pre-formulated aqueous HEC solution into the serum base. The serum base was first produced following the same procedure described above to maintain identical composition and concentrations of all constituents except for HEC.

The aqueous HEC solution was prepared separately by dispersing hydroxyethyl cellulose in distilled water under continuous stirring until complete hydration and dissolution were achieved. Defined aliquots of this HEC solution were then gradually added to 5 g portions of the serum base, followed by stirring for 30 min to ensure uniform distribution of the polymer within the serum matrix. By adjusting the amount of HEC solution added, a series of HEC-containing serums with different effective HEC concentrations was obtained.

All formulations were allowed to equilibrate under ambient conditions prior to subsequent physicochemical and spectroscopic analyses.

The moisture retention performance of cosmetic serums with and without HEC was assessed using a skin capacitance-based moisture analyzer (Entascan, SPOH Co., Korea). This instrument quantifies skin hydration by detecting variations in electrical capacitance, which are



Scheme 1. Manufacturing and polymer network formation process of hydroxyethyl cellulose-based cosmetic serum.

directly related to the water content within the stratum corneum. All measurements were performed under controlled ambient conditions, maintaining room temperature and typical indoor humidity. Prior to serum application, the test area on the dorsal side of the hand was allowed to equilibrate for at least 10 min, after which the initial skin hydration value was recorded as the baseline. A fixed amount of serum was then uniformly applied to the designated area and allowed to spread naturally without occlusion. Skin hydration was measured immediately after application (0 min) and at predetermined time points of 10 and 30 min. For reference, additional measurements were conducted on untreated skin as well as skin treated with the HEC-free serum. Each experiment was repeated a minimum of five times, and the mean value was reported as the representative hydration level.

Moisture retention capability was evaluated by monitoring the temporal evolution of skin hydration following serum application. The relative moisture loss was calculated from the decrease in hydration percentage with respect to the initial post-application value, enabling direct comparison of hydration durability between HEC-free and HEC-containing formulations.

SEM was employed to investigate the surface morphology of cosmetic serum formulations in the absence and presence of HEC. The surface features of the neat serum are shown in Fig. 3(a, b), whereas those of the HEC-containing serum are presented in Fig. 3(c, d). Prior to imaging, serum samples were cast onto clean substrates and dried under ambient conditions to eliminate residual moisture. The dried specimens were subsequently sputter-coated with a thin platinum layer to enhance surface conductivity. All SEM images were obtained under identical operating conditions to ensure reliable comparison between samples. No additional low molecular weight surfactants were introduced during sample preparation.

The thermal dehydration behavior of the serum formulations was examined by TGA using a Universal V4.5 A system (TA Instruments). Measurements were conducted by heating the samples from 30 °C to 300 °C at a constant rate of 10 °C/min, allowing evaluation of the thermally induced mass loss associated with water evaporation and formulation stability.

FT-IR spectroscopy was carried out using a *V*ERTEX 70/70 *V* spectrometer (Bruker Optics) to analyze the molecular interactions between hydroxyethyl cellulose and serum components. Spectra were collected in the range of 400–4000 cm^{-1} with a resolution of 4 cm^{-1} and by averaging 16 scans for each sample. Prior to analysis, all samples were dried in a vacuum oven for 24 h to remove residual moisture and ensure reliable spectral interpretation.

Nuclear Magnetic Resonance (NMR) was employed as a supplementary tool to examine molecular-level interactions and local proton environments in the serum formulations. Samples including the HEC-free serum, HEC-containing serum, sodium hyaluronate/HEC mixture, and neat sodium hyaluronate were dissolved in DMSO-d_6 and analyzed using a 60 MHz benchtop NMR spectrometer (Nanalysis 60e).

3. Results and discussion

Fig. 1 presents the time-dependent moisture retention profiles of serum formulations with and without HEC following topical application. All moisture measurements were conducted at a controlled temperature of 22.1 °C and a relative humidity of 30%, and the serum formulations were stored under the same conditions to ensure consistency. For each measurement, 0.5 mL of the sample was applied. The untreated skin exhibited an initial moisture level of approximately 36%, indicating a relatively dry condition requiring external hydration. Upon application of a neat serum formulation without HEC, the skin moisture content rapidly increased to approximately 66%, demonstrating an immediate and pronounced moisturizing effect. This elevated level was maintained at approximately 65% for up to 1 h; however, a notable decline was observed after 2 h, with moisture levels falling below 60%, indicating substantial water loss and limited long-term hydration efficacy. In contrast, the HEC-containing serum, prepared at a distilled water to HEC molar ratio of 1.90×10^{-6}, exhibited significantly enhanced moisture retention performance. When applied to untreated skin with an initial moisture level of 32%, the skin moisture content immediately increased to approximately 75%, indicating improved hydration capacity. Notably, within the initial 10 min after application, the HEC-containing serum exhibited slightly lower moisture retention compared to the HEC-free formulation, which can be attributed to the restricted mobility of water molecules within the polymer network. However, this initial limitation was gradually compensated over time, and the HEC-containing system demonstrated superior long-term moisture retention behavior. As shown in Fig. 2, the long-term moisture retention capability of the HEC-containing serum was superior to that of the HEC-free formulation. According to the 6 h moisture retention test, the serum without HEC exhibited a final moisture level of approximately 36%, showing no significant improvement relative to the baseline and even a slight decrease. In contrast, the HEC-containing serum maintained a higher moisture level of approximately 44% after 6 h, indicating a net

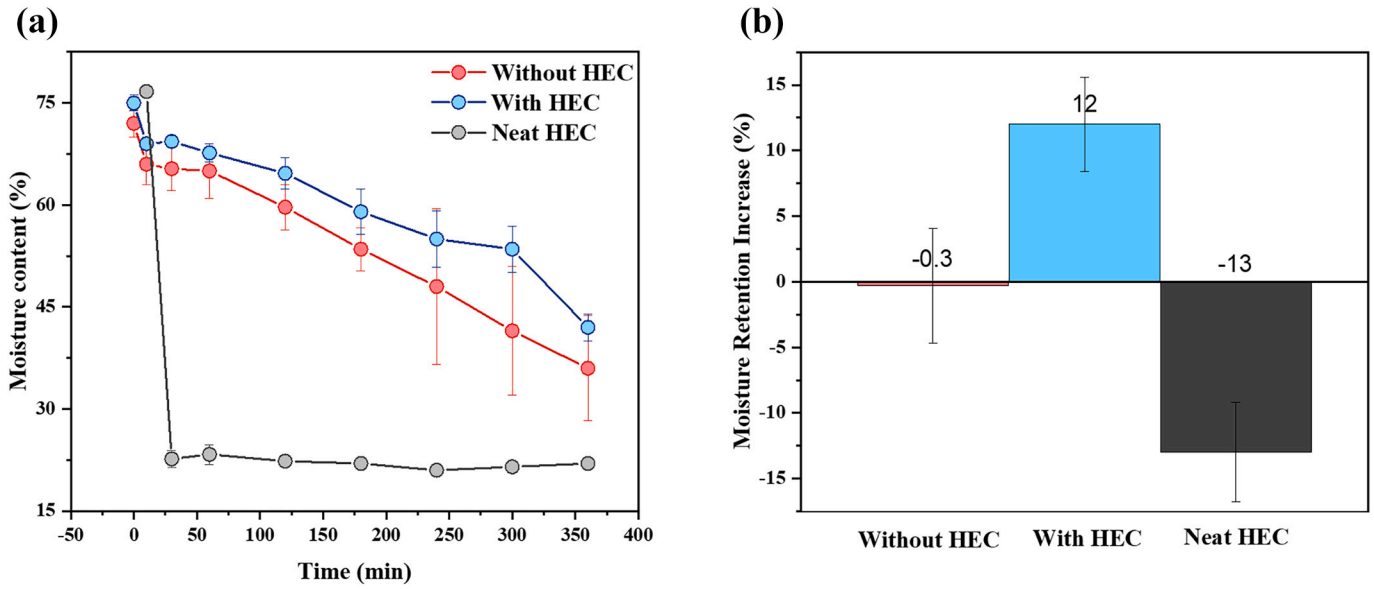


Fig. 1. Time-dependent moisture retention profiles (a) and net moisture retention increase after 6 h (b) for serum formulations with and without HEC.

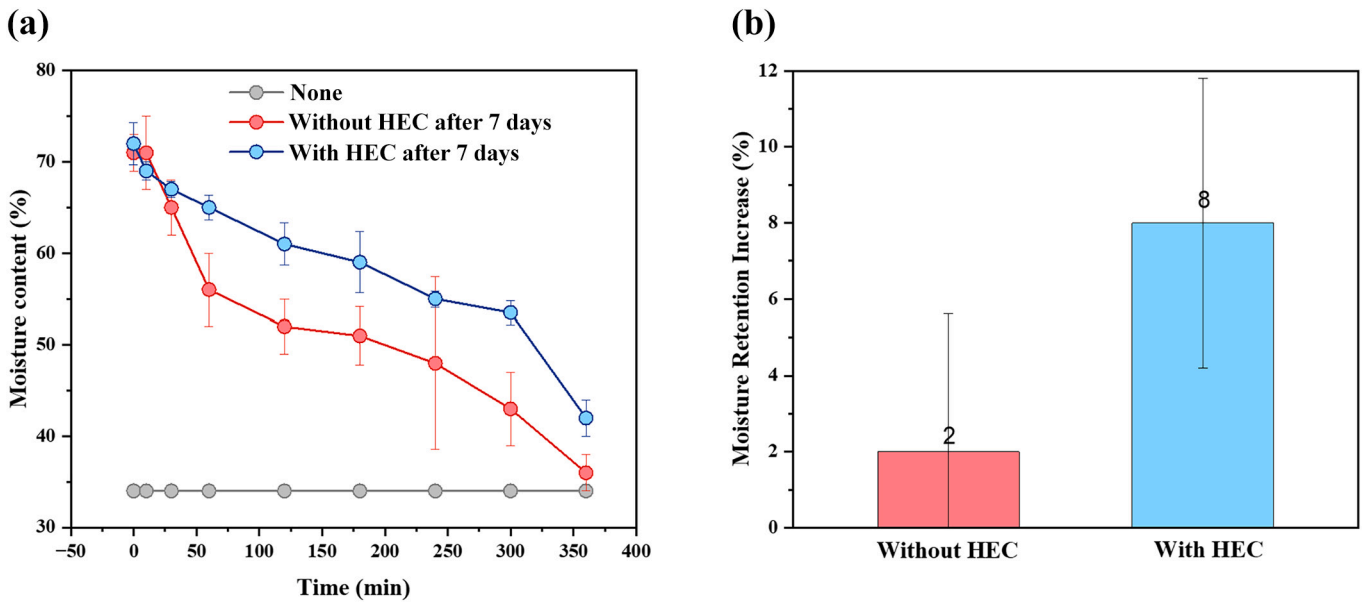


Fig. 2. Storage stability of moisture retention behavior in serum formulations with HEC: (a) time-dependent moisture profiles and (b) net moisture retention increase after 7 days.

increase in skin hydration compared to the initial condition. These results show that the HEC-containing serum sustained skin moisture more effectively over time than the HEC-free formulation.

The stability of the moisturizing performance upon storage was further evaluated by re-examining both the HEC-free and HEC-containing serum formulations after storage at room temperature for 7 days, as presented in Fig. 2. As shown in Fig. 2(a), the HEC-containing serum exhibited an initial hydration level of approximately 74%, which decreased modestly to 69% after 10 min and remained nearly constant thereafter, indicating only a ~ 5% reduction over 30 min. This behavior closely matches that of the freshly prepared HEC-containing formulation, demonstrating that the hydration performance is well preserved during storage.

In contrast, the serum without HEC showed a more pronounced decrease in moisture content over time, reflecting inferior moisture retention capability. As summarized in Fig. 2(b), the HEC-containing formulation exhibited a significantly higher net moisture retention increase (~8%) compared to the HEC-free serum (~2%), further confirming the enhanced and sustained hydration performance. These results indicate that the carbohydrate polymer network established by HEC not only improves moisture retention but also maintains its structural and functional integrity over time. The sustained hydration performance highlights the robustness of the HEC-induced polymeric scaffold and its effectiveness in immobilizing water within surfactant-free cosmetic serum systems.

As shown in Fig. 3(a, b), the serum formulated without hydroxyethyl

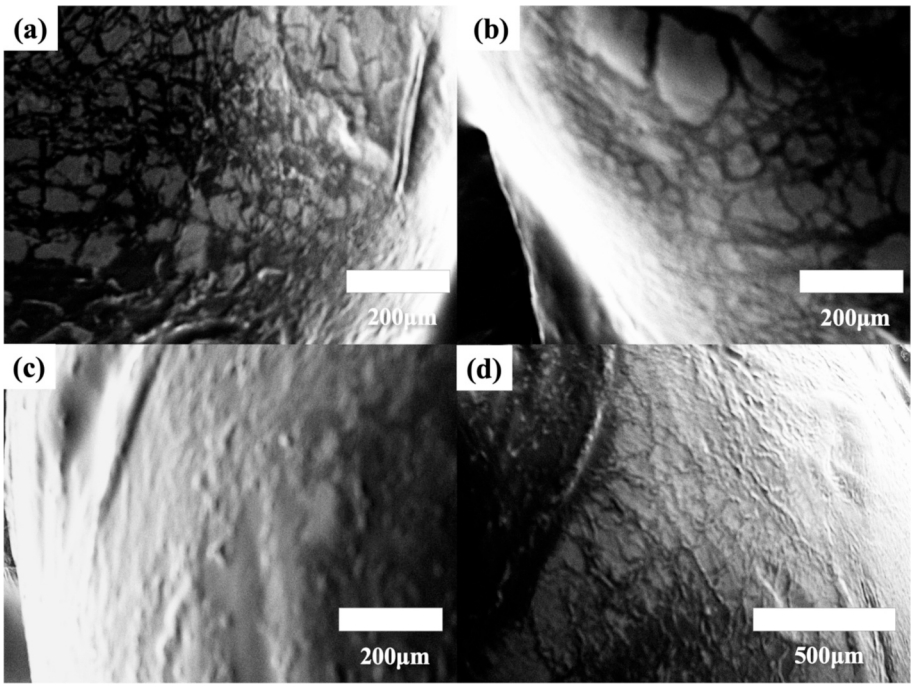


Fig. 3. SEM micrographs of serum microstructure in the absence and presence of HEC.

cellulose exhibits a discontinuous and heterogeneous microstructure, characterized by irregular domains and the presence of microcracks. This morphology reflects the absence of a continuous structural framework capable of maintaining cohesive organization within the matrix. In contrast, Fig. 3(c, d) demonstrates that the serum containing hydroxyethyl cellulose displays a smooth, compact, and highly interconnected polymer network. The formation of a coherent matrix that bridges individual microdomains results in a uniform and dense morphology. This network-like architecture highlights the function of hydroxyethyl cellulose as a carbohydrate polymer scaffold that stabilizes the serum microstructure, promotes effective film formation, and supports improved moisture retention.

Thermogravimetric analysis (TGA) was carried out to investigate the thermal dehydration behavior of cosmetic serum formulations as a function of HEC content. Fig. 4 presents the TGA curves of the neat serum and the HEC-containing serums prepared at different DI water-to-HEC molar ratios, while the corresponding derivative thermogravimetric (DTG) profiles are shown in Fig. 4(c).

All formulations exhibited two dominant mass-loss stages within the temperature range of 30–300 °C. The first event, occurring at approximately 50–60 °C, is attributed to the removal of weakly bound or free water molecules. The second mass-loss step, observed near 95–110 °C, corresponds to the evaporation of more strongly associated water populations interacting with polymeric components in the serum matrix. The overall similarity of the mass-loss patterns among all samples indicates that the incorporation of HEC does not introduce additional thermal degradation mechanisms within the investigated temperature window.

Nevertheless, clear and systematic variations in dehydration behavior were observed as a function of HEC content. In particular, the temperature corresponding to the maximum rate of mass loss progressively shifted toward lower values with increasing HEC concentration. This trend should not be interpreted as a reduction in the intrinsic thermal stability of the formulation; rather, it reflects HEC concentration-dependent changes in the binding state, spatial distribution, and mobility of water molecules. The carbohydrate backbone of HEC, enriched with hydroxyl and ether functionalities, facilitates extensive hydrogen bonding with water and other hydrophilic constituents, promoting the formation of polymer-associated water that is released over a broader and more continuous temperature interval. Importantly, this concentration-dependent dehydration behavior indicates that HEC alters the local water-binding environment of the

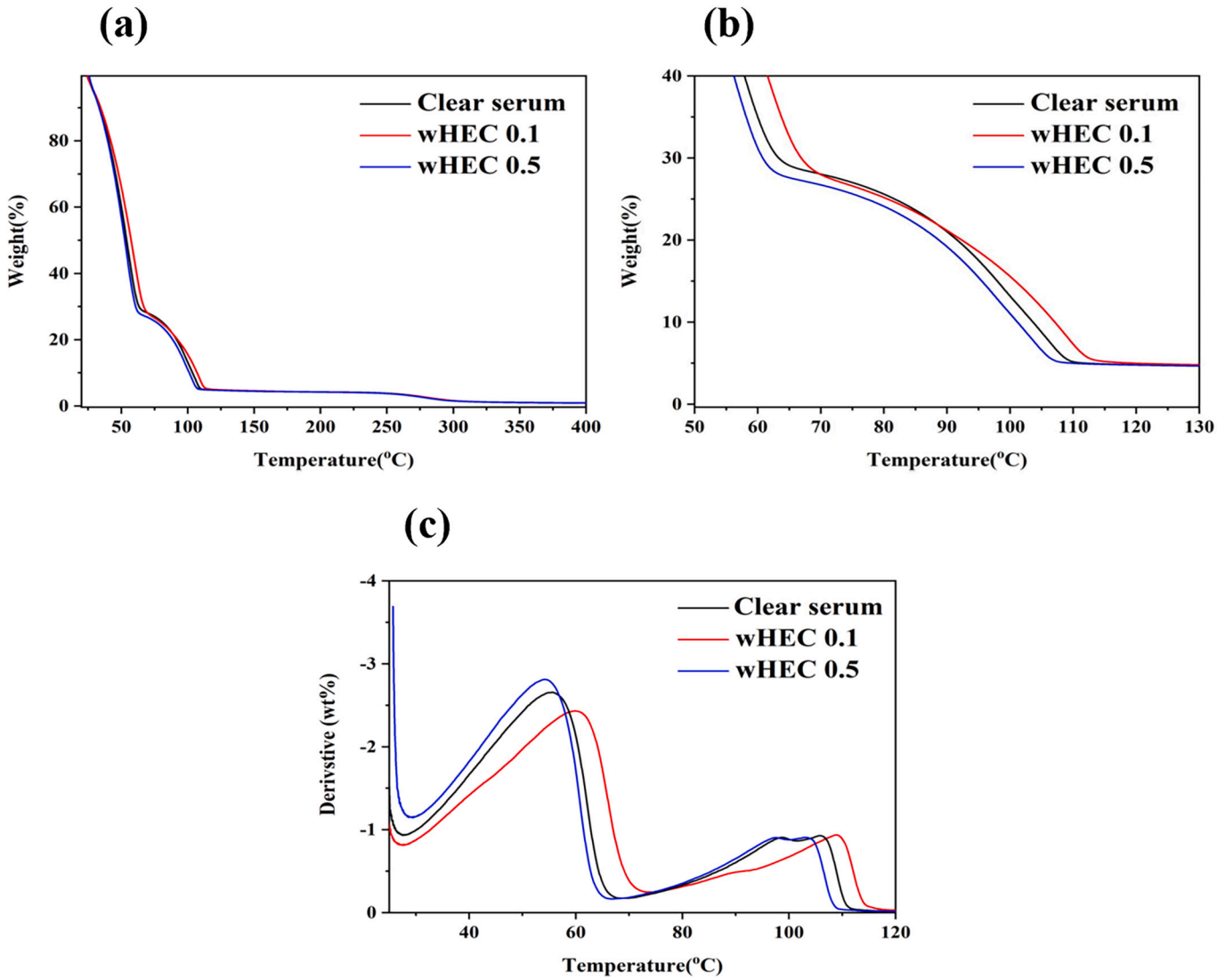


Fig. 4. Thermogravimetric analysis (TGA) and derivative thermogravimetric (DTG) profiles of serum formulations with varying HEC content. (a) Overall TGA curves showing temperature-dependent mass loss behavior of the neat serum and HEC-containing formulations (wHEC 0.1 and wHEC 0.5). (b) Enlarged view of the low-temperature region highlighting dehydration behavior near 100 °C. (c) Corresponding DTG curves illustrating mass loss rates as a function of temperature.

serum matrix. As the HEC content increases, the distribution and mobility of water molecules are modified, leading to changes in the temperature and rate of mass loss during dehydration. These results suggest that HEC does not simply improve thermal stability, but rather changes the binding state and release behavior of water within the formulation. Notably, the formulation containing an intermediate HEC concentration exhibited the most balanced dehydration profile, indicating optimal polymer dispersion and the formation of a well-developed hydrated network structure. These TGA results are in strong agreement with SEM observations showing a homogeneous and continuous microstructure in HEC-containing serums, as well as with FT-IR results indicating hydrogen bonding and polymer network formation. Taken together, the thermal, morphological, and spectroscopic analyses confirm that HEC reorganizes the serum matrix at both molecular and microstructural levels by modulating water-binding environments and hydration dynamics, rather than by altering the intrinsic thermal stability of the system.

Fourier-transform infrared (FT-IR) spectroscopy was employed to investigate intermolecular interactions and structural reorganization in the serum formulations upon incorporation of HEC. The FT-IR spectra of the neat serum and HEC-containing formulations at different DI-water/HEC molar ratios are presented in Fig. 5, while the deconvolution results of the carbonyl (C=O) and ether (C-O-C) stretching regions are shown in Figs. 6 and 7, respectively.

The carbonyl stretching region (approximately 1615–1680 cm^{-1}), primarily associated with sodium hyaluronate and other carbonyl-containing components, exhibited systematic changes upon HEC incorporation. The deconvolution percentages of the carbonyl groups are summaraized in Table 1. In the neat serum, the spectrum was dominated by a central band at 1641–1653 cm^{-1}, accounting for 61.8% of the total peak area, while the lower-wavenumber region (1615–1629 cm^{-1}) contributed only 4.9%, indicating a limited extent of hydrogen-bonding interactions in the absence of HEC.

Upon addition of HEC, a significant increase in the relative contribution of the low-wavenumber band was observed, reaching 23.9% and 18.7% for the respective formulations. This shift toward lower wavenumbers reflects hydrogen-bond-mediated weakening of the C=O bond, indicating enhanced intermolecular interactions between HEC and carbonyl-containing serum components. Such behavior suggests that HEC participates in hydrogen bonding with carbonyl groups, modifying the local interaction environment.

At higher HEC content, a partial recovery of the central carbonyl band was observed, accompanied by a slight decrease in the low-wavenumber contribution. This trend indicates a concentration-dependent interaction mechanism, where localized HEC-component interactions at lower concentrations evolve into more distributed polymer-polymer interactions at higher concentrations, leading to a more extended network structure.

Further insight into structural organization was obtained from the ether (C-O-C) stretching region (1000–1150 cm^{-1}). The deconvolution percentages of the ether - related bands are summarized in Table 2. In neat HEC, the ether-related bands were broadly distributed, indicating a relatively disordered conformational state. In contrast, HEC-containing serum formulations exhibited a pronounced increase in intensity in the central region (1050–1055 cm^{-1}), with peak area contributions increasing to 57.1% and 65.1%, respectively. This redistribution of spectral intensity indicates a transition toward a more uniform and constrained ether environment, suggesting reduced conformational freedom of HEC chains due to intermolecular interactions within the serum matrix. The concurrent decrease in low- and high-wavenumber components further supports the formation of a more organized polymer network. From these results, the carbonyl and ether region analyses demonstrate that incorporation of HEC significantly alters the intermolecular interaction landscape of the serum through hydrogen-bond-mediated interactions. These interactions lead to reorganization of local functional group environments and the formation of a hydrated polymer network. This network is expected to influence the mobility and spatial distribution of water molecules, providing a structural basis for the enhanced moisture retention observed in HEC-containing formulations. These results are further supported by complementary NMR analysis, which probes changes in local proton environments associated with these interactions.

To further support the intermolecular interaction mechanisms identified by FT-IR analysis, ^{1}H NMR spectroscopy was employed to probe changes in local proton environments upon incorporation of HEC. The spectra of the serum formulations with and without HEC are presented in Fig. 8. Both spectra exhibit similar overall profiles, with characteristic resonance signals in the region of 3.2–4.5 ppm corresponding to protons in oxygenated chemical environments (e.g., -CH-O- and -CH-OH groups). This similarity suggests that no significant chemical transformation of the formulation components occurs upon HEC incorporation.

However, a subtle but consistent chemical shift variation was observed in this region. In the HEC-free serum, the oxygen-adjacent

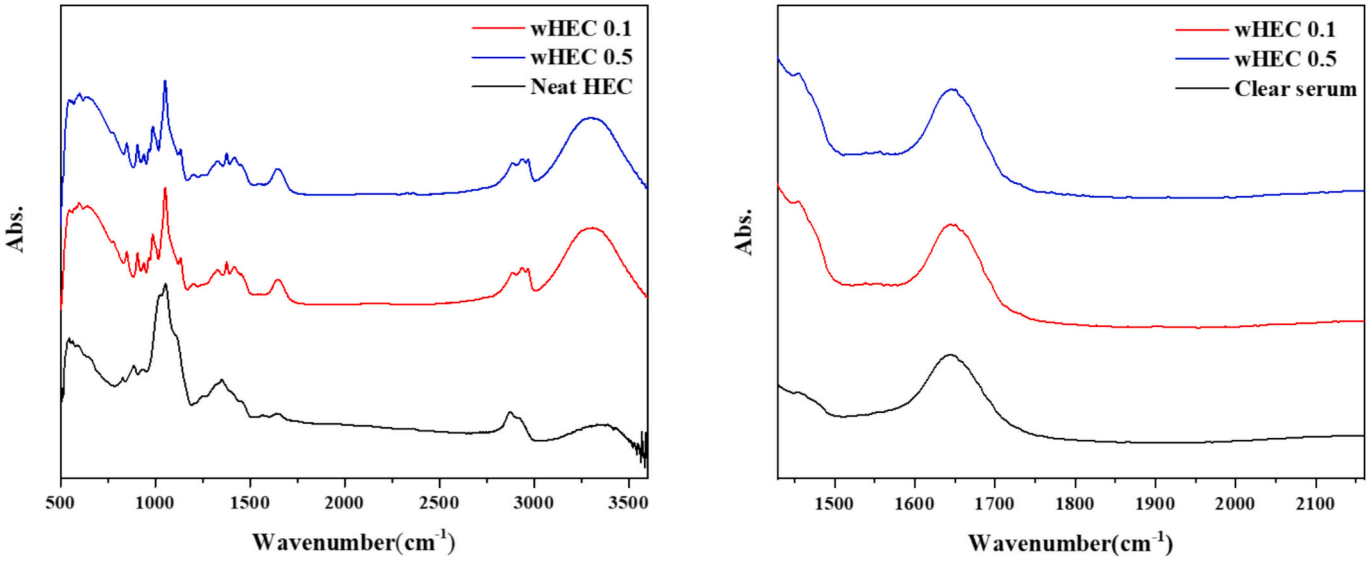


Fig. 5. Overlay of FT-IR spectra for neat serum, serum with DI-water/HEC molar ratio of 1.90×10^{-6} (wHEC 0.5), and serum with DI-water/HEC molar ratio of 1.02×10^{-5} (wHEC 1.5), highlighting carbonyl region differences.

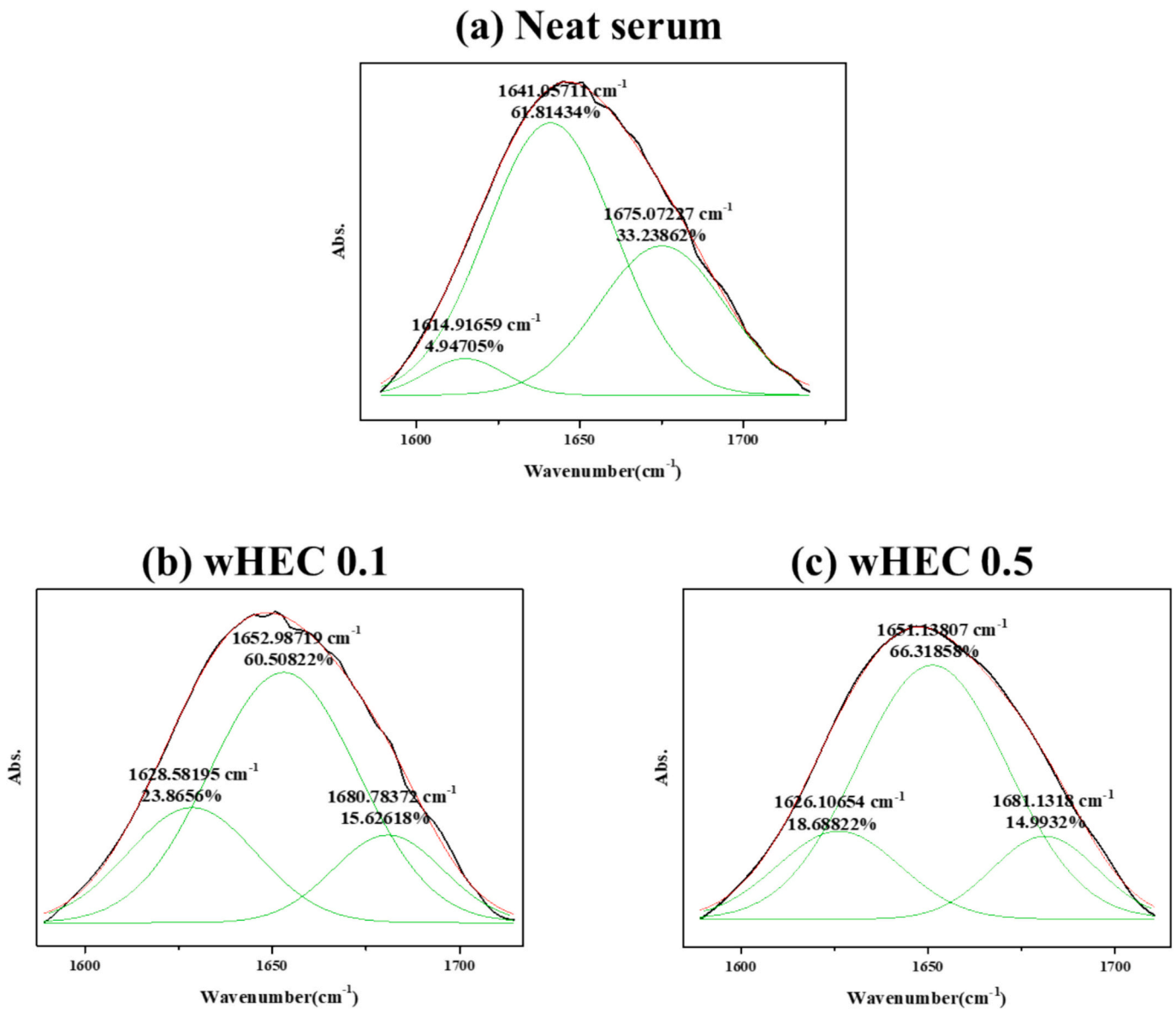


Fig. 6. Deconvolution analysis of the carbonyl stretching region for (a) the neat serum, (b) the serum containing hydroxyethyl cellulose at a DI-water/HEC molar ratio of 1.90×10^{-6}, and (c) the serum containing hydroxyethyl cellulose at a DI-water/HEC molar ratio of 1.02×10^{-5}.

Table 1
Deconvolution percentages of the carbonyl groups in the FT-IR spectra of cosmetic serums with and without HEC.

Wavenumber (cm^{-1})	Neat serum	Serum containing DI-water/HEC molar ratio of 1.90×10^{-6}	Serum containing DI-water/HEC molar ratio of 1.02×10^{-5}
1614.9–1628.6	4.9%	23.9%	18.7%
1641.1–1653.0	61.8%	60.5%	66.3%
1675.1–1681.1	33.2%	15.6%	15.0%

proton signal appears at δ ≒ 4.25 ppm, whereas in the HEC-containing formulation, this peak shifts slightly to δ ≒ 4.27 ppm. This downfield shift indicates a reduction in local electron density and is consistent with hydrogen-bond-mediated deshielding. In addition to the chemical shift variation, the HEC-containing system exhibits slight peak broadening compared to the HEC-free serum, suggesting increased heterogeneity in local proton environments and possibly reduced molecular mobility. These spectral features are consistent with the formation of intermolecular interactions and partial structural confinement within the system.

Thus, the combined FT-IR and NMR analyses demonstrate that incorporation of HEC induces hydrogen-bond-mediated interactions that reorganize the local molecular environment and promote the formation of a hydrated polymer network. This network is expected to modulate water mobility and contribute to the enhanced and sustained moisture retention observed in HEC-containing serum formulations. Therefore, analyses of the carbonyl and ether stretching regions indicate that HEC plays an active role in organizing the serum at the molecular level, rather than serving merely as an inert viscosity modifier. The formation of hydrogen bonds between the hydroxyl groups of HEC and the carbonyl groups of serum constituents anchors the polymer chains within the formulation, while the redistribution and ordering of ether linkages signify the emergence of a coherent carbohydrate-based polymer network. Furthermore, these spectroscopic results are in excellent agreement with the SEM observations, which revealed a homogeneous and continuous microstructure, as well as with the TGA data, which showed altered dehydration behavior without introducing additional thermal degradation pathways.

Thus, the morphological, thermal, and spectroscopic evidence

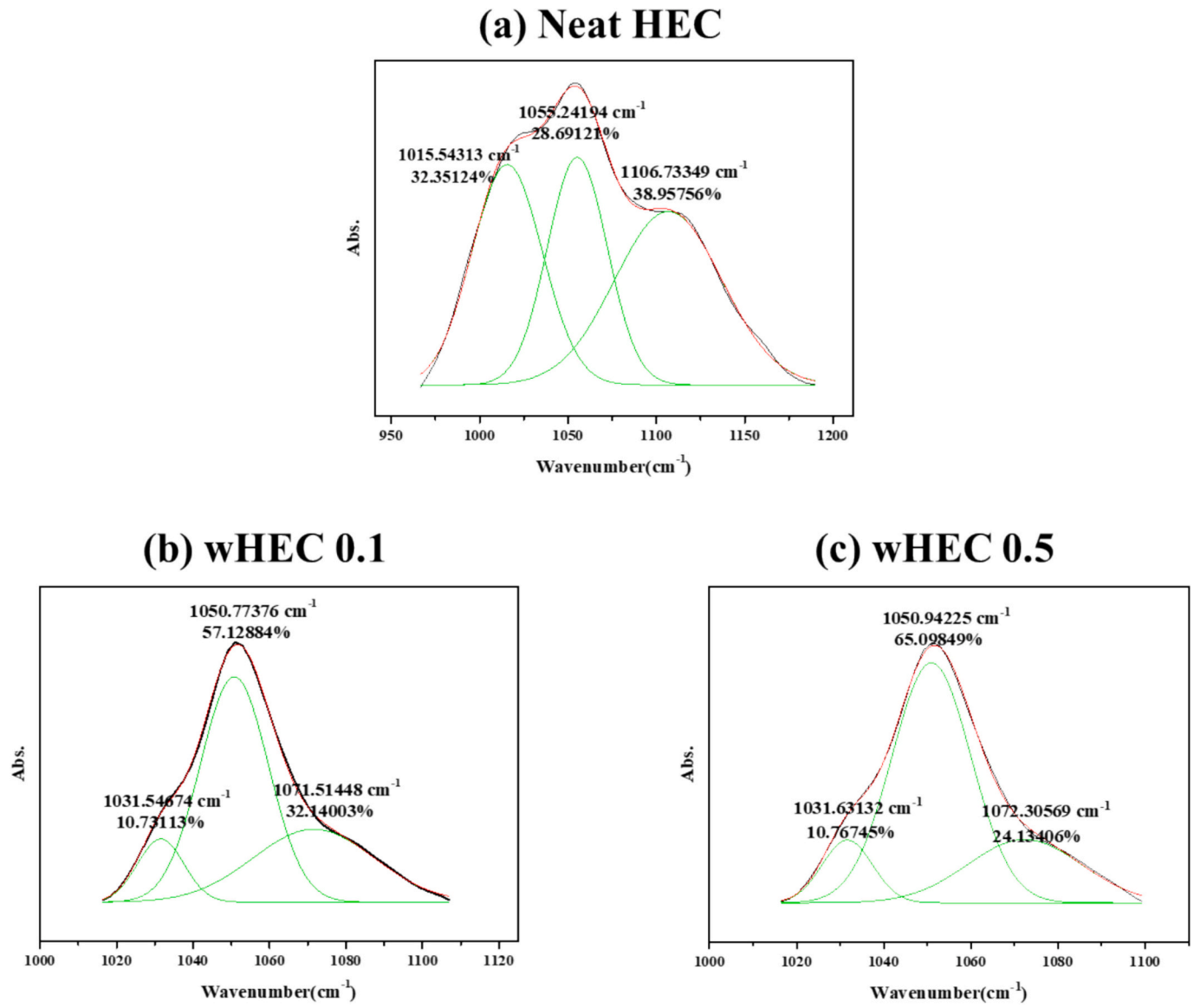


Fig. 7. Deconvolution analysis of the ether stretching region for (a) the neat serum, (b) the serum containing hydroxyethyl cellulose at a DI-water/HEC molar ratio of 1.90×10^{-6}, and (c) the serum containing hydroxyethyl cellulose at a DI-water/HEC molar ratio of 1.02×10^{-5}.

Table 2
Deconvolution percentages of the ether groups in the FT-IR spectra of neat HEC and cosmetic serums containing HEC at different DI-water/HEC molar ratios.

Wavenumber (cm^{-1})	Neat HEC	Serum containing DI-water/HEC molar ratio of 1.90×10^{-6}	Serum containing DI-water/HEC molar ratio of 1.02×10^{-5}
1015.5–1031.6	32.4%	10.7%	10.7%
1050.7–1055.2	28.7%	57.1%	65.1%
1071.5–1106.7	39.0%	32.1%	24.1%

demonstrates that HEC stabilizes the serum matrix by constructing a hydrated polymer network that reorganizes local functional group environments, restricts the mobility of water molecules, and reinforces the overall structural integrity of the formulation. Schematic illustration (Scheme 2) summarizes the role of hydroxyethyl cellulose in enhancing hydration, thermal dehydration behavior, and surface uniformity of cosmetic serum through hydrated polymer network formation.

4. Conclusion

This study demonstrates that HEC, a cellulose-derived carbohydrate polymer, plays a critical role in enhancing both the structural stability and moisturizing performance of polymer-based cosmetic serums. HEC-containing formulations exhibited significantly improved moisture retention, maintaining higher hydration levels over time and after storage, thereby confirming the durability of its hydration effect. Morphological analysis revealed that HEC induces the formation of a smooth, compact, and homogeneous microstructure, suggesting enhanced structural cohesion within the serum matrix. Notably, such structural uniformity was achieved without the use of low molecular weight surfactants, indicating that HEC intrinsically functions as an effective structural stabilizer. Thermogravimetric analysis showed altered dehydration behavior in HEC-containing systems, reflecting changes in water-binding states and mobility rather than intrinsic thermal stability. Spectroscopic analyses further supported these findings: FT-IR results confirmed hydrogen-bonding interactions between HEC and sodium hyaluronate, while ^{1}H NMR analysis indicated reduced molecular mobility through peak broadening and chemical shift

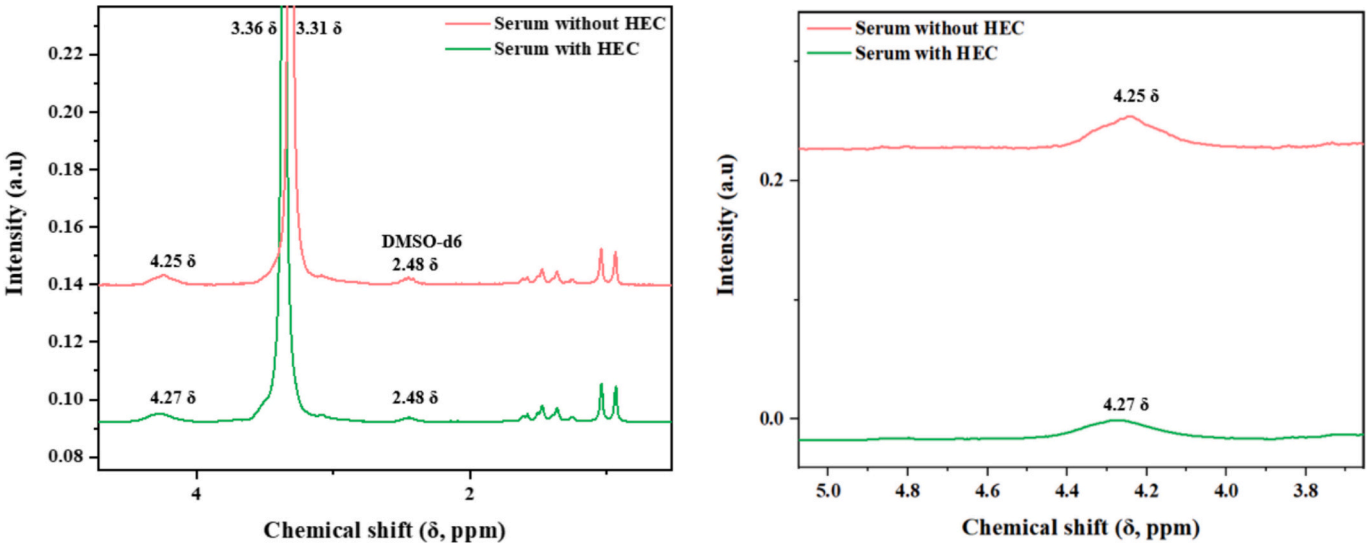
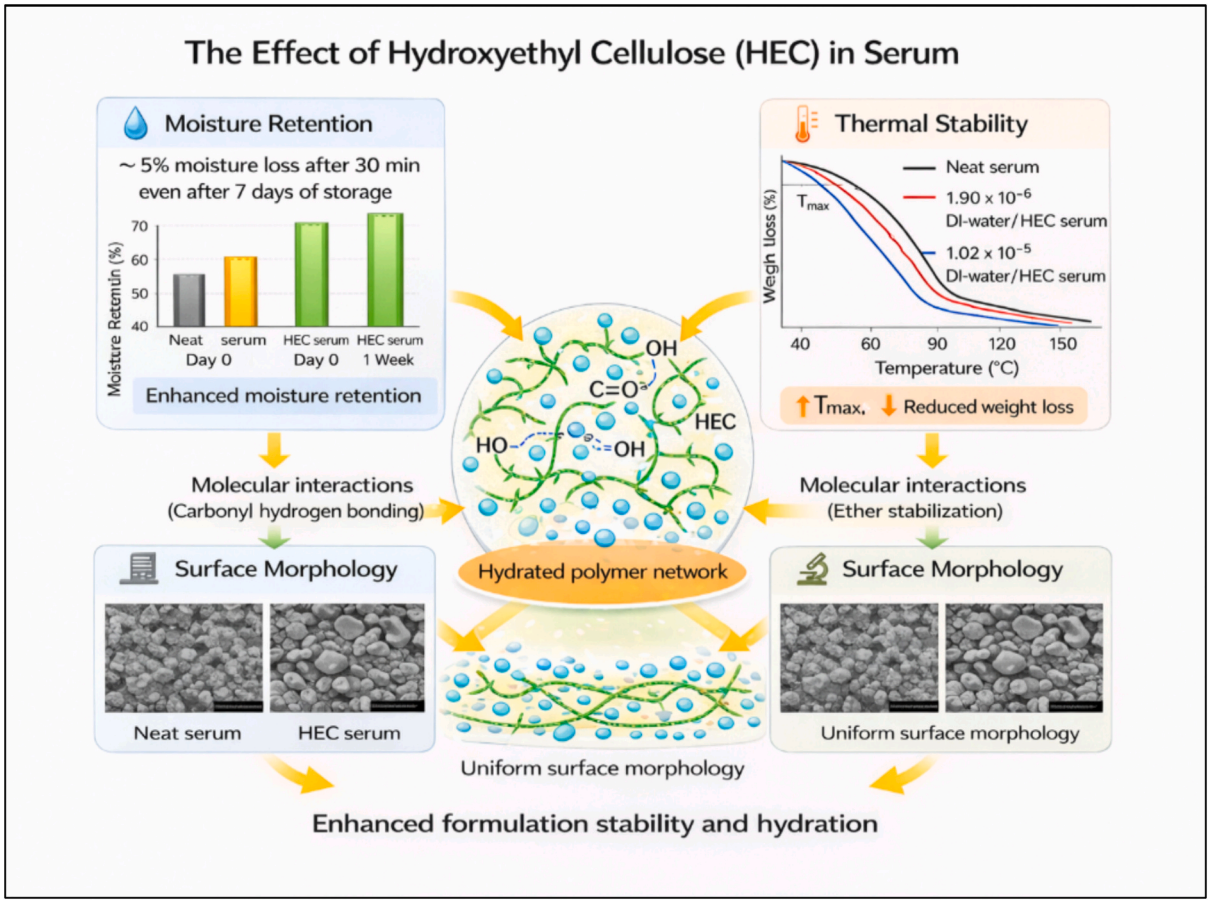


Fig. 8. [1]H NMR spectra of serum formulations with and without hydroxyethyl cellulose (HEC) in DMSO-d_6. The inset highlights the oxygen-adjacent proton region (3.6–4.5 ppm), where subtle variations in chemical shift and peak shape are observed upon HEC incorporation.



Scheme 2. Molecular mechanism of HEC-induced polymer network formation and moisture retention in cosmetic serums

variations. Importantly, the concentration-dependent trends observed across these analyses suggest that HEC progressively reorganizes the hydrated polymer matrix, thereby regulating the distribution and binding state of water molecules. This molecular and microstructural reorganization is directly linked to the sustained moisture retention performance. Thus, HEC functions not merely as a viscosity modifier but as an active structuring agent that stabilizes and reorganizes the serum matrix through hydrogen-bond-mediated network formation. Unlike

other natural polymers that rely on electrostatic interactions or chemical crosslinking, HEC enables effective stabilization and moisture retention without additional surfactants or crosslinking processes.

CRediT authorship contribution statement

Eun Chae Cho: Writing – original draft. **Sang Wook Kang:** Writing – review & editing.

Consent for publication

All of our authors consent to the publication of this paper.

Ethics approval and consent to participate

This study following Compliance with Ethical Standards; this study does not involve human participants, animals, and potential conflicts of interest.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data that has been used is confidential.

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