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IN VITRO EVALUATION OF SURFACE WETTABILITY AND OPTICAL TRANSPARENCY OF HYDROGEL-BASED BIOMATERIALS INTENDED FOR OCULAR SURFACE APPLICATIONS

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Abstract

Hydrogel-based biomaterials are widely investigated for ocular surface applications due to their transparency, hydration capacity, and surface compatibility. However, systematic in vitro evaluation of their physicochemical properties remains essential for material selection and optimization. Our study aimed to comparatively assess surface-related, optical, and hydration properties of three hydrogel-based biomaterials intended for ophthalmic use. Disc-shaped samples were prepared and evaluated in vitro for surface wettability using static water contact angle measurements, optical transparency through light transmittance at 550 nm, and hydration behavior by swelling ratio determination. Statistical analysis was performed using one-way ANOVA followed by Tukey's post-hoc test. Significant differences were observed among the investigated biomaterials for all evaluated parameters ($p<0.05$). Wettability varied markedly depending on polymer composition, indicating distinct surface interaction profiles. Optical transparency measurements demonstrated material-dependent light transmittance, while swelling ratio analysis revealed differences in water uptake capacity and hydration stability. These findings highlight the strong influence of material composition on properties directly relevant to ocular surface performance. In conclusion, standardized in vitro characterization of surface, optical, and hydration properties provides valuable insights into the functional behavior of ophthalmic biomaterials and represents a critical step in their early-stage development before preclinical or clinical evaluation.

Keywords: ophthalmic biomaterials, hydrogels, surface wettability, optical transparency, swelling behavior, in vitro study.

1. Introduction

The development of biomaterials for ophthalmic applications has advanced significantly over the past decades, driven by the need for transparent, hydrated, and surface-compatible materials capable of maintaining ocular comfort and functional integrity. Among these applications, materials intended for direct contact with the ocular surface, such as therapeutic contact lenses, corneal substitutes, and surface-protective hydrogels, must meet stringent optical and physicochemical requirements while preserving biocompatibility and structural stability [1].

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In this context, hydrogel-based biomaterials have emerged as leading candidates due to their high water content, tunable mechanical behavior, and optical transparency comparable to native corneal tissue [2].

Gelatin methacrylate (GelMA)-based systems have attracted increasing attention for corneal-related applications owing to their transparency, processability, and capacity to mimic extracellular matrix features [3]. Their adaptability has enabled the fabrication of hydrogel films and contact lens-like constructs with tailored surface and bulk properties, supporting their potential use in ocular surface regeneration and protection [2,4]. Similarly, gelatin-derived and polyethylene glycol-modified hydrogels have been explored for bandage contact lenses, where surface wettability and hydration behavior are critical for tear film stability and patient comfort [5].

Beyond GelMA-based materials, soft hydrogel contact lenses composed of pHEMA and related polymers remain a benchmark for evaluating surface wettability and optical performance in ophthalmic biomaterials research [6]. Advances in surface modification strategies, including layer-by-layer coatings and molecular imprinting, have further expanded the functional capabilities of hydrogel lenses while maintaining essential physicochemical properties [5,7]. These developments highlight the importance of systematically characterizing surface-related parameters, particularly wettability, which directly influences tear film interaction and protein adsorption [8].

Silicone hydrogel systems and interpenetrating polymer networks have also contributed valuable insights into the relationship between polymer composition, transparency, and hydration behavior [9]. Studies focusing on swelling dynamics and light transmittance have demonstrated that subtle variations in polymer architecture can significantly affect optical clarity and water uptake, both of which are critical for ocular applications [10]. Additionally, hybrid hydrogels combining natural and synthetic polymers have been proposed as corneal repair materials, emphasizing the relevance of transparency and hydration balance in maintaining visual function [11].

Recent progress in biofabrication and three-dimensional structuring of corneal substitutes has further underscored the need for rigorous physicochemical characterization of candidate biomaterials before preclinical or clinical translation [12]. High-strength natural polymer hydrogels and layered constructs have demonstrated promising optical and hydration-related properties, reinforcing the role of in vitro assessment as a foundational step in biomaterials development [11-13]. Although clinical and translational approaches continue to evolve, established ophthalmic materials research consistently identifies surface wettability, optical transparency, and swelling behavior as core determinants of material performance [14]. These parameters are closely linked to oxygen permeability and water content, which remain essential benchmarks in the evaluation of ophthalmic hydrogel materials [15].

Our study focuses on the comparative evaluation of the surface, optical, and hydration properties of selected hydrogel-based biomaterials intended for ocular surface applications, providing relevant experimental data for material selection and optimization, without relying on clinical or in vivo models.

Materials and Methods

Biomaterials and sample preparation

Three polymer-based hydrogel biomaterials intended for ocular surface applications were investigated: poly(2-hydroxyethyl methacrylate) (pHEMA), alginate, and gelatin methacrylate (GelMA). For each material, disc-shaped samples (diameter: 10 mm; thickness: 1.5 ± 0.1 mm) were prepared under standardized laboratory conditions to ensure reproducibility. All samples were visually inspected to exclude macroscopic defects and stored in phosphate-buffered saline (PBS, pH 7.4) at room temperature for 24 h before testing to reach hydration equilibrium. A total of 15 specimens were analyzed, with n = 5 samples per biomaterial group.

Surface wettability assessment

Surface wettability was evaluated by measuring the static water contact angle using the sessile drop method. A 5 µL droplet of distilled water was gently deposited onto the surface of each hydrated sample using a calibrated micropipette. Contact angle images were captured within 5 s after droplet deposition using an optical contact angle goniometer. For each specimen, three independent measurements were performed at different surface locations, and the mean value was used for statistical analysis. Results were expressed in degrees (°).

Optical transparency measurement

Optical properties were assessed by measuring light transmittance in the visible spectrum. Samples were placed in a quartz cuvette filled with PBS, and optical transmittance was recorded at a wavelength of 550 nm using a UV–Vis spectrophotometer. PBS was used as a blank reference. Measurements were performed in triplicate for each sample, and the mean transmittance value (%) was calculated.

Swelling behavior analysis

Hydration capacity was evaluated through swelling ratio determination. Samples were first dried to constant weight at room temperature and weighed to obtain the dry mass (W_dry). Subsequently, specimens were immersed in PBS (pH 7.4) for 24 h at room temperature, gently blotted to remove surface excess fluid, and reweighed to obtain the wet mass (W_wet).

The swelling ratio was calculated using the following equation:

$$\text{Swelling ratio} = \frac{W_{wet}}{W_{dry}}$$

Statistical analysis

Analyses were performed in GraphPad Prism 10.2.0 (Boston, MA, USA). Data were expressed as mean ± standard deviation (SD). The normality of data distribution was assessed using the Shapiro-Wilk test. Since all datasets showed normal distribution ($p > 0.05$), one-way analysis of variance (ANOVA) was applied to evaluate differences among the three biomaterial groups. When statistically significant differences were detected, Tukey's post-hoc test was used for pairwise comparisons. A value of $p < 0.05$ was considered statistically significant.

Results

Statistical assessment and group differences

Normality of data distribution was assessed using the Shapiro–Wilk test. Based on the normal distribution, one-way ANOVA was applied to evaluate global differences among the three biomaterial groups. Statistical significance was set at $p < 0.05$.

Table 1. Statistical assessment and global group differences

Parameter	Statistical test	Test value	p-value	Interpretation
Contact angle (°)	Shapiro-Wilk	W = 0.96-0.98	> 0.05	Normal distribution
	One-way ANOVA	F = 225.54	3.03×10^{-10}	Significant difference between groups
Optical transmittance (%)	Shapiro-Wilk	W = 0.95-0.99	> 0.05	Normal distribution
	One-way ANOVA	F = 52.61	1.15×10^{-6}	Significant difference between groups
Swelling ratio (Wwet/Wdry)	Shapiro–Wilk	W = 0.94-0.97	> 0.05	Normal distribution
	One-way ANOVA	F = 488.18	3.20×10^{-12}	Significant difference between groups

Surface-related properties of biomaterials

Surface-related performance was quantified through static water contact angle measurements (wettability) (n = 5 per group). Normality assumptions were met (Shapiro–Wilk, $p > 0.05$), therefore, one-way ANOVA followed by Tukey's post-hoc test was applied. Contact angle values differed significantly among the three biomaterial groups (ANOVA, $p < 0.001$), with alginate showing the lowest contact angle, GelMA intermediate values, and pHEMA the highest values, indicating distinct surface wettability profiles.

Table 2. Surface-related properties (wettability) of the investigated biomaterials

Biomaterial	Contact angle (°)	Statistical significance
pHEMA	64.8 ± 1.9	a
GelMA	55.0 ± 1.6	b
Alginate	42.0 ± 1.6	c

Values are presented as mean ± SD (n = 5). Different letters indicate statistically significant differences between groups (Tukey HSD, $p < 0.05$).

Optical and hydration properties

Optical transparency and hydration behavior were evaluated by measuring light transmittance at 550 nm and the swelling ratio (Wwet/Wdry) of the investigated biomaterials (n = 5 per group). All datasets followed a normal distribution (Shapiro–Wilk test, $p > 0.05$); therefore, one-way ANOVA with Tukey's post-hoc test was applied. Statistically significant differences were observed among the three biomaterial groups for both optical and hydration-related parameters ($p < 0.001$).

Table 3. Optical and hydration properties of the investigated biomaterials

Biomaterial	Transmittance at 550 nm (%)	Swelling ratio (Wwet/Wdry)	Post-hoc grouping
pHEMA	92.4 ± 1.1	1.58 ± 0.03	a
GelMA	88.8 ± 0.8	2.00 ± 0.04	b
Alginate	85.6 ± 1.1	2.44 ± 0.06	c

Values are expressed as mean ± standard deviation (n = 5) (Table 3). Different superscript letters indicate statistically significant differences between biomaterial groups based on Tukey's post-hoc test ($p < 0.05$).

Discussion

Our study in vitro evaluated surface-related, optical, and hydration properties of hydrogel-based biomaterials intended for ocular surface applications, focusing on parameters that are widely recognized as critical for ophthalmic performance. Surface wettability, optical transparency, and swelling behavior were selected as key indicators due to their direct influence on tear film interaction, visual clarity, and material stability under physiological conditions [1,2].

Surface wettability analysis demonstrated statistically significant differences among the investigated biomaterials, highlighting the strong dependence of contact angle values on polymer composition. This finding is consistent with previous observations that hydrogel chemistry and crosslinking density critically modulate surface hydrophilicity, which in turn affects tear film spreading and ocular comfort [2,6]. Materials exhibiting lower contact angles are generally associated with improved wettability and reduced friction at the ocular surface, a property considered desirable for therapeutic and bandage contact lenses [5,8]. The distinct wettability profiles observed in our study support the concept that even structurally similar hydrogels can display markedly different surface behaviors when formulated for ophthalmic use [7].

Optical transparency remains a non-negotiable requirement for biomaterials intended for corneal contact or substitution. The significant intergroup differences in light transmittance observed in this study align with prior reports indicating that polymer network homogeneity, water content, and phase separation phenomena play decisive roles in optical performance

[1,9,10]. The high transparency values recorded for specific hydrogel formulations are comparable to those reported for established ophthalmic materials and experimental corneal substitutes, reinforcing their suitability for applications where visual axis integrity must be preserved [3,11].

Hydration behavior, as reflected by the swelling ratio, further differentiated the evaluated biomaterials. Increased swelling capacity is commonly associated with enhanced water retention and oxygen diffusion, yet excessive swelling may compromise mechanical stability and dimensional fidelity [10,15]. The balanced hydration profiles observed for intermediate formulations suggest a favorable compromise between water uptake and structural integrity, a feature emphasized in previous studies on hydrogel contact lenses and corneal repair scaffolds [4,12]. These findings underscore the importance of tailoring swelling behavior to match the functional demands of the ocular surface environment [13].

Importantly, the in vitro design of our study allows for the isolation of material-driven effects without confounding biological variables. While preclinical and clinical investigations provide essential translational insights [12,14], early-stage physicochemical characterization remains a prerequisite for rational biomaterial selection and optimization. Within this context, the present results contribute experimental evidence supporting the relevance of standardized surface, optical, and hydration assessments in ophthalmic biomaterials research.

Conclusions

Our study in vitro demonstrated that hydrogel-based biomaterials intended for ocular surface applications exhibit distinct surface-related, optical, and hydration properties that are strongly dependent on polymer composition. Statistically significant differences in wettability, optical transparency, and swelling behavior were identified among the investigated materials, underscoring the importance of comprehensive physicochemical characterization when evaluating biomaterials for ophthalmic use. These parameters are directly relevant to tear film interaction, visual performance, and material stability, and therefore represent essential criteria in the early stages of biomaterial selection and optimization. The findings highlight the value of standardized in vitro assessment as a robust and ethically unrestricted approach for comparing candidate ophthalmic biomaterials. By isolating material-driven effects without biological confounders, such evaluations provide a rational foundation for subsequent preclinical development and application-specific refinement. Overall, the results support the integration of surface, optical, and hydration analyses as core components in the development pipeline of hydrogel-based biomaterials for ocular surface applications.

References

1. Farasatkia A, Kharaziha M, Ashrafizadeh F, Salehi S. *Transparent silk/gelatin methacrylate (GelMA) fibrillar film for corneal regeneration.* **Mater Sci Eng C Mater Biol Appl.** 2021;120:111744. doi:10.1016/j.msec.2020.111744.

2. Maldonado-Codina C, Efron N. *Dynamic wettability of pHEMA-based hydrogel contact lenses.* **Ophthalmic Physiol Opt.** 2006;26(4):408-418. doi:10.1111/j.1475-1313.2006.00394.x.
3. Kilic Bektas C, Burcu A, Gedikoglu G, Telek HH, Ornek F, Hasirci V. *Methacrylated gelatin hydrogels as corneal stroma substitutes: in vivo study.* **J Biomater Sci Polym Ed.** 2019;30(18):1803-1821. doi:10.1080/09205063.2019.1666236.
4. Bose S, Phan CM, Rizwan M, Tse JW, Yim E, Jones L. *Fabrication and characterization of an enzyme-triggered, therapeutic-releasing hydrogel bandage contact lens material.* **Pharmaceutics.** 2023;16(1):26. doi:10.3390/pharmaceutics16010026.
5. Zidan G, Greene CA, Etxabide A, Rupenthal ID, Seyfoddin A. *Gelatine-based drug-eluting bandage contact lenses: effect of PEGDA concentration and manufacturing technique.* **Int J Pharm.** 2021;599:120452. doi:10.1016/j.ijpharm.2021.120452.
6. Silva D, de Sousa HC, Gil MH, Santos LF, Moutinho GM, Salema-Oom M, et al. *Diclofenac sustained release from sterilised soft contact lens materials using an optimised layer-by-layer coating.* **Int J Pharm.** 2020;585:119506. doi:10.1016/j.ijpharm.2020.119506.
7. Silva D, de Sousa HC, Gil MH, Santos LF, Amaral RA, Saraiva JA, et al. *Imprinted hydrogels with LbL coating for dual drug release from soft contact lenses materials.* **Mater Sci Eng C Mater Biol Appl.** 2021;120:111687. doi:10.1016/j.msec.2020.111687.
8. Hui A, Willcox M, Jones L. *In vitro and in vivo evaluation of novel ciprofloxacin-releasing silicone hydrogel contact lenses.* **Invest Ophthalmol Vis Sci.** 2014;55(8):4896-4904. doi:10.1167/iovs.14-14855.
9. Chien HW, Kuo CJ. *Preparation, material properties and antimicrobial efficacy of silicone hydrogel by modulating silicone and hydrophilic monomer.* **J Biomater Sci Polym Ed.** 2019;30(12):1050-1067. doi:10.1080/09205063.2019.1620593.
10. Xu J, Zhang L, Zhang Y, Li T, Huo G. *Simultaneous interpenetrating silicone hydrogel based on radical/addition polymerization for extended release of ocular therapeutics.* **J Biomater Sci Polym Ed.** 2014;25(2):121-135. doi:10.1080/09205063.2013.841793.
11. Chen F, Le P, Fernandes-Cunha GM, Heilshorn SC, Myung D. *Bio-orthogonally crosslinked hyaluronate-collagen hydrogel for suture-free corneal defect repair.* **Biomaterials.** 2020;255:120176. doi:10.1016/j.biomaterials.2020.120176.
12. Basoz D, Akalinli A, Buyuksungur S, Celebi ARC, Yucel D, Hasirci N, et al. *Preclinical testing of 3D printed, cell loaded hydrogel based corneal substitutes on rabbit model.* **Macromol Biosci.** 2025;25(7):e2400595. doi:10.1002/mabi.202400595.
13. Nie X, Tang Y, Wu T, Zhao X, Xu Z, Yang R, et al. *3D printing sequentially strengthening high-strength natural polymer hydrogel bilayer scaffold for cornea regeneration.* **Regen Biomater.** 2024;11:rbae012. doi:10.1093/rb/rbae012.
14. Kitagawa K, Yanagisawa S, Watanabe K, Yunoki T, Hayashi A, Okabe M, et al. *A hyperdry amniotic membrane patch using a tissue adhesive for corneal perforations and bleb leaks.* **Am J Ophthalmol.** 2009;148(3):383-389. doi:10.1016/j.ajo.2009.03.030.

15. Efron N, Morgan PB, Cameron ID, Brennan NA, Goodwin M. *Oxygen permeability and water content of silicone hydrogel contact lens materials.* **Optom Vis Sci.** 2007;84(4):328-337. doi:10.1097/OPX.0b013e31804375ed.

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