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UV-curable polyether acrylate-based antifog coatings: enhanced hydrophilicity and durability in polycarbonate applications

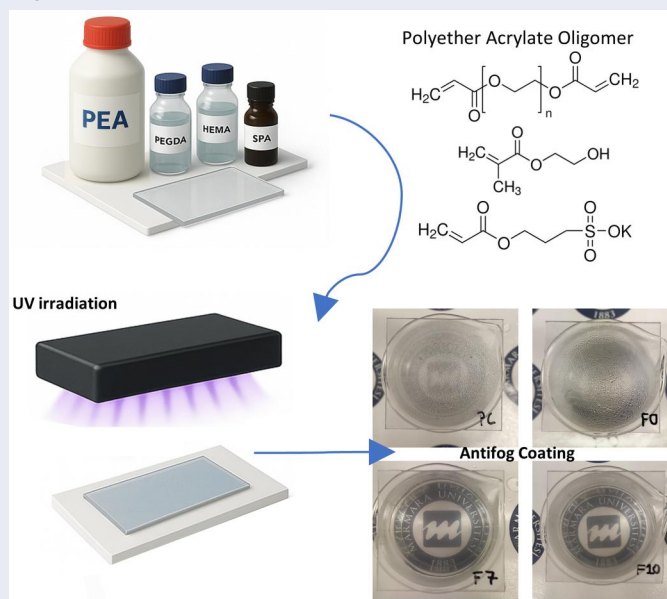
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ABSTRACT

The degradation of optical clarity in transparent materials poses serious challenges in applications such as automotive windshields, helmet visors, and medical devices, primarily due to fog formation. Fogging occurs when high ambient energy coincides with low surface free energy, leading to moisture condensation and light scattering. A UV-curable antifog coating was developed to address this issue, utilizing formulations that included a low-viscosity tetra-functional polyether acrylate oligomer, polyethylene glycol diacrylate, 2-hydroxyethyl methacrylate, and potassium 3-sulfopropyl acrylate (SPA) for improved hydrophilicity. The formulations were applied to polycarbonate substrates and cured under UV light. The coatings maintained over 90% light transmittance in the 300–600 nm range and reduced the water contact angle of polycarbonate from $\sim 74^\circ$ (uncoated) to $\sim 22\text{--}8^\circ$ depending on SPA content. Swelling ratios were moderate (25–32%), indicating a stable crosslinked hydrophilic network. Formulations containing 5–10 wt% SPA exhibited superior antifog performance without haze formation, while mechanical tests confirmed high surface hardness (4H–5H) and excellent adhesion. These findings demonstrate that the developed formulation provides a highly durable, optically transparent, and hydrophilic antifog coating suitable for advanced optical applications.

GRAPHICAL ABSTRACT



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KEYWORDS

Antifog coating; UV cured film; polyether acrylate; potassium 3-sulfopropyl acrylate; PEGDA; HEMA

1. Introduction

Transparent polymeric substrates such as polycarbonate (PC) are indispensable in a wide range of optical and engineering applications, including protective eyewear, automotive windshields, helmet visors, medical devices, packaging films, and advanced display technologies, owing to their high optical transparency, lightweight nature, and excellent mechanical

strength.^[1–3] However, the functionality and safety of these systems are often compromised by fogging, which results from the condensation of ambient water vapor on relatively cooler surfaces. The nucleation of microscopic water droplets leads to light scattering and reduced transmittance, thereby impairing visibility and, in critical applications, creating severe safety concerns.^[4–8]

Table 1. Molar equivalents of reactants for UV-curable coatings.

Formulation	LR8982 (mmol-eq)	HEMA (mmol-eq)	PEGDA (mmol-eq)	SPA (mmol-eq)	Total (mmol-eq)
F0	0.056	4.61	1.391	0	6.058
F3	0.056	4.61	1.391	0.258	6.316
F5	0.056	4.61	1.391	0.43	6.488
F7	0.056	4.61	1.391	0.603	6.66
F10	0.056	4.61	1.391	0.861	6.919
F15	0.056	4.61	1.391	1.291	7.349
F20	0.056	4.61	1.391	1.722	7.78

To overcome this problem, extensive research has focused on antifogging strategies. The most established approach involves generating hydrophilic or superhydrophilic surfaces, which promote rapid spreading of condensed water into a continuous film, thus preventing discrete droplet formation. Surfactant-based coatings, hydrophilic polymers, hydrogel films, and photocatalytic oxides such as TiO_2 have been widely investigated in this context.^[9–12] Despite their effectiveness, such coatings often exhibit poor long-term durability, limited mechanical robustness, and optical instability. Moreover, solvent-based formulations raise environmental and processing concerns.^[13]

In recent years, UV-curable coatings have emerged as a promising alternative, offering rapid photopolymerization, superior adhesion to polymeric substrates, controllable cross-link density, and environmentally benign solvent-free processing.^[14,15] Within these systems, incorporation of functional monomers has proven essential to tailoring surface chemistry and optimizing antifog efficiency. In particular, sulfonated acrylate monomers have attracted increasing attention because the strong polarity of the $-\text{SO}_3^-$ group significantly enhances water spreading, reduces contact angle, and stabilizes a uniform thin water film.^[16,17] Mechanistically, sulfonate groups provide ionic hydration shells and hydrogen-bonding interactions that sustain hydrophilicity even after repeated exposure to humid environments, offering a more robust antifog mechanism than nonionic hydrophilic additives.

Historically, the use of potassium 3-sulfopropyl acrylate (SPA) in UV-curable formulations was first explored in industrial reports and technical literature more than a decade ago, where its ionic functionality was shown to provide durable transparency and antifogging stability compared with conventional poly(ethylene glycol)-based systems.^[18,19] Building on these findings, recent academic studies have advanced the field through the design of zwitter-wettable or amphiphilic UV-curable coatings. For example, Zhong et al.^[11] developed fast UV-curable zwitter-wettable coatings with reliable antifogging and frost-resisting performance; Mossayebi et al.^[8] demonstrated chemically robust nanoscale amphiphilic coatings; and Zhu et al.^[17] reported transparent hydrophilic coatings combining antifog, self-cleaning, and antibacterial functionalities. These advances consistently underscore the pivotal role of highly polar or ionic monomers in achieving long-lasting antifogging effects under demanding conditions.

Accordingly, the present study addresses the research gap by systematically evaluating the role of SPA content (5–20 wt%) in UV-curable polyether acrylate/PEGDA/HEMA coatings on PC substrates. Comprehensive

Table 2. Weight composition of reactants for UV-curable antifog coatings.

Formulation	LR8982 (g)	HEMA (g)	PEGDA (g)	SPA (g)	IRGACURE 184
F0	0.7	0.6	0.4	–	0.05
F3	0.7	0.6	0.4	0.06	0.05
F5	0.7	0.6	0.4	0.10	0.05
F7	0.7	0.6	0.4	0.14	0.05
F10	0.7	0.6	0.4	0.20	0.05
F15	0.7	0.6	0.4	0.30	0.05
F20	0.7	0.6	0.4	0.40	0.05

characterization—including UV-vis transmittance, water contact angle, fogging resistance under steam exposure, swelling behavior, and mechanical/chemical stability—was performed to elucidate the correlation between SPA concentration and coating performance. Our results reveal that intermediate SPA contents (5–10 wt%) yield an optimal balance between transparency, antifogging efficiency, and mechanical robustness, while excessive SPA loading (>15 wt%) leads to haze despite eliminating fog formation. By combining mechanistic understanding with systematic experimental evaluation, this study provides fundamental insights and practical guidelines for the rational design of durable, transparent, and environmentally sustainable antifog coatings for next-generation optical and biomedical applications.

2. Experimental

2.1. Materials

Polycarbonate (PC) plate, polyether acrylate oligomer LR8982 (BASF, Germany), polyethylene glycol diacrylate (PEGDA), 2-hydroxyethyl methacrylate (HEMA), potassium 3-sulfopropyl acrylate (SPA) (Sigma Aldrich, Netherlands), and Irgacure 184 (Ciba Specialty Chemicals, Switzerland).

2.2. Preparation of coating formulations

The coating formulations were prepared by combining a commercial polyether acrylate oligomer with two reactive monomers: 2-hydroxyethyl methacrylate and polyethylene glycol diacrylate to promote crosslinking and film integrity. To enhance surface hydrophilicity and antifog performance, potassium 3-sulfopropyl acrylate (SPA) was incorporated in varying concentrations (5–10 wt%) depending on the formulation, Irgacure 184 was added as the photoinitiator. All components were mixed thoroughly at room temperature until a homogeneous solution was obtained. The formulations are given in Tables 1 and 2.

2.3. Application and curing on polycarbonate substrates

Each coating formulation was applied onto clean PC plates using a 30 μm film applicator. The coatings were drawn uniformly across the surface in a single pass to ensure consistent film thickness. The coated substrates were then cured under UV irradiation using a high-intensity UV lamp for complete crosslinking.

2.4. Fabrication of free-standing films

To prepare free-standing films, the same formulations were poured into Teflon[®] molds with dimensions of 50 mm $\times$ 10 mm $\times$ 1 mm. The molds were exposed to UV light for 5 min using a high-pressure UV curing system. After curing, flexible and transparent films approximately 1 mm in thickness were obtained and demolded. These films were subsequently used for structural, thermal and surface characterizations. Figure 1 shows a schematic representation of the film preparation procedure.

3. Characterization techniques

3.1. Film curing equipment

3.1.1. UV irradiation system (handheld)

A high-pressure mercury arc lamp (Ultrawit 300, 300 W, Osram) equipped with a quartz glass housing and a tungsten filament was used to cure the films. The spectral output closely resembles natural sunlight enabling effective photopolymerization.

3.1.2. Laboratory-scale UV curing unit

For coatings applied on PC plates, UV curing was performed using a custom-built laboratory-scale curing machine (EMA

Industrial Machinery, Turkey) providing controlled and uniform irradiation.

3.2. Chemical and optical characterization

3.2.1. Fourier-transform infrared Spectroscopy (ATR-FTIR)

Functional group analysis of cured coatings was performed using a PerkinElmer Spectrum 100 ATR-FTIR spectrophotometer. Spectra were recorded in the range of 4000–380 cm^{-1} to confirm characteristic bonding features of the formulation components.

3.2.2. UV-visible spectroscopy

Optical transmittance of the coatings in the visible region (300–600 nm) was evaluated using a Shimadzu UV-2450 spectrophotometer providing insight into the transparency and optical quality of the coated surfaces.

3.2.3. Contact angle measurements

The static water contact angle was measured using a Krüss FM41 contact angle goniometer (Serial No. 20001606). Three water droplets were placed on each surface at room temperature and the average of the measurements was used to assess the hydrophilicity of SPA-containing formulations.

3.3. Thermal and structural analysis

3.3.1. Thermogravimetric analysis (TGA)

Thermal stability of the free-standing films was investigated using a PerkinElmer Pyris TGA system under nitrogen atmosphere. Samples were heated from 30 $^{\circ}\text{C}$ to 750 $^{\circ}\text{C}$ at a constant rate of 10 $^{\circ}\text{C}/\text{min}$ to determine degradation temperatures and residual mass.

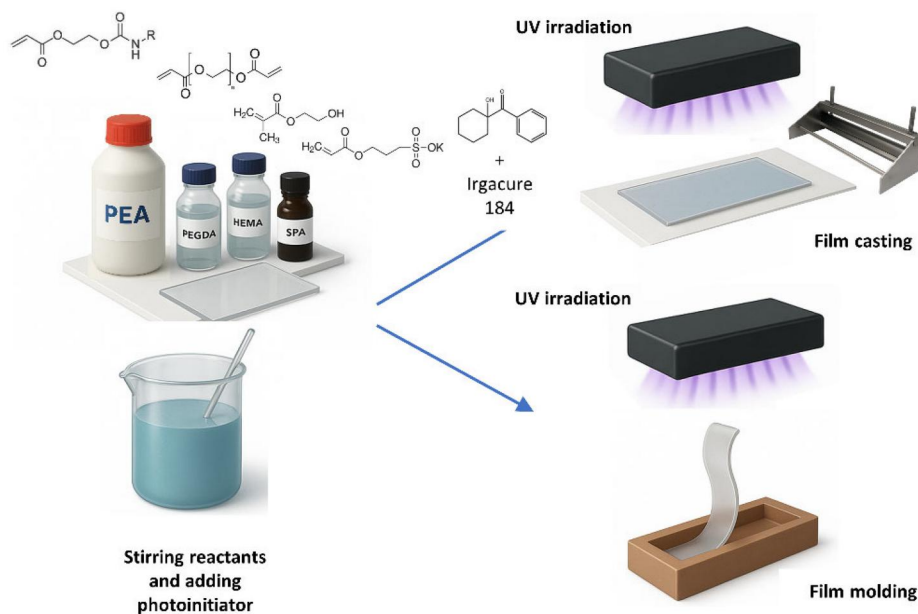


Figure 1. Schematic representation of film preparation.

3.3.2. Scanning Electron Microscopy (SEM)

Fractured cross-sections of gold-sputtered free-standing films were examined using a Philips XL 30 ESEM-FEG/EDAX SEM instrument for surface morphology, elemental composition and elemental mapping. SEM analyses were performed at Boğaziçi University.

3.4. Evaluation of antifogging and coating properties

3.4.1. Fogging test

Antifog performance was evaluated *via* direct steam exposure. Coated samples were held over a beaker containing freshly boiled water with the coating surface facing downward toward the vapor. Fog formation was visually inspected immediately after exposure.

3.5. Mechanical and chemical resistance tests

3.5.1. Pencil hardness test

Surface hardness was determined according to ASTM D3363-74 using a series of pencils ranging from 1H to 6H. Each pencil was applied at a 45° angle under consistent force. The hardest pencil that did not scratch the surface was recorded as the coating's pencil hardness. Five measurements were taken for each sample and the average value was reported.

3.5.2. Cross-cut adhesion test

Adhesion of the coatings to PC substrates was evaluated using a Gardco cross-cut adhesion tester according to ASTM D3359. A 1 mm × 1 mm grid was cut into the coating layer using a specialized blade. Following brushing and tape application (Scotch tape), the number of detached squares was counted and the adhesion percentage calculated using:

$$\text{Adhesion(\%)} = \frac{A}{A_0} \times 100$$

where A_0 is the initial number of squares and A is the number remaining after tape removal. Results were further classified on a 0–5 rating scale based on the amount of detachment.

3.5.3. Solvent rub test

The chemical resistance of the coatings was evaluated using a methyl ethyl ketone (MEK) rub test. A cotton cloth soaked with MEK was rubbed over the coated surface in a back-and-forth motion with each cycle counted as one rub. Changes in appearance or damage to the coating were recorded.

3.5.4. Chemical resistance

Chemical resistance was assessed by placing a drop of concentrated sulfuric acid (H_2SO_4), sodium hydroxide (NaOH), and xylene directly onto the coated surface. Samples were

left undisturbed for 24 h, after which surface changes such as discoloration, blistering, or degradation were noted.

3.5.5. Swelling test

Swelling behavior was assessed by immersing dried free-standing films in distilled water for 24 h. Initial dry mass (M_0) and swollen mass after immersion (M_1) were recorded and the swelling percentage was calculated as:

$$\text{Swelling(\%)} = \frac{M_1 - M_0}{M_0} \times 100$$

Three replicate measurements were taken per formulation and the average swelling ratio was reported.

3.5.6. Solvents used

For surface and chemical resistance evaluations, technical grade solvents such as xylene, sulfuric acid, sodium hydroxide, and methyl ethyl ketone (MEK) were used without further purification.

4. Results and discussion

The characterization of mixtures prepared with polyacrylate oligomer, four-functional LR 8982, difunctional PEGDA, mono functional HEMA and mono functional SPA in varying ratios for non-fogging coating formulations was performed using ATR-FTIR spectroscopy. The ATR-FTIR characterization of the formulations, obtained from the surfaces of the uncured formulation and the coated PC layer after UV curing, is shown in Figure 2(a).

The ATR-FTIR spectra of the coatings confirm the successful incorporation of acrylate and sulfonated functionalities (Figure 2a). The absorption band at $\sim 1180 \text{ cm}^{-1}$ corresponds to C–O stretching of ester groups typical of acrylate backbones.^[18] The peak near 1350 cm^{-1} arises from the asymmetric S=O stretching of sulfonate groups introduced by SPA, with increasing intensity at higher SPA contents. The strong band at $\sim 1720 \text{ cm}^{-1}$ is assigned to the C=O stretching vibration of acrylate and methacrylate moieties.^[19,20] The broad absorption band centered around 3400 cm^{-1} is attributed to hydroxyl groups, originating from both residual HEMA and moisture affinity of sulfonated domains.^[21–24] Collectively, these spectral features support the formation of crosslinked, hydrophilic networks consistent with the designed formulation.

The optical transmittance of the coatings was initially evaluated in the 300–600 nm region to confirm that the incorporation of SPA does not compromise the intrinsic transparency of PC (Figure 2b). However, it should be noted that the most relevant range for practical optical applications lies within 380–780 nm, which corresponds to the visible spectrum perceived by the human eye. In addition, a complete assessment of transparency in polymeric coatings requires not only total light transmittance but also the separation of parallel (direct) transmission and diffuse scattering, the latter being quantified as “haze.”^[22] Although haze was not measured in the present study, our results consistently

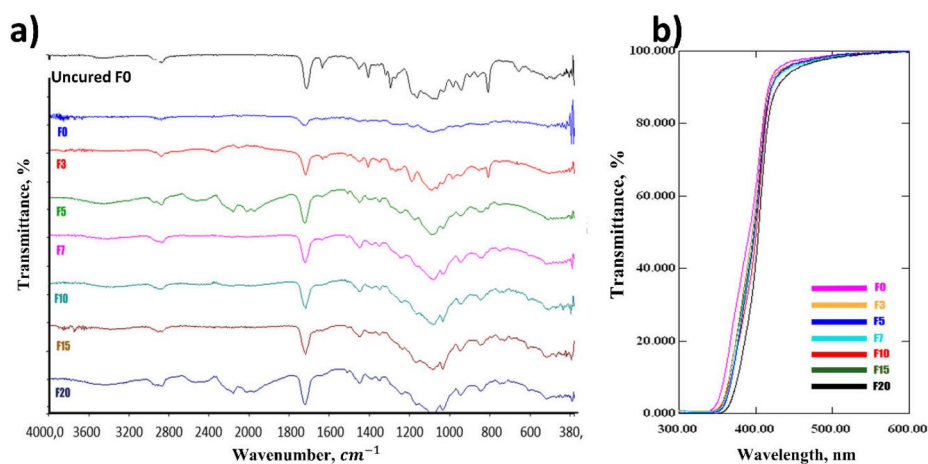


Figure 2. (a) Characterization of the coating structure using FTIR and (b) light transmittance of free films in the visible region.

indicate that excessive SPA loading (>15 wt%) induced visual cloudiness, qualitatively supporting the importance of haze analysis. Future work will therefore extend optical measurements to the 380–780 nm region and include quantitative haze determination for a more rigorous evaluation of transparency.

Contact angle measurements were performed by depositing distilled water, a polar solvent, onto polycarbonate surfaces. The native water contact angle of uncoated polycarbonate is reported to be approximately 74° .^[25,26] In this study, PC substrates were coated with formulations containing increasing amounts of SPA and distilled water droplets were applied to the surface for measurement. The contact angles formed between the water droplets and each coated surface were recorded and are visually presented in Figure 3. The mean contact angle values, calculated from three independent measurements per sample, are summarized in Table 3. It should be noted that the present study reports only the static contact angle, which provides a basic measure of surface wettability. However, for vapor-barrier and antifog surfaces, dynamic wettability parameters such as contact angle hysteresis (advancing and receding angles) and the slip angle (the minimum tilt angle at which a droplet begins to slide) are considered more decisive.^[27,28] These measurements provide insights into droplet mobility, surface pinning, and the energy barriers governing condensation/evaporation cycles. Although not included in the current work, future investigations will incorporate these analyses to better correlate SPA content with functional antifog performance.

As shown in Table 3, increasing the SPA content in the coating significantly reduced the water contact angle. This indicates enhanced surface wettability, attributed to the suppression of water cohesion and improved spreading behavior on the coating surface.

The antifog performance of the coatings was evaluated through a steam exposure test. This was conducted by placing freshly boiled water into a beaker and positioning the coated surface of the polycarbonate (PC) sample directly above the beaker opening, allowing the surface to be exposed to water vapor. Observations for each sample are

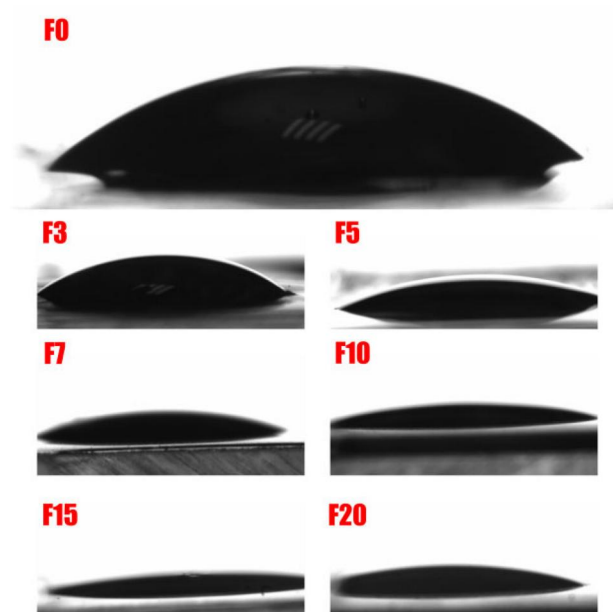


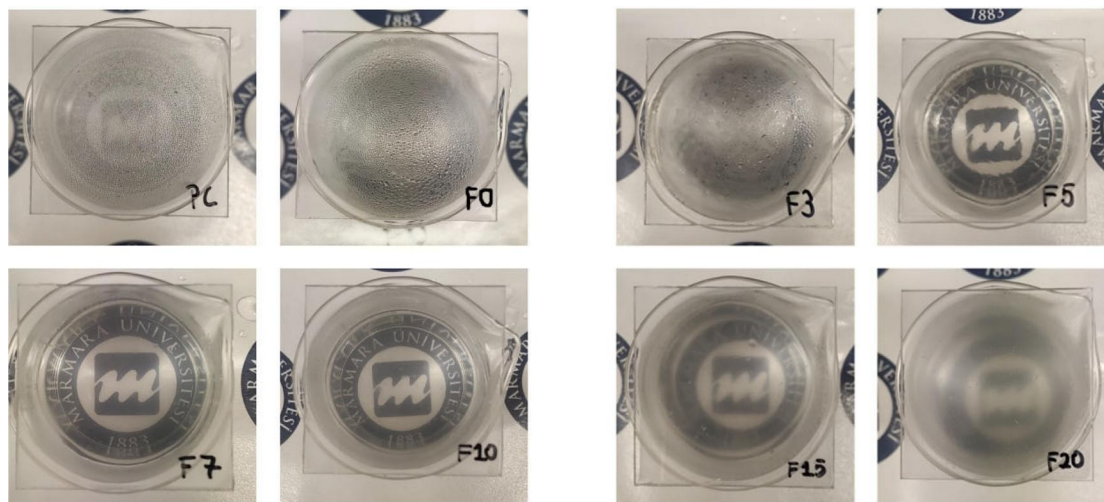
Figure 3. Images of the contact angle formed by coated polycarbonate plates when in contact with water.

summarized in Table 3 and representative images captured during the fogging test are presented in Figure 4.

While fog formation was evident on the uncoated PC surface as well as on coatings with formulations F0 and F3, formulations F5, F7, and F10 demonstrated excellent anti-fogging performance along with high optical transparency. Although no fog formation was observed for F15 and F20 formulations, the higher SPA content resulted in a hazy appearance, indicating that excessive SPA may compromise visual clarity despite preventing fog condensation. The anti-fog performance was assessed qualitatively by exposing coated PC substrates to boiling water vapor, followed by visual inspection (Figure 4). While this approach demonstrates clear differences in fog formation between samples, it is a nonstandard and operator-dependent method. More rigorous assessment of antifog coatings generally requires quantification of mist onset time (time until fog first appears), transmission stability during condensation, and mist clearance time (time required to regain transparency after

Table 3. Contact angle values and fog test results of the prepared coatings.

Tests	F0	F3	F5	F7	F10	F15	F20
Contact angle	47.70	36.09	27.87	22.34	8.73	8.42	2.87
Fog test	Fogging	Fogging	No fog formation	No fog formation	No fog formation	No fog formation	No fog formation

**Figure 4.** Fog formation on prepared coatings.

fogging).^[29,30] Additionally, the visual observation that F15 and F20 do not fog but exhibit “haze” indicates the need for quantitative haze and clarity measurements (e.g. ASTM D1003 standard test for haze and luminous transmittance).^[31] Although not included in this study, future work will incorporate these standardized metrics to provide a more comprehensive evaluation of antifog performance and optical quality.

The fracture surface morphologies of the coatings were examined using Scanning Electron Microscopy (Figure 5). Based on the surface morphologies, it can be said that the coatings have dense cross-links and a solid surface that is close to ideal with no voids.

The thermal stability of the UV-curable antifog coatings was assessed using thermogravimetric analysis (TGA). Free-standing film samples were heated from 30 °C to 750 °C at a rate of 10 °C/min under a nitrogen atmosphere. The resulting thermograms provided insight into the thermal degradation behavior of the materials. TGA spectra of the prepared coatings are presented in Figure 6 and the corresponding thermal decomposition data are summarized in Table 4.

As shown in Table 4, the incorporation of SPA into the formulations resulted in a clear improvement in thermal stability. With increasing SPA content, the total mass loss decreased (from 99.45% for F0 to 87.58% for F20), consistent with the higher char residue formed at elevated SPA loadings. At the same time, the onset temperature of thermal degradation (T_5) increased significantly, from 250 °C for the F3 sample to 275 °C for F15 and up to 289 °C for F20. A slight increase in T_{50} was also observed (420 °C for F0 to 431 °C for F20). These results indicate that SPA not only promotes greater thermal residue formation but also shifts the degradation to higher temperatures, thereby enhancing the overall thermal resistance of the coatings.^[32,33]

Nevertheless, the improved thermal stability observed with increasing SPA should be interpreted cautiously. The increase in ash content and the higher T_5 % values indeed reflect the contribution of inorganic potassium sulfonate, which forms nonvolatile residues upon degradation. This mineral loading effect partly explains the reduced overall mass loss. However, the systematic shift of degradation onset to higher temperatures also suggests that the incorporation of ionic sulfonate groups within the crosslinked acrylate matrix introduces stronger intermolecular interactions and reduced chain mobility, thereby retarding thermal decomposition. Therefore, the enhanced thermal stability is considered to result from a synergistic effect of inorganic residue formation and ionic reinforcement of the polymer network, rather than exclusively from mineral loading.

The swelling ratios obtained from the swelling test of the antifog coatings are presented in Table 5. Despite the presence of a crosslinked polymeric network, measurable swelling (25%–32%) was observed due to the inherently hydrophilic nature of the coatings, which arises from the affinity of polar functional groups within the formulation. While these values confirm the hydrophilic character of the films, it should be noted that such high water uptake in thinner coatings typically results in haze formation and reduced modulus. In the present study, no direct correlation between swelling behavior and the optical/mechanical performance data (transmittance and hardness) was established. A more comprehensive evaluation would require swelling kinetics as a function of time and film thickness, as well as moisture absorption isotherms obtained by Dynamic Vapor Sorption (DVS).^[34,35] Although not performed in this work, these analyses are planned for future studies to elucidate the coupling between water uptake, transparency, and mechanical stability in SPA-based antifog coatings.

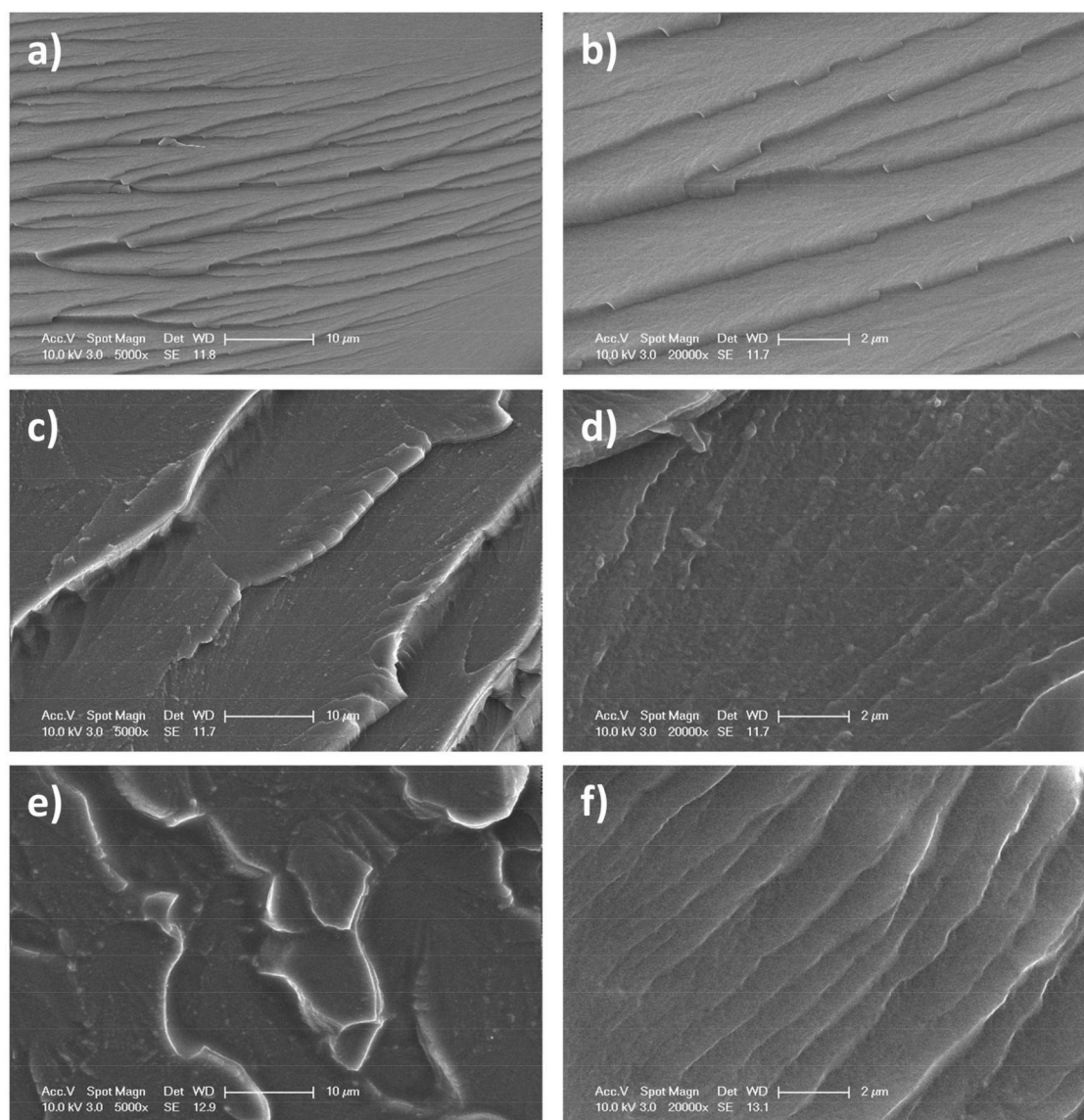


Figure 5. SEM images of samples with (a,b) F3 formulation, (c,d) F7 formulation, and (e,f) F15 formulation.

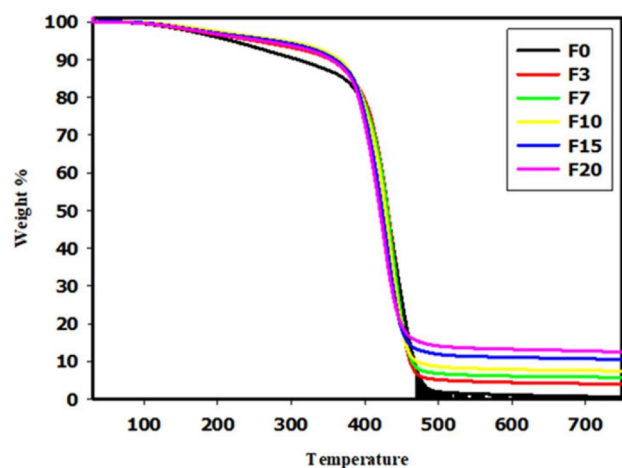


Figure 6. TGA thermograms of non-fogging coatings.

Table 4. TGA analysis results of films that do not fog in a nitrogen atmosphere.

Sample	T ₅ (°C)	T ₅₀ (°C)	Ash (%)
F0	218	420	0.55
F3	250	423	3.96
F5	255	424	5.66
F7	259	425	7.45
F10	260	427	7.40
F15	275	430	10.42
F20	289	431	12.42

Table 5. Swelling behavior, pencil hardness, and MEK rub resistance of UV-curable coatings.

Test	F0	F3	F5	F7	F10	F15	F20
Swelling ratio	25.03	28.80	32.18	31.45	27.95	27.89	26.97
Pencil hardness	H	H	4H	4H	4H	5H	5H
MEK rubbing	300+	300+	300+	300+	300+	300+	300+

The results of the pencil hardness test revealed that surface hardness values ranged between H and 5H. As shown in Table 5, formulations with higher SPA concentrations,

particularly F5 and beyond, which also exhibited excellent antifogging performance, demonstrated pencil hardness values exceeding 4H. This indicates that the incorporation of

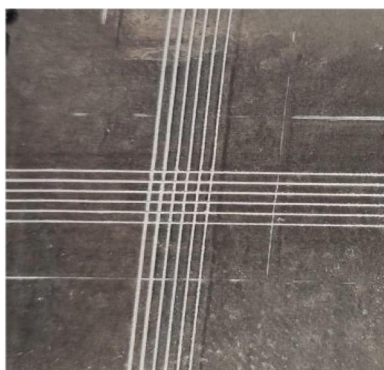


Figure 7. Cross-cutting applied to the coating surface.

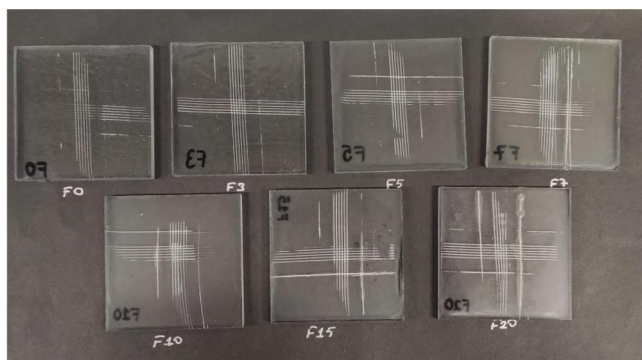


Figure 8. Adhesion performance of anti-fog coatings on polycarbonate plate surfaces.

SPA not only enhances antifog properties but also contributes to improved mechanical durability of the coatings.

As illustrated in [Figure 7](#), a cross-hatch pattern was created on the coated surface using parallel cuts spaced 1 mm apart. The adhesion performance was evaluated based on the amount of coating removed by adhesive tape and the results, reflecting the degree of adhesion between the coating and the substrate, are summarized in [Table 5](#).

Cross-cut adhesion tests demonstrated excellent adhesion across all coating formulations, with no observable detachment of coating fragments, as shown in [Figure 8](#). The removal rate was determined to be 0%, indicating strong interfacial bonding between the hydrophilic coating formulations and the polycarbonate (PC) substrate. These results confirm the effective interaction and compatibility between the coating and the PC surface.

The solvent resistance of the antifog coatings was evaluated using the methyl ethyl ketone (MEK) rub test. In this method, each back-and-forth motion was counted as a single rub. As shown in [Table 5](#), all formulations withstood more than 300 rubs without visible damage, indicating excellent resistance to solvent attack. These results confirm the strong chemical stability of the coatings under aggressive solvent exposure.

The chemical resistance of the antifog coatings was assessed by applying various chemical agents onto the sample surfaces and allowing them to remain in contact for 24 h. Upon exposure to concentrated sulfuric acid (H_2SO_4), discoloration and surface degradation such as yellowing and pitting were observed. In the case of concentrated sodium

hydroxide (NaOH), blistering and partial delamination of the coatings occurred. However, no visible changes were detected on the surfaces treated with xylene, indicating high resistance to non-polar organic solvents.

5. Conclusions

In this study, UV-curable antifog coatings were successfully developed to prevent fog formation on optically transparent polycarbonate surfaces. Coating formulations containing varying concentrations of potassium 3-sulfopropyl acrylate (SPA) yielded highly crosslinked, hydrophilic networks, where the sulfonate ($-\text{SO}_3^-$) groups from SPA and hydroxyl ($-\text{OH}$) groups from HEMA significantly enhanced surface hydrophilicity, promoting water spreading and suppressing condensation. As evidenced by fog and contact angle tests, water droplets dispersed uniformly on the coated surfaces, thereby preventing light scattering and preserving optical clarity. FTIR confirmed the formation of crosslinked polymer networks, while UV-Vis spectroscopy demonstrated that SPA incorporation maintained transparency within the 300–600 nm range. Mechanical and chemical stability were supported by swelling, hardness, adhesion, solvent rub and resistance tests, and TGA indicated improved thermal endurance. Among all tested formulations, those containing 5–10 wt% SPA (F5, F7, and F10) exhibited the best balance of light transmittance, antifog performance, and durability, making them promising candidates for optical applications. Nevertheless, it should be noted that optical characterization was limited to 300–600 nm and haze was not quantified and only static contact angles and qualitative fogging tests were performed. Future research will therefore focus on extending optical analysis to the full visible range (380–780 nm) with haze determination, incorporating dynamic wettability parameters (advancing/receding angles and slip angle), and evaluating long-term performance under abrasion, washing, and humidity aging. These additional studies will provide a more comprehensive understanding of the structure-property relationships and accelerate the translation of SPA-based UV-curable coatings into advanced optical and biomedical applications.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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