# Challenges and persistence of contact lenses in wastewater treatment plants: Environmental implications

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### Abstract

Contact Lens (CLs) are often disposed of via toilet or sinks, ending up in the wastewater treatment plants (WWTPs). Millions of CLs enter WWTPs worldwide each year in macro and micro sizes. Despite WWTPs' ability to remove solids, CLs can persist and potentially contaminate watercourses and soils. This study evaluates whether different CLs degrade in WWTP aeration tanks. Six daily CLs (Nelfilcon A, Delefilcon A, Nesofilcon A, Stenfilcon A, Narafilcon A, Somofilcon A) and four monthly CLs (Lotrafilcon B, Comfilcon A, Senofilcon A, and Samfilcon A) were immersed in aeration tanks for twelve weeks. Their physical and chemical properties, including water content (WC), refractive index (RI), chemical properties (Fourier Transform Infrared Spectroscopy), and mechanical properties were assessed.

Results show that all CLs maintained their physical appearance after 12 weeks. Neither Nelfilcon A nor Narafilcon A exhibited significant changes in WC and RI, (p > 0.05, Tukey test), while other daily lenses showed variations in at least one parameter.

Among monthly CLs, only Senofilcon A showed significant differences in both WC ( $p<0.001$, Tukey test) and RI ( $p<0.0001$, Tukey test). No differences in Young's modulus were observed for any lenses ( $p>0.05$ Tukey test). However, Somofilcon A displayed significant changes in stress at break ( $p<0.0001$, Tukey test), and Elongation at Break ( $p<0.05$, Tukey test). No changes were found in the chemical structure of any CLs suggesting that twelve weeks in WWTP aeration tanks is insufficient for CLs degradation. These findings highlight CLs as a potential emerging pollutant, emphasizing their persistence in sludge or migration into watercourses and soils. 

# Introduction

Contact lenses (CLs) may cause a negative environmental impact due to the disposal of both lenses, their packaging, and the packing solutions, which usually consist of a buffer solution with preservatives to keep the lenses sterile [1]. Though cardboard boxes and plastic blisters can be recyclable, the lenses and the packing solutions are often discarded in organic waste or flushed down the toilet or lavatory. A study suggests that the environmental impact resulting from the waste produced by CLs products is minor compared to domestic waste [2]. However, in the United States of America, 1.8 to 3.36 billion lenses are annually discarded down the toilet, ending in Wastewater Treatment Plants (WWTP) [3]. As the prevalence of myopia continues to increase in the human population, the number of individuals opting to wear CLs is anticipated to rise [4]. Daily and monthly disposable modalities are the most favored choices. According to the International Contact Lens Prescribing in 2023, daily disposables represent the most widely prescribed lens (52 %), followed by monthly lenses (35 %) [5].

At WWTP, solid items are blocked in the pretreatment, especially solids with a diameter of 2 cm and heavy solids. The remaining solids in suspension and scum are removed in the primary treatment [6]. However, solids, such as CLs, can break apart within the wastewater, facilitating their transport through the sewer network to the WWTP [7]. In the secondary treatment of WWTP, the biological process occurs in the aeration tanks, where microbial biomass removes pollutants and degrades dissolved organic matter [8]. The microorganisms, mainly bacteria, but also fungi and protozoa, are concentrated in aeration tanks, receiving soluble oxygen and carbon sources from the effluent [9]. Retention time in activated tanks varies from hours to days depending on WWTPs and affects microbial community composition and system functions [3,9]. In the second part of the secondary treatment, biological sludge is separated by sedimentation, and the effluent is then directed to the tertiary treatment [10], where it could be filtered and disinfected before being discharged. The sludge is also treated and often used as soil fertilizer [9,11].

Despite the lack of studies on bacterial degradation of CLs polymers in aeration tanks, it is known that microorganisms, such as bacteria, can damage synthetic polymers' structure and function [12]. The polymer's chemical structure, molecular weight, and specific microorganisms present on material surfaces influence this [13,14]. However, lenses consist of a polymeric gel structure, containing monomers like hydroxyethyl methacrylate (HEMA), crosslinked to ethylene glycol dimethyl acrylate or silicone hydrogel (SiHy), and other monomers to increase the performance of the lenses [15-18]. These materials can maintain their physical dimensions or revert to their original shape under external forces [19,20]. Understanding the degradation process of these materials is essential. While degradation involves a loss of properties, deterioration is associated with a decline in performance and functionality [21,22]. Previous studies have demonstrated that CLs undergo minimal alterations in their physicochemical properties after exposure to various conditions, indicating their stability [23-25]. However, in WWTPs, a study suggested that lenses behave like microbeads and microfibers, potentially passing through water treatment processes without degradation [3]. If they pass through WWTP, they may end up in watercourses or be retained in the sludge, which is commonly used as fertilizer [11].

The hypothesis is that bacterial biomass can degrade the CL polymers, but more than one week may be required [3,14]. This study aims to assess the capacity of different lenses to degrade in the aeration tanks of WWTP [3,14].This research will provide insights into whether bacterial biomass can degrade CL polymers or if CLs should be considered a potential environmental threat.

# Material and methods

To conduct the tests in the WWTP, six daily disposable CLs (Nelfilcon A, Delefilcon A, Nesofilcon A, Stenfilcon A, Narafilcon A, and Somofilcon A) and four monthly CL (Lotrafilcon B, Comfilcon A, Senofilcon A, and Samfilcon A) were selected based on their relevance in the international market and material composition, disregarding the lens power [26]. The selected lenses were new but beyond their expiration date. Their compositions, chemical, and physical characteristics are detailed in Table 1. Although lens power was not considered in this study, Table 1 presents the Refractive Index (RI) and center thickness corresponding to a standard power of -3.00 D . These values are commonly used as references, though they may vary slightly with different powers [27].

## In situ experiments in a wastewater treatment plant

The tests were conducted at Braga's WWTP (Portugal), which includes primary, secondary, and tertiary treatment stages. This study was conducted during the transition from late winter to early spring, specifically during the biological wastewater treatment process in aeration tanks, where bacteria decompose dissolved organic waste. The study was conducted from January to April 2022, with an average temperature of $6.9^{\circ} C$, characterized by large
thermal amplitudes (approximately $17.2^{\circ} C$ ). The average precipitation during this

period was 65.78 mm , with February having the least precipitation ( 31.9 mm ) and March the most ( 144.3 mm ). A total of ten different lens materials were used, with ten lenses of each material placed into separate fine mesh bags (e.g., ten lenses of Delefilcon A in one bag and ten lenses of Nelfilcon A in another). To ensure replicability, three bags per material were used at each time point, resulting in a total of thirty lenses from each material included in the study. The bags were placed in a weighted plastic basket to ensure full immersion in the aeration tanks. Steel cables secured the baskets to the tank edge, passing through the foam on the surface without touching the bottom. The lenses were immersed for twelve weeks, with all bags submerged simultaneously. At weeks 1, 3, 6, and 12, three bags per material were collected, and the lenses were washed and stored in deionized water for subsequent analysis. Analyses were also performed on new lenses, which were similarly cleaned and stored in deionized water before immersion.

# Water content and refractive index

Water content (WC) and RI were measured using the digital automated refractometer CLR 12-70 (Index Instruments, Cambridge, United Kingdom). This equipment directly reads the RI through back reflection at 589 nm and estimates WC based on a derived correlation with the RI [18]. Before measurement, CLs were gently cleaned to remove excess deionized water. Three lenses per bag were analyzed, and each lens was measured three times to increase reliability. The mean value of these measurements was used for analysis.

# Attenuated total reflectance- Fourier Transform Infrared Spectroscopy

New and twelve-week incubated CLs were characterized by Fourier Transform Infrared Spectroscopy-Attenuated Total Reflectance (FTIR-ATR). After being cleaned with deionized water and dehydrated at room temperature ( $20-22^{\circ}C$ ), analyses were performed using a Spectrum Two ™ spectrometer by PerkinElmer coupled with an UATR accessory (single reflection crystal diamond; PerkinElmer). Spectra were acquired in the range of $4000\ cm^{-1}$ to $400\ cm^{-1}$ using 64 scans. A normalization of $0-100$ was performed with OriginPro 10.0 (OriginLab, Northampton, MA).

# Mechanical properties

To assess the impact of immersion in WWTP on CL's mechanical properties, mechanical tests were performed on both new lenses and those placed in WWTP aeration tanks. Four lenses per bag were tested. After removing excess deionized water, CLs were cut to $14\times10\ mm$ and tested using a Shimadzu Autograph Test Machine, Model AG-500, using a crosshead speed of $2\ mm\ min^{-1}$, at room temperature until lens breakage.

Engineering stress, $\sigma$, was calculated by dividing the load F (force $(N)$ ), by the original cross-sectional area of the lens, $A_0$, using equation (1) [17,20].

$$\sigma=\frac{F}{A_0}$$ Equation 1

The percentage of elongation was calculated by dividing the length between gauge marks (L) by the original gauge length (L0), then multiplying the result by 100, as shown in Equation (2).

Table 1
Polymer type and characteristics of the CL selected to conduct this work. All information is provided by the manufacturer.

| USAN | Manufacturer | Water Content (%) | Refractive Index -3.00D (hydrated) | Center thickness (mm) for -3.00 D | Young's Modulus (MPa) | Polymer Composition | Replacement Schedule |
|---|---|---|---|---|---|---|---|
| Nelfilcon A | Alcon | 69 | 1.3800 | 0.10 | 0.89 | PVA; HPMC; PEG | Daily |
| Delefilcon A | Alcon | 33; 80 (surface water gradient) | 1.4200 | 0.09 | 0.7 | Core: DMA, TRIS AM, siloxane macromer Surface: Polyamidoamine copolymer and AAA | |
| Nesofilcon A | Baush & Lomb | 78 | 1.3740 | 0.10 | 0.49 | HEMA, PVP, NVP | |
| Stenfilcon A | Cooper Vision | 54 | 1.4010 | 0.08 | 0.40 | SiHy, PDMS-MA, VMA, BzMA | |
| Narafilcon A | Johnson & Johnson | 48 | 1.4100 | 0.07 | 0.66 | MPDMS, DMA, HEMA, siloxane macromer, TEGDMA, PVP | |
| Somofilcon A | Cooper Vision | 56 | 1.4008 | 0.07 | 0.5 | Alkyl methacrylates, siloxane monomers + NVP | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Lotrafil con B | Alcon | 33 | 1.4200 | 0.08 | 1.0 | DMA, TRIS, Siloxane monomer | Monthly |
| Comfilc on A | Cooper Vision | 48 | 1.4000 | 0.08 | 0.75 | M3U, FMM, TAIC, IBM, nMNVA, NVP, HOB | |
| Senofil con A | Johnson & Johnson | 38 | 1.4200 | 0.07 | 0.73 | HEMA, MPDMS, DMA, PVP, siloxane macromer, TEGDMA | |
| Samfilc on A | Baush & Lomb | 46 | 1.4110 | 0.07 | 0.7 | SiHy, PVP (PVP grows around and throughou t the silicone backbone) | |

USAN: United States Adopted Name; MPa: Megapascal; PVA: polyvinyl alcohol; HPMC: Hydroxypropylmethylcellulose; PEG: Polyethylene glycol; DMA: N, N-Dimethylacrylamide; Tris AM: Tris(2-methacryloxyethyl) phosphate; AAA: N-allyl amino acetate; MPDMS: Monofunctional polydimethylsiloxane; HEMA: poly-2-Hydroxyethyl methacrylate; TEGDMA: Ethylene glycol dimethacrylate; PVP: Polyvinylpyrrolidone; NVP: N-Vinylpyrrolidone; PDMS: polydimethylsiloxane; SiHy: Silicone Hydrogel; VMA: Vinylmethyl Acetamide; BzMa: Benzotriazolyl Methacrylate; Tris: Trimethylsiloxane; M3U: awbis(methacryloyloxyethyl iminocarboxy ethyloxypropyl)-poly(-dimethylsiloxane)-poly(trifluoropropylmethylsiloxane)-poly(methoxy-poly(ethylene glycol) propylmethylsiloxane; FMM: $\alpha$-methacryloyloxyethyl iminocarbox yethyloxypropyl-poly(dimethylsiloxy)-butyldimethylsilane; TAIC: 1,3,5-triallyl-1,3,5-triazine-2,4,6(1H,3H,5H)-trione; IBM: Isobornyl methacrylate; nMNVA: N-methil-Nvinil acetamida; HOB: 2-hydroxybutyl methacrylate.

Percentage of elongation ¿ $\frac{L}{L_0} \times 100$

Equation 2

Tensile Strength (TS) was calculated by dividing engineering stress S, by the original cross-section area using Equation (3).

$$TS = \frac{S}{A_0}$$ Equation 3

Young's Modulus was calculated from the slope of the stressstrain curve's straight line, typically in the material's elastic deformation region, indicating the lens's stiffness.

## Statistical analysis

All experiments were conducted in triplicate, meaning measurements were taken from three different lenses per bag for each parameter. The results are presented as the mean ± standard deviation (SD) of these independent measurements. Statistical analysis was performed using GraphPad Prism 9.1 software (GraphPad Software, Inc., La Jolla, CA). Normality was assessed using the Shapiro-Wilk test. For comparisons involving more than two means, a One-way Analysis of Variance (ANOVA) was employed, followed by Tukey's test for multiple comparisons.

# Results and discussion

The CLs were immersed for twelve weeks, significantly longer than typical residuals, allowing CLs or micromaterials from prior treatment stages to persist in the tanks [10]. This immersion spanned late Winter and early Spring, characterized by large thermal amplitudes and heavy precipitation. Large thermal amplitudes stimulate microbial activity, while heavy precipitation results in elevated sewage flow and can cause aeration tanks to overflow [28,29].

Additionally, this timing was chosen because late winter and early spring typically represent a period of higher water levels and flow rates in the treatment process, which more accurately reflects the conditions that lenses would experience in real-world scenarios. In contrast, summer may have lower water levels due to increased evaporation and reduced rainfall, potentially influencing degradation rates.

Fig. 1 shows the appearance of CLs after immersion in the aeration tanks for one, three, six, and twelve weeks. The CLs maintained their physical appearance, but daily CLs (Delefilcon A, Nesofilcon A, Stenfilcon A, and Somofilcon A) acquired a brown color from the third week. Monthly CLs (Comfilcon A, Senofilcon A, and Samfilcon A) exhibited the same brown color starting from the sixth week. Nelfilcon A and Lotrafilcon B did not acquire any color.

The appearance of CLs after immersion (Fig. 1), shows that they largely maintained their physical structure, including their shape and size. However, notable changes were observed in the appearance of the lens material, particularly in terms of coloration, suggesting that environmental factors or degradation altered the lens. CLs, as hydrophilic polymer networks, can absorb substances when pre-soaked [30]. Lotrafilcon B likely did not discolor due to hydrophilic surface treatment [30], suggesting the brown color may result from the absorption of organic compounds or chemicals in the tanks. Alternatively, deposits or thin films formed by water components and microorganisms could cause color changes. Higher WC increases affinity for organic deposits [31,32], leading to earlier brown discoloration in daily CLs than monthly CLs, possibly due to higher WC in the daily CLs tested (Table 1). However, Lotrafilcon B, with the lowest WC (33 %), and Nelfilcon A, with a high WC (69 %), do not show discoloration, warranting further investigation. The ionicity of the lenses can influence protein deposition and potentially contribute to the brown discoloration. All CLs used in this study are Group I (Nelfilcon A, Nesofilcon A, Stenfilcon A and Samfilcon A) or Group II (Delefilcon A, Narafilcon

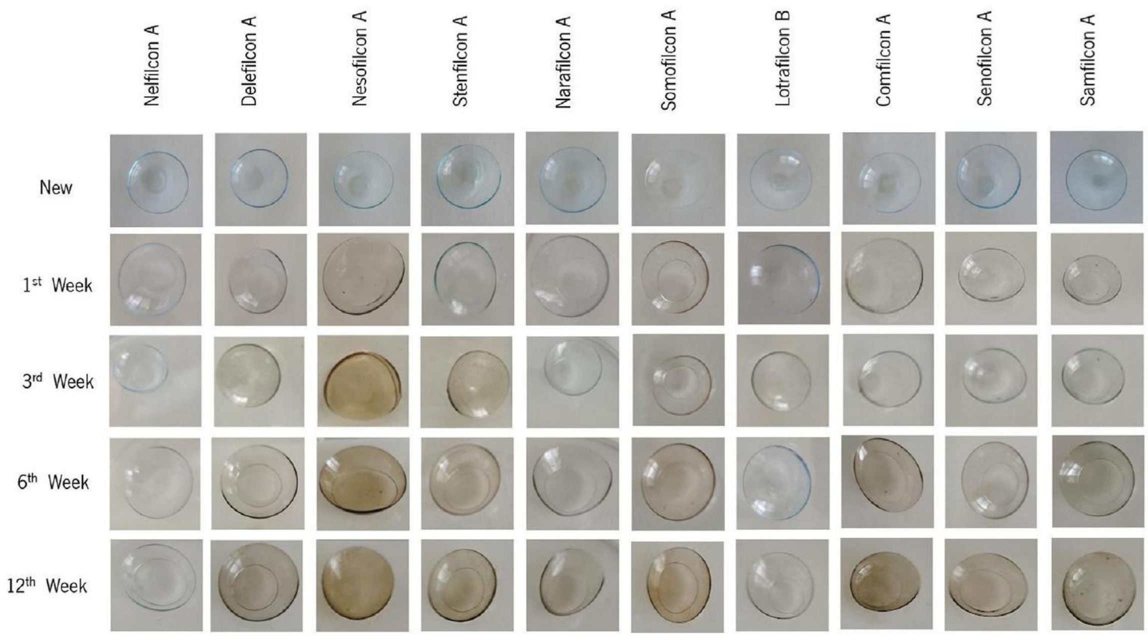


**Fig. 1.** Physical appearance of new daily contact Lenses (Nelfilcon A, Delefilcon A, Nesofilcon A, Stenfilcon A, Narafilcon A, and Somofilcon A), and new monthly contact lenses

(Lotrafilcon B, Comfilcon A, Senofilcon S, Samfilcon A) and after immersion in the aeration tanks of Braga's WWTP for one, three, six and twelve weeks. All contact lenses are

hydrated.

A, Somofilcon A, Lotrafilcon B, Comfilcon A, Senofilcon A), both of which are classified as non-ionic according to the FDA classification system. Group I lenses show the lowest amount of protein deposit, with Group II also showing low levels of protein deposits [33]. Therefore, in this study, it is unlikely that ionicity played a significant role in the discoloration process.

# Water content and refractive index

After immersion in the aeration tanks, daily CLs showed varying WC values (Fig. 2A). Delefilcon A exhibited the most significant change, with its WC dropping from 100.4 ± 0.2 % initially to 30.9 ± 0.3 % after one week, slightly increasing to 31.3 ± 1.5 % after twelve weeks ($p < 0.0001$, Tukey test). Nelfilcon A maintained stable WC values around 75.5 ± 0.5 %, with minimal changes after one, three, six, and twelve weeks of immersion ($p > 0.05$, Tukey test).

Nesofilcon A's WC increased slightly from $78.4 \pm 0.5\%$ to $79.6 \pm 0.6\%$ after three weeks, returning to the initial value after twelve weeks, with significant changes only after three and six weeks ( $p<0.01$, Tukey test). Stenfilcon A's WC after twelve weeks remained stable at around $54.5\%$, with a minor increase during the first six weeks with significant differences ( $p<0.01$ after one week and p < 0.001 after three and six weeks, Tukey test). Narafilcon A maintained a stable WC of $47.4\%$, with no significant changes ( $p>0.05$, Tukey test). Somofilcon A exhibited a WC of $56.9 \pm 0.5\%$ initially, which decreased to $54.7 \pm 1.5\%$ after six weeks but returned to $56.4 \pm 0.5\%$ after twelve weeks, similar to the initial value.

Among monthly CLs, only Senofilcon A showed statistically significant differences ( $p<0.001$, Tukey test) after twelve weeks in aeration tanks, with its WC increasing from $34.8 \pm 2.9\%$ to $39.9 \pm 2.1\%$ (Fig. 2B). Lotrafilcon B had a WC of $31.3 \pm 0.6\%$ initially and $31.5 \pm 0.6\%$ after twelve weeks. Comfilcon A measured $49.2 \pm 0.4\%$ initially and $49.0 \pm 0.6\%$ after twelve weeks. Samfilcon A had a WC of $45.9 \pm 0.4\%$ initially and $45.4 \pm 1.4\%$ after twelve
weeks. These differences were not statistically significant ( $p>0.05$, Tukey test).

For RI values (Fig. 2C), only Delefilcon A (daily CL), and Senofilcon A (monthly CL), showed statistical differences after twelve weeks of immersion. Delefilcon A's RI increased from $1.3357 \pm 0.0002$ to $1.4182 \pm 0.0022$ after twelve weeks ( $p<0.0001$, Tukey test), and Senofilcon A's RI varied from $1.4261 \pm 0.0043$ to $1.4211 \pm 0.0035$ after one week, $1.4261 \pm 0.0026$ after three weeks, $1.4231 \pm 0.0037$ after six weeks, and $1.4181 \pm 0.0031$ after twelve weeks. These changes were statistically significant at one, three, and six weeks ( $p<0.001$, Tukey test) and at twelve weeks ( $p<0.0001$, Tukey test). No statistically significant variations were observed in the other five daily CLs (Nelfilcon A, Nesofilcon A, Stenfilcon A, Narafilcon A, and Somofilcon A) or the other threemonthly CLs (Lotrafilcon B, Comfilcon A, and Samfilcon A) after the immersion period.

The results of WC and RI, monthly CLs showed greater resistance to changes compared to daily CLs (Fig. 2). Nelfilcon A and Narafilcon A exhibited no significant differences, possibly due to Nesofilcon A's dehydration resistance from N-Vinyl pyrrolidone, also found in Somofilcon A and Comfilcon A [18]. However, Somofilcon A showed differences in WC. Senofilcon A, the only monthly CL with significant changes, contains HEMA. Unlike Nesofilcon A and Narafilcon A, which also have HEMA but maintain their WC value. Despite a few statistical differences, overall RI and WC values did not substantially change, except for Delefilcon A which experienced a significant decrease in WC and an increase in RI post-immersion. This result can be explained by the water gradient within the material, a characteristic provided by the manufacturer [34]. The water gradient phenomenon refers to the uneven distribution of water within the CL, with higher surface concentration and lower core concentration. After immersion, the surface water dissipates, and the obtained value is from the core ( $33\%$ ). These results highlight the lack of a clear pattern regarding lens composition and their response to exposure to biological treatment at WWTP.

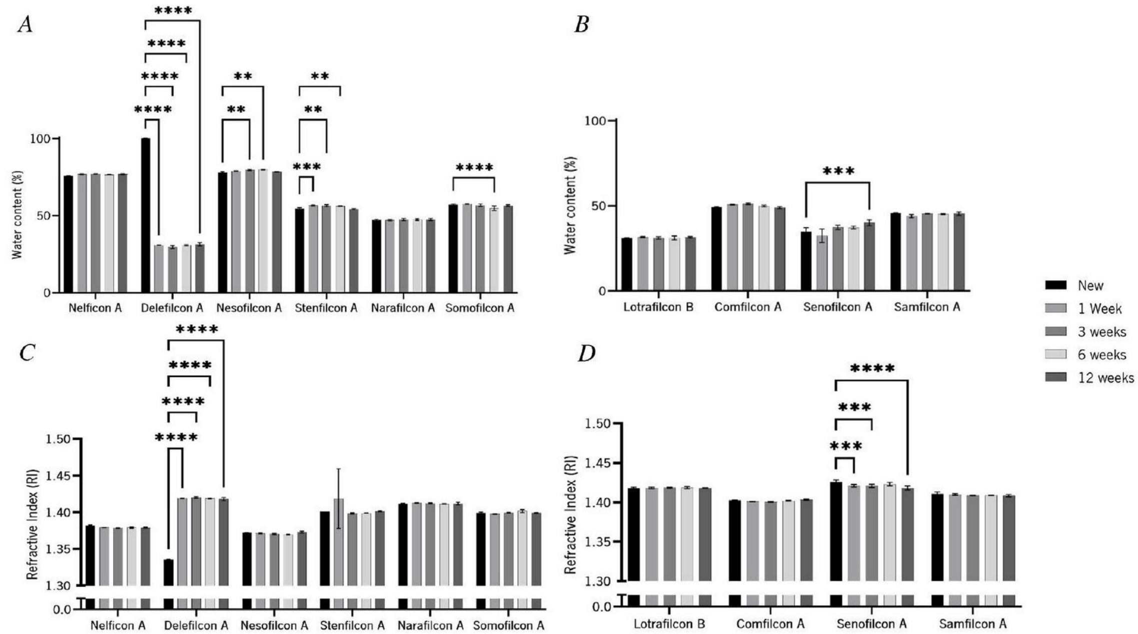


**Fig. 2.** Water Content (%) of new Nelfilcon A, Delefilcon A, Stenfilcon A, Nesofilcon A, Narafilcon A, and Comfilcon A after immersion in the WWTP aeration tanks for one, three, six, and twelve weeks (A) and their respective Refractive Index (C). Water content (%) of new Lotrafilcon B, Comfilcon A, Senofilcon A, and Samfilcon A after immersion in WWTP aeration tanks for one, three, six, and twelve weeks (B) and their respective Refractive Index (D). Data represent the mean ± standard deviation of 27 measurements per condition (3 lenses × 3 measurements per lens × 3 replicates). Statistically significant differences are indicated by asterisks: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$, and ****$p < 0.0001$ when compared to the new lens.

# Fourier Transform Infrared Spectroscopy-attenuated total reflectance

Fig. 3 presents FTIR-ATR spectra for new daily CLs (black line) and those immersed in Braga's WWTP aeration tanks for twelve weeks (dotted line). The spectra for daily CLs were identical for both new and immersed lenses, particularly in the region corresponding to the fingerprint of the lens polymer, which ranges from $1500\ cm^{-1}$ to $500\ cm^{-1}$. However, Nelfilcon A (Fig. 3A), Stenfilcon A (Fig. 3C), Nesofilcon A (Fig. 3D), Narafilcon A (Fig. 3E), and Somofilcon A (Fig. 3F), displayed increased O-H stretching peak intensity ( $3000-3600\ cm^{-1}$ ) after immersion. Only Nelfilcon A (Fig. 3A) did not exhibit decreased peak intensity in the $400-720\ cm^{-1}$ region. No new peaks were observed in any of the daily CLs after immersion.

Fig. 4 shows FTIR-ATR spectra for new monthly CLs (black line) and after twelve weeks of immersion (dotted line) for Lotrafilcon B (Fig. 4A), Comfilcon A (Fig. 4B), Senofilcon A (Fig. 4C), and Samfilcon A (Fig. 4D). Similar to daily CLs, the O-H stretching peak (30003600 $cm^{-1}$ ) increased after immersion for all monthly CLs. In Comfilcon A (Fig. 4C), the C-H stretching peak ( $2920\ cm^{-1}$ ) present in the new lens spectra was absent after immersion. Lotrafilcon B (Fig. 4A) and Samfilcon A (Fig. 4D) showed decreased peak intensity at $910-920\ cm^{-1}$.

Regarding FTIR-ATR results, no new peaks were observed in either daily or monthly CLs after immersion, indicating no alterations in the chemical bonds of the CL polymers (Figs. 3 and 4). An increase in O-H stretching peaks ( $3600-3000\ cm^{-1}$ ) suggests the presence of organic compounds on the lens surface, which were not observed in Delefilcon A due to its high-water content hydrogel surface (Fig. 3B). Delefilcon A's hydrophilic polymer network might incorporate organic matter, explaining its brown discoloration (Fig. 1) and absence of surface $O-H$ groups. These findings align with a previous study, showing that prolonged exposure did not induce chemical changes in lenses [3].

# Mechanical properties

The mechanical test on Nelfilcon A was not performed as the lens could not be cut due to its thin and delicate structure, making it unsuitable for reliable mechanical analysis. The elongation at break (Fig. 5A and B) corresponds to the percentage of elongation just before the lens broke, while stress at break (Fig. 5E and F) corresponds to the tensile strength at the same point. These values were calculated using Equations (2)and (3) respectively. In Fig. 5A, the elongation at break for new Delefilcon A ( $25.9 \pm 3.1\,\%$ ) and Somofilcon A ( $55.8 \pm 11.2\,\%$ ) was higher compared to that after twelve weeks in the WWTP ( $18.9 \pm 15.4\,\%$ and $16.2 \pm 4.9\,\%$ ), respectively with a significant difference observed for Somofilcon A ( $p<0.05$, Tukey test). For Stenfilcon A, the difference between the new lens ( $51.4 \pm 15.7\,\%$ ) and after twelve weeks ( $50.3 \pm 23.4\,\%$ ) was minor and not statistically significant ( $p>0.05$, Tukey test). Similarly, Fig. 5B shows higher values for new Comfilcon A, Senofilcon A, and Samfilcon A compared to the values observed after twelve weeks of immersion in WWTP. Comfilcon A decreased from $47.8 \pm 14.3\,\%$ to $37.0 \pm 17.4\,\%$, Senofilcon A decreased from $41.9 \pm 10.5\,\%$ to $22.9 \pm 13.6\,\%$ , and Samfilcon A decreased from $39.3 \pm 10.5\,\%$ to $29.2 \pm 13.0\,\%$. Despite this, the differences were not statistically significant (p > 0.05, Tukey test). In contrast, the elongation at break of the new Nesofilcon A ( $16.3 \pm 2.3\,\%$ ),

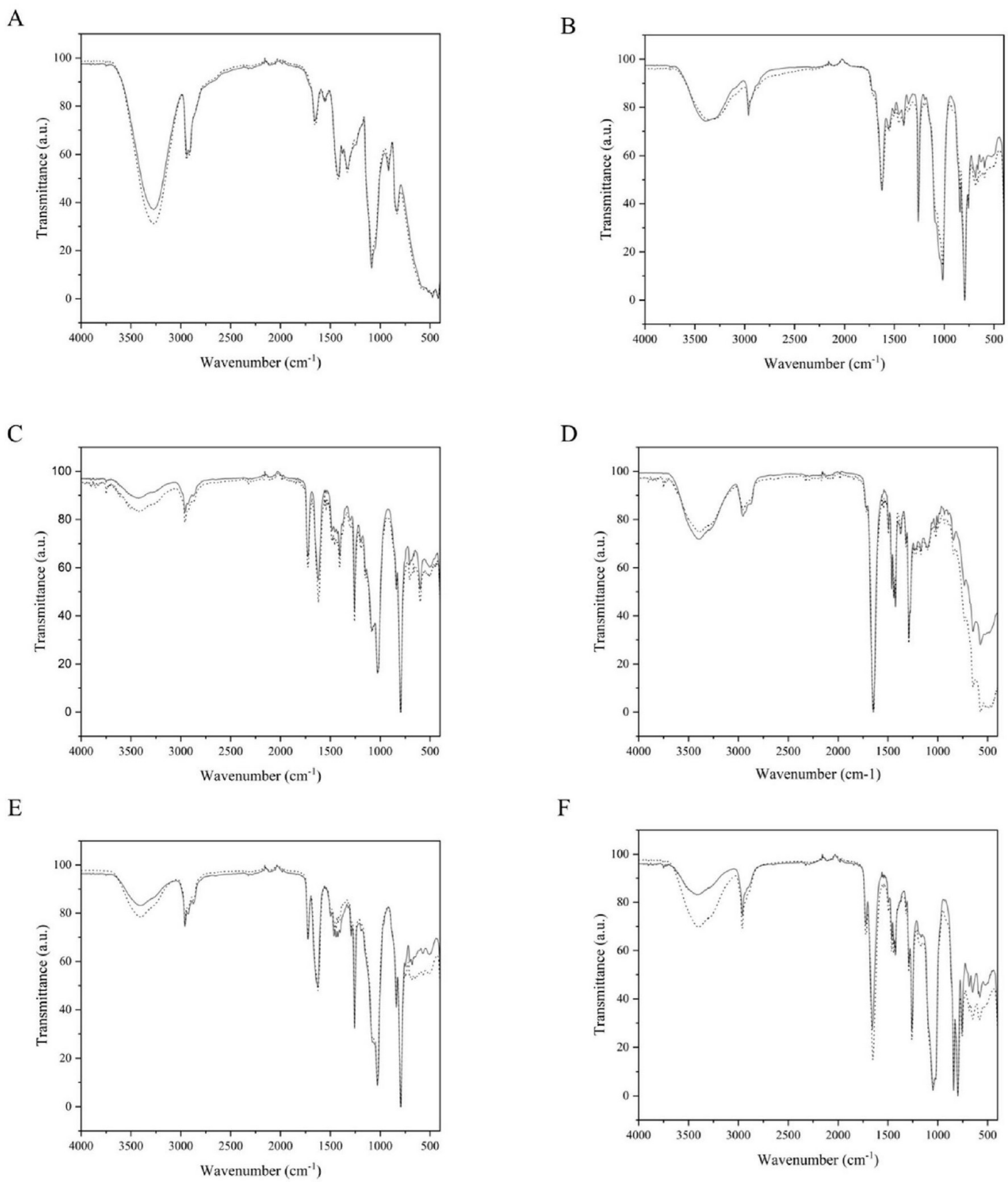


Fig. 3. FTIR-ATR spectra for the new lens (black line) and after twelve weeks immersed in Braga's WWTP aeration tanks (dot line) of Nelfilcon A (A), Delefilcon A (B), Stenfilcon A (C), Nesofilcon A (D), Narafilcon A (E) and Somofilcon A (F).

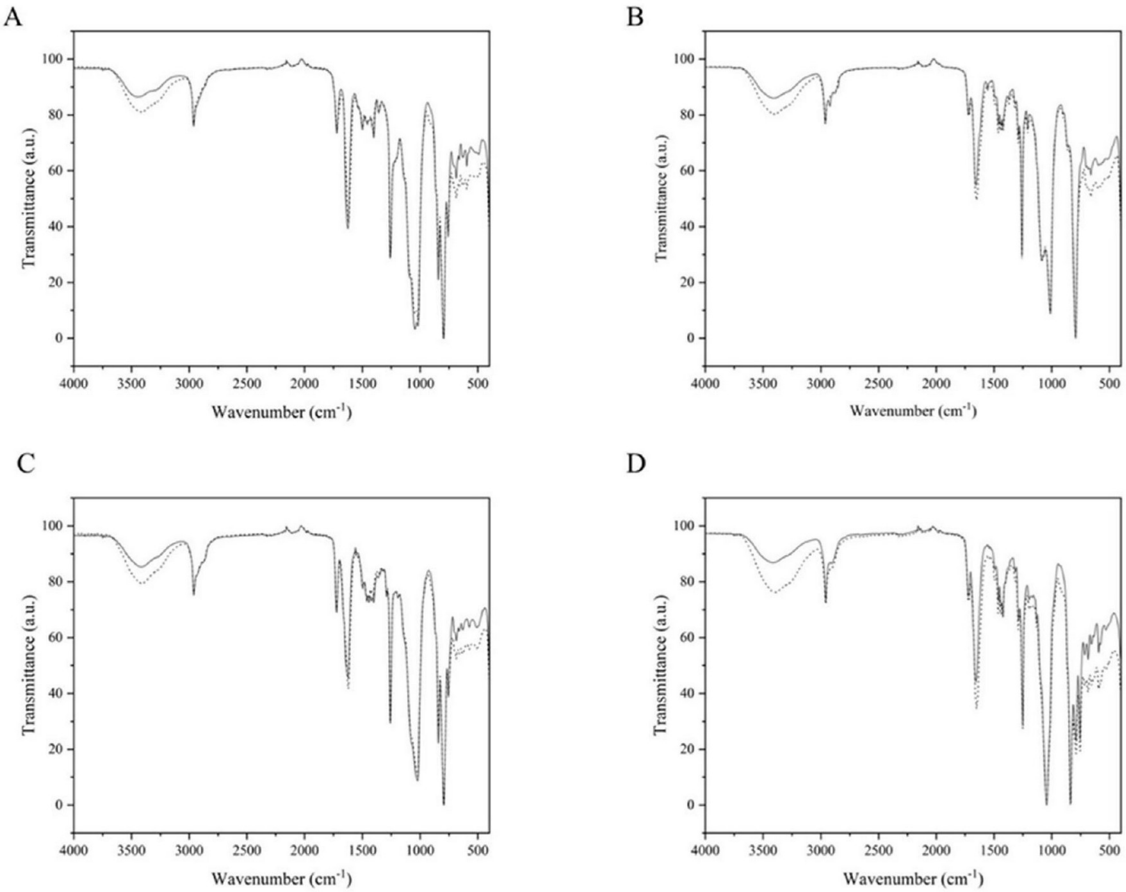


**Fig. 4.** ATR–FTIR spectra for the new lens (black line) and after twelve weeks immersed in aeration tanks of Braga's WWTP (red line) of Lotrafilcon B (A), Comfilcon A (B), Senofilcon A (C), and Samfilcon A (D).

Narafilcon A ( 46.3 ± 29.7 % ), and Lotrafilcon B ( 15.9 ± 6.1 % ) was lower than the values obtained after twelve weeks, which were 38.9 ± 15.4 %, 50.3 ± 23.4 %, and 16.2 ± 4.9 %, respectively. Nevertheless, the differences were not statistically significant ( $p > 0.05$, Tukey test).

Fig. 5C shows the results of Young's Modulus for the daily CLs and in Fig. 5D the results for the monthly CLs. After twelve weeks in aeration tanks, the Young's Modulus increased for Delefilcon A, Narafilcon A, and Somofilcon A, but decreased for Nesofilcon A and remained unchanged for Stenfilcon A (Fig. 5C). Specifically, Delefilcon A increased from $1.1 \pm 0.6\,MPa$ to $1.2 \pm 0.3\,MPa$, Narafilcon A increased from $0.6 \pm 0.2\,MPa$ to $0.7 \pm 0.2\,MPa$, and Somofilcon A increased from $0.6 \pm 0.1\,MPa$ to $0.7 \pm 0.2\,MPa$. Conversely, Nesofilcon A decreased from $0.7 \pm 0.1\,MPa$ to $0.5 \pm 0.1\,MPa$, while Stenfilcon A maintained a value of $0.6 \pm 0.1\,MPa$ throughout the study.

Regarding monthly CLs (Fig. 5D), Lotrafilcon B decreased from $1.4 \pm 0.4\,MPa$ to $1.2 \pm 0.4\,MPa$, while Samfilcon A increased from $0.7 \pm 0.1\,MPa$ to $0.8 \pm 0.2\,MPa$. The

Young's Modulus values for Comfilcon A and Senofilcon A remained constant. Specifically, Comfilcon A increased from $0.75 \pm 0.1\,MPa$ to $0.8 \pm 0.2\,MPa$, and

Senofilcon A increased from $0.65 \pm 0.1\,MPa$ to $0.7 \pm 0.2\,MPa$ after twelve weeks in WWTP. However, these changes were not statistically significant ( $p > 0.05$, Tukey test) for any of the lenses, indicating no significant alteration in Young's Modulus between new lenses and those placed after twelve weeks of exposure in WWTP.

For daily CLs (Fig. 5E), the stress at break (MPa) changed after twelve weeks in aeration tanks. Delefilcon A, Stenfilcon A, and Somofilcon A experienced decreases, while Nesofilcon A and Narafilcon A showed increases. Specifically, for Delefilcon A, the stress at break decreased from $0.3 \pm 0.2\,MPa$ to $0.2 \pm 0.1\,MPa$, though the differences were not statistically significant ( $p > 0.05$, Tukey test). Stenfilcon A exhibited a decrease from $0.4 \pm 0.1\,MPa$ to $0.2 \pm 0.1\,MPa$, with statistically significant differences ( $p < 0.01$, Tukey test). Somofilcon A showed a notable decrease from $0.6 \pm 0.2\,MPa$ to $0.1 \pm 0.1\,MPa$ ( $p < 0.0001$, Tukey test). Conversely, Nesofilcon A increased from $0.2 \pm 0.0\,MPa$ to $0.3 \pm 0.1\,MPa$, and Narafilcon A increased from $0.2 \pm 0.1\,MPa$ to $0.3 \pm 0.1\,MPa$, with no statistically significant differences ( $p > 0.05$, Tukey test).

Despite the increased Young's Modulus values for Lotrafilcon B and Samfilcon A, the stress at break for all four monthly CLs assessed was lower compared to new lenses (Fig. 5F), ranging from

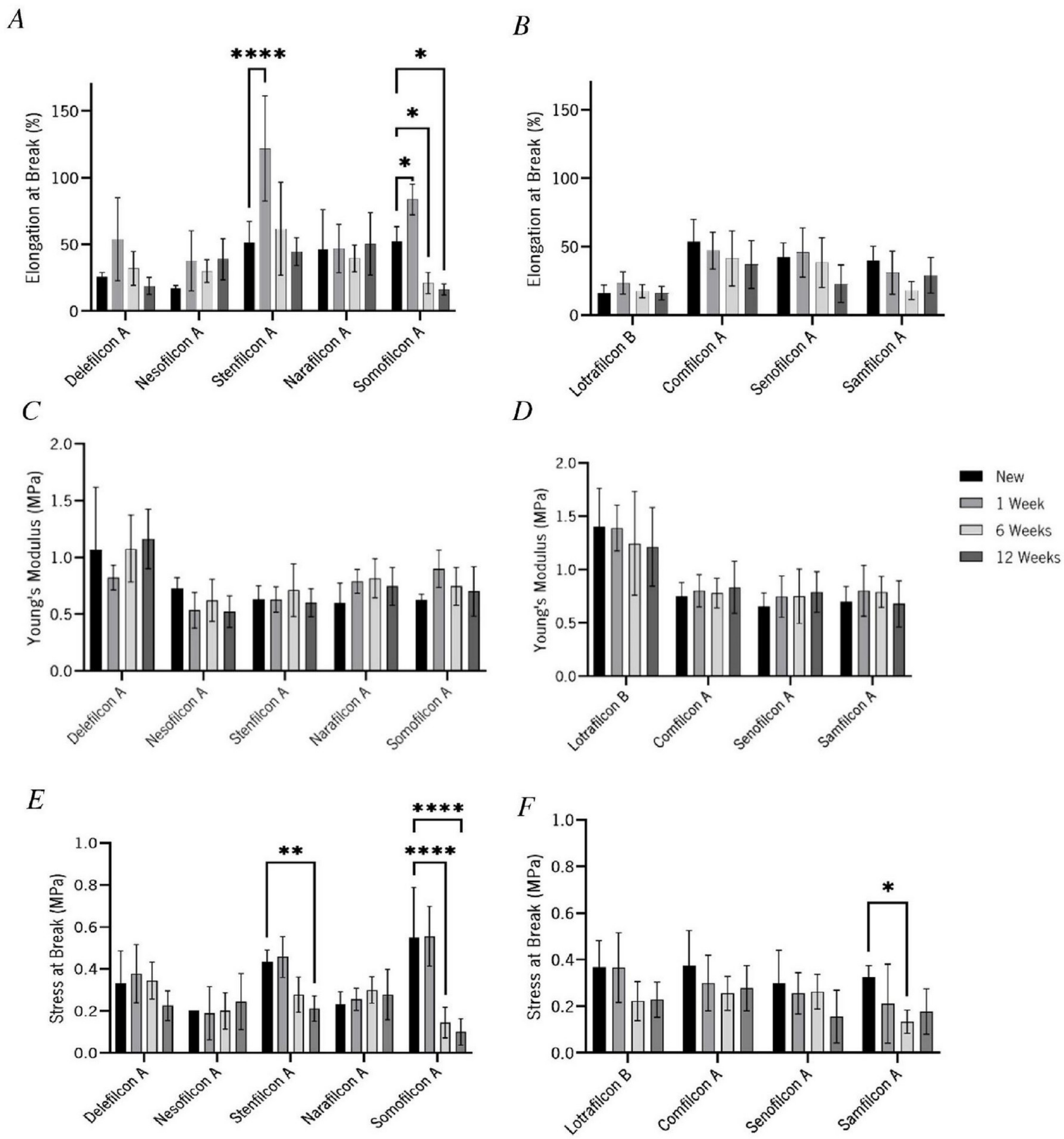


Fig. 5. Elongation at Break for daily CLs (A) and for monthly CLs (B), Young's Modulus for daily CLs (C) and for monthly CLs (D) and Stress at break for daily CLs (E) and for monthly CLs (F) after immersion in Braga's WWTP aeration tanks for one, six and twelve weeks. Data represent the mean ± standard deviation of 9 measurements per condition ( 3 lenses $\times 3$ replicates). Statistically significant differences were indicated by asterisks: ¿ $p<0.05$, ¿*¿ $p<0.01$, ¿*¿ $p<0.001$ ¿, and ¿*¿*¿ $p<0.0001$ ¿ when compared to the corresponding new. $0.4 \pm 0.1\ MPa$ to $0.2 \pm 0.1\ MPa$ for Lotrafilcon B, from $0.4 \pm 0.2\ MPa$ to $0.3 \pm 0.1\ MPa$ for Comfilcon A, from $0.3 \pm 0.2\ MPa$ to $0.2 \pm 0.1\ MPa$ for Senofilcon A, and from $0.3 \pm 0.0\ MPa$ to $0.2 \pm 0.1\ MPa$ for Samfilcon. However, these differences were not statistically significant ( $p>0.05$, Tukey test).

Efforts were made to ensure uniformity in sample sizes.

However, the concave geometry of the lens may have contributed to the high standard deviation observed in the tensile results (Fig. 5). Stress at break calculations used manufacturer-provided thickness for -3.00 power lenses, without accounting for lens power variations or thickness differences between the center and periphery, which could increase error in Young's Modulus and
stress at break [35]. In the future, pre-measuring the exact lens thickness before testing could help improve the results reliability.

Stenfilcon A contains HEMA and polyvinylpyrrolidone (PVP) in its composition (Table 1) and exhibited reduced elongation at break (Fig. 5A). PVP is resistant to biological degradation and effectively blocks enzymes, allowing it to remain unchanged through conventional WWTP processes [36]. Therefore, the percentage of this polymer in Stenfilcon A may be lower compared to Nesofilcon A and Narafilcon A which also contain PVP in their composition (Table 1), and do not exhibit reduced elongation at break.

Somofilcon A showed the most impaired tensile properties after immersion, indicating increased rigidity and decreased resistance to breakage. Overall, CLs exhibited varied responses to aeration tank treatment, with no consistent behavior between daily and monthly CLs. However, monthly CLs generally demonstrated greater mechanical resistance, suggesting they may be more resistant to degradation in WWTP. However, the study also highlights the inefficiency of WWTP in breaking down this pollutant.

CLs that resist degradation in WWTP may end up in soil or watercourses, posing risks to ecosystems. Hydrated CL will sediment due to gravity in WWTP and therefore end up in the primary and secondary sludge [3]. As sludge is commonly used as fertilizer, the soil is likely the ultimate destination for CLs [11]. Once in the soil, CL can persist and fragment into smaller sizes and potentially become a common soil pollutant affecting the health and biota of the soil. Alternatively, if CLs break into micro-size particles within WWTP and therefore don't settle, they may be released into watercourses behaving like microplastics. An estimated that 20 % of microplastics suspended in the water after treatment in the WWTPs are discarded into watercourses [37]. Consequently, CLs are expected to behave like microplastics if they reach watercourses like micro-size particles disrupting aquatic ecosystems by interfering with leaf litter decomposition and posing ingestion risks to aquatic organisms [38,39]. Additionally, the brown discoloration observed in some CLs (Fig. 1) may indicate absorption of WWTP chemicals. Since WWTP often fails to eliminate drugs efficiently, CLs could potentially absorb and transport these contaminants into watercourses and soil, exacerbating environmental challenges [30,40,41].

# Conclusions

In summary, mitigating the environmental impact of CLs requires a multifaceted approach. This includes developing effective waste management and disposal strategies, such as recycling programs, and emphasizing the need to increase public awareness for proper disposal of CLs and reduce environmental pollution. Additionally, further research is needed to understand the fate and behavior of CLs in wastewater treatment systems and natural aquatic environments to inform sustainable solutions and minimize environmental harm.

# CRediT authorship contribution statement

Rita Martins- Alves: Writing - original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. Ana Vera Machado: Writing - review & editing, Validation, Resources, Methodology, Formal analysis, Conceptualization. Fernanda Cássio: Writing - review & editing, Validation, Supervision, Resources, Conceptualization. Madalena Lira: Writing - review & editing, Validation, Resources, Methodology, Conceptualization.

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# 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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