Development of 3D-Printed Glasses for Color Vision Deficiency

Fahad Alam,* Ahmed E. Salih, Mohamed Elsherif, and Haider Butt*

Color vision deficiency (CVD) is a common ocular disorder that hampers patients’ color distinction capabilities, causing difficulties in their daily life routine. Till date, a CVD cure is not developed, and treatment courses, such as gene therapy, are yet to be applied on humans. Hence, patients opt for wearable visual aids such as tinted glasses/contact lenses, which achieve the latter by filtering out problematic wavelengths for blue–yellow (440–500 nm) and red–green (540–580 nm) CVD patients, thus, enabling them to distinguish between the colors. Herein, the development of 3D printed glasses for color blindness management is reported. A commercially available highly transparent resin (>95%) is utilized, and two wavelength filtering dyes, with absorption ranges of 550–580 and 440–510 nm, respectively, are mixed with the resin. The tinted glasses are successfully 3D printed using Masked SLA 3D printer; dyes incorporated within the glasses exhibit high stability over 1-week period. The manufactured glasses successfully block more than 50% of the undesired wavelengths along with showing high transparency (>85%) to the remaining portion of the visible light spectrum. When using the developed glasses, volunteers show substantial improvements in Ishihara test scores, which signify the potential of these glasses as CVD wearables.

1. Introduction

Color distinction is vital in daily life practices as it aids in identifying and distinguishing different objects along with emphasizing the visual perceived information. Yet, color vision deficiency (CVD) or colorblindness is a very common congenital disorder that limits the ability of the patient to distinguish between shades of certain colors.[1] CVD patients experience difficulties in distinguishing colors in their daily lives, such as traffic lights, LED lights on some devices, ripened or raw vegetables and fruits, and colors of sports’ jerseys along with an overall depression stemming from the idea that they cannot enjoy a variety of aesthetical experiences (Figure 1). Moreover, according to prior studies, approximately 7%–8% of male population and 0.4%–0.5% of female population are suffering from congenital CVD.[2,3]

Human eyes perceive colors with the help of photoreceptor cells also known as cone cells present in the eye’s retina.[4,5] The cone cells are categorized based on the wavelengths they are sensitive toward, that is, short (S), medium (M), and large (L); those are also commonly termed as blue, green, and red cone cells, respectively (Figure 1E–H). Moreover, normal color vision is trichromatic, in which all three cones are present in the eye and are well functioning; however, colorblind patients usually suffer from a missing or faulty cone cell. According to the latter, CVD can be divided as follows: protanomaly (faulty L-cone) or protanopia (missing L-cone), deuteronomalay (faulty M-cone) or deuteronopia (missing M-cone), and tritanomaly (faulty S-cone) or tritanopia (missing S-cone). Further, protans and deutans are commonly categorized as red–green CVD patients whereas tritans are usually referred to as blue–yellow CVD patients.[6] Among these types of CVDs, red–green is the most common.[7,8]

Furthermore, there are several methods for determining the CVD type and its severity. One of these approaches is the use of pseudoisochromatic testing plates, which seem to be of a single color to people suffering from CVD. The Ishihara test is the most popular and is commonly available among the optometrists.[9,10] There are many variations of the test, each with a different number of tests plate, but the 38-plate version is the most common. The Ishihara test can only detect red–green colorblindness and cannot classify a patient as a protan, deutan, or tritan.[11] Other tests, such as Hardy–Rand–Rittler (HRR), Fransworth–Munsell (FM) 100 Hue, and Fransworth D-15, can be used to get such detailed information.[12,13] Another testing method involves the usage of anomaloscopes, which utilize control knobs that reflect the form and severity of the CVD.[14] Anomaloscopes use control knobs to align two images with their color brightness. They are the most complex to use, even though they offer a reliable classification of all CVD conditions.
Since no cure for CVD has been developed yet and gene therapy treatments were only employed on mice and primates, patients utilize color-filtering glasses and contact lenses to enhance their color perception. The recent study by Wong et al. demonstrates the work done to improve the color recognition ability of the colorblind patient by developing 3D-printed medication labels. However, the technology is not yet well developed but there is a potential to help the CVD patients by medication management. The concept of wavelength filter–based visuals aids was first introduced by Seebeck where he claimed that with the aid of red and green filters, colorblind patients, who initially failed to distinguish between certain colors, were now able to differentiate them. Since then, research has significantly advanced the properties and materials of the utilized CVD wearables, which opened up the doors for the commercialization of such products. In fact, Enchroma is one of the leading companies that develops glasses for colorblind patients since 2012. Chromagen is another company that focuses on contact lenses tinted with dyes for CVD sufferers. These companies claim that their products are highly effective, but patient-specific customization of the glasses is still a big challenge. Furthermore, developments in the additive manufacturing technology (3D printing) have paved the way for the fabrication of optical devices that are customized as per the applications’ requirements.

In the current work, 3D printing was utilized to manufacture customized glasses for colorblindness management. A transparent resin (Dentaclear, Asiga) was utilized, and two wavelength-filtering dyes, namely Atto 565 and Atto 488, were mixed within the liquid resin to provide the tinting effect. Three different dye
concentrations (0.5%, 1%, and 1.5%) were added to the liquid resin, and the resulting mixture was 3D printed. Upon successful 3D printing, the tinted glasses were characterized for their optical properties; the aforementioned properties were compared to those of the commercially available colorblind glasses. Finally, the 3D-printed CVD glasses were tested on two colorblind volunteers to assess their practical effectiveness.

2. Experimental Section

2.1. Materials

A photocurable transparent resin, DentaClear, was purchased from ASIGA (Alexandria, NSW, Australia). The resin consisted of methacrylate and diphenyl phosphine oxide mixtures (detailed information is provided in the Supporting Information). Dentaclear resin was more transparent than many other utilized commercial resins. Moreover, isopropyl alcohol (IPA) and dimethyl sulfoxide (DMSO) were purchased from Merck KGaA (Darmstadt, Germany). The liquid resin was modified using two Atto dyes (Atto 565 and Atto 488, purchased from Sigma-Aldrich) to attain the wavelength-filtering ability. A gray resin, standard 3D printing resin, purchased from Wanhao was utilized for 3D printing of the glasses’ frame. A commercially available transparent polyvinyl chloride (PVC) smooth plastic film and deionized (DI) water were also used in the experiments.

2.2. Preparation 3D Model of Glasses and Frame

The 3D model of the glasses and frame for 3D printing were prepared using a computer-aided designing (CAD) software, SOLIDWORKS. The dimensions of the glass (Figure 2A) and the frames (Figure 2D) were optimized accordingly so that the glasses can fit well in the frame. This design of the glass was inspired from the commercially available designs. The modifications that were done allowed the temples to be folded like other glasses. The designed CAD models of the glasses and frame were saved in stereolithography (STL) format and were converted into Geometric Code (G-code) through the 3D printer’s slicing tool (PrusaSlicer 2.3.3.). The images of the glasses and their frame in the 3D printer slicing tool are shown in Figure 2B,E, respectively.

2.3. Preparation of Atto Dye–Mixed Resin

For 3D printing of glass lenses, the Atto dyes (Atto 565 and Atto 488) were mixed individually as well as in combined form, in the Dentaclear photocurable resin. DMSO was utilized as the solvent to prepare the liquefied dye solution. For that purpose, 1 mg powder of dyes were dissolved in 1 mL of DMSO followed by mixing with the help of vortex for 5 min to obtain the liquid form of dyes. The prepared solution (1 mL DMSO + 1 mg dye solution) was added to 100 mL of photo resin (DentaClear). In the next step, more liquid resins were added to get the lower concentrations of the dyes in the resin. A total of three different dilutions were made and samples were 3D printed. We checked the National Fire Protection Association rating and found that the DMSO had a rating of 1,2, 0, which indicated that it was slightly hazardous in case when inhaled but safe for skins. Whereas, the Atto dyes have been extensively studied for life science applications, exhibiting a negligible safety concern.

2.4. 3D Printing

3D printing of the glasses’ components was carried out utilizing a masked STL apparatus (MSLA) 3D printer (Prusa SL1, Czech Republic).[24] The 3D printing parameters played a crucial role on the resulting properties of the manufactured parts. Hence, the printing parameters (curing time and layer thickness) were optimized to achieve the desired optical and mechanical properties. The utilized printing parameters are presented in Table 1, and the 3D printing process is demonstrated schematically in Figure 2. The steps involved in 3D printing were 1) CAD model preparation, 2) slicing, 3) 3D printing, and 4) post processing.
Moreover, the durability and quality of the glasses were directly
analyzer. The transmission spectra of the samples were
which light was polarized with a polarizer and measured using
glasses was also performed employing a customized setup, in
fracture (Figure 3A,C).[26] The tests were performed at ambient tempera-
tests and materials (ASTM) D638 standards (type iv)
was mixed with the liquid resin. Furthermore, three samples
spectrum for CVD patients, that is, 480–510 and 550–580 nm,
approximately prepared using DMSO, but it was still within the required
shift in the peak of Atto 488 was observed when the dye solution
was utilized for further processes. Sharp transmission dips,
at ≈565 and ≈508 nm, were observed in the transmission spectra
of Atto 565 and Atto 488, respectively (Figure 3A–C). Although a
shift in the peak of Atto 488 was observed when the dye solution
was prepared using DMSO, but it was still within the required
range (480–510 nm). On the contrary, mixing Atto 565 with
DMSO had no apparent effect on the dye’s optical properties
as the observed transmission dip remained at the same
wavelength, that is, at ≈565.

The dye solutions were then mixed with the liquid resin
mixture (DentaClear); the resulting transmission spectra were
measured and are provided in Figure 3D–F. No optical
alterations from the previous spectra were noted as the dye
was mixed with the liquid resin. Furthermore, three samples
derve, each with a different dye concentration (0.5%, 1.0%,
and 1.5% dye wt%), were prepared for 3D printing of the glasses,
and their resulting spectra are presented in Figure 3G–I. Similar
to the previous spectra, the transmission spectra of the
3D-printed glasses remained unchanged, which indicates that
photocuring due to 3D printing had no effect on the optical

(washing). Prior to printing, a PVC film was attached on top of
the build plate, and then, the dye-mixed resin was poured into
resin vat. Glasses were printed directly on the surface of the
PVC film to achieve a smooth surface finish. However, to fabri-
cate the frames, supports as well as pads were added before print-
ing. After 3D printing, the parts were washed in IPA and
sonicated to ensure all uncured resin was removed from the
printed parts. Finally, the support structures were removed,
and the glasses were inserted into the printed frame.

2.5. Characterization

The optical properties of the 3D-printed glasses were character-
ized by a UV–vis spectrophotometer (USB 4000+, by Ocean
Optics), which had a detection range of 400–1100 nm. The transmission spectra of the Atto dyes, dye-mixed resin, and
3D-printed glasses were measured. Transmission spectra were
presented in form of intensity (%) with respect to wavelength
(nm). Optical polarization spectroscopic analysis of the tinted
glasses was also performed employing a customized setup,
in which light was polarized with a polarizer and measured using
an analyzer. The transmission spectra of the samples were
recorded at various polarization angles ranging from 0° to 90°.
Moreover, the durability and quality of the glasses were directly
related to the mechanical properties of the materials utilized for
the frame and glass lenses.[25] Hence, tensile and bending tests
were performed on the materials of the 3D-printed frame and
glass lenses to characterize their mechanical properties.
A rectangular flat bar (80 × 12.17 × 2.8 mm) was designed using
SOLIDWORKS and 3D printed utilizing the same printing
parameters of the glass lenses and frame to ensure a similarity
in mechanical performance (Figure 3B,D). Quasi-static uniaxial
tensile tests were conducted according to American society for
testing and materials (ASTM) D638 standards (type iv)
(Figure 3A,C).[26] The tests were performed at ambient tempera-
ture (≈24 °C) utilizing a uniaxial tensile machine (UTM) from
Zwick Roell Z005 fitted with a 2.5 kN load cell, at a constant
crosshead speed of 1 mm min⁻¹. The load versus displacement
curves, obtained from the tensile and bending tests, were used to
calculate the modulus of elasticity, ultimate tensile strength, and
elongation (%). The stress–strain curve was also deduced from
the tensile load–displacement plots. The cross-sectional area
(13 × 3 mm) and the gage length (54 mm) were used to calculate
the stress and strain at each point, respectively. To obtain the
bending properties, the three-point test was performed according
to ASTM D790 standard (Figure 3B).[27] The bending tests were
conducted at a speed of 1 mm min⁻¹, and the span between
the supports was fixed at 40 mm. Furthermore, colorblind vol-
unteers were subjected to the Ishihara test using the 3D-printed
tinted glasses. The Ishihara test used had 38 plates, which
consisted of randomly arranged dots with different colors that formed
distinct numbers. The volunteers were asked to look through the
samples and recognize the numbers written on each plate within a
defined viewing time, with and without the tinted glasses.

One important property for glasses materials is the surface
hardness and scratch resistance because the glasses are exposed
to a lot of scratch and indents while in application. The bulk hard-
ness of the 3D-printed glass lenses were measured by perform-
ing Vickers’ hardness test using Duramin-A2500 by applying 5
Kgf load and a dwell time of 10 s. Before the indentation test,
samples were cleaned with ethanol. As shown in Figure S3,
Supporting Information, the diagonals of indent (d1 and d2)
were measured using an optical microscope. The Vickers
hardness (HV) was calculated by using the dimensions of the
diagonals and the expression (Equation i, ii). The details of
indent used, and formula used for calculation of HV is
mentioned in Figure S3, Supporting Information.

Table 1. Optimized printing parameters for the fabrication process.

| Printing parameters | Specifications |
|---------------------|----------------|
| Layer thickness     | 25 microns for glasses and 50 microns for frame |
| Curing time         | Glasses: burn layers – 30 s, normal layers – 15 s
|                     | Frame: burn layers – 30 s, normal layers – 20 s |
| Print speed         | 6 s per layer |
| Vat tilt time       | 5 s (Fast), 8 s (Slow) |
| Support             | Glasses: no support, printed directly on the build platform
|                     | Frame: at the bottom most of the model, pillar diameter – 1 mm |
| Brim                | 1.6 mm length only in frame |
| Pad                 | Glasses: no pad
|                     | Frame: below the object (1 mm thick) |
properties of the dyes. The transmission intensity at the dip decreased as the concentration of the dye within the glass increased, which indicates that the rate of light blocked from the glasses can be customized by controlling the dye's concentration. It is worth noting that a dip at around $\lambda=405$ nm was observed in all the samples irrespective of the dye concentration; the latter was also observed in 3D-printed transparent (no dye mixed) samples, which confirms that the dip is due to the intrinsic optical properties of the resin and not the dyes.

Moreover, an additional sample was prepared by mixing both the dyes (0.5% Atto 565 + 0.5% Atto 488) with the resin, and the resulting transmission spectrum is shown in Figure 3I; the two distinct dips at 565 and 508 nm confirm the presence of both dyes. Also, the stability of the dyes within the 3D-printed glasses was examined by measuring their transmission spectra over a 1 week period, while they are stored in water. Results indicate that leakage did not occur, as no change in the spectra was observed and presented in Figure S1, Supporting Information. Furthermore, the shelf life of the 3D-printed samples was also examined by keeping the glasses open at ambient conditions for a week; similarly, no change in the spectra was noted, please refer to Figure S2, Supporting Information. These results indicate that the dyes incorporated into the glasses have long-lasting properties with adequate stability.

Mechanical properties such as tensile and bending (flexural) are crucial in quantifying the longevity and durability of the 3D-printed polymeric materials. The mechanical properties of the glasses and frame materials (DentaClear and Gray resins) were characterized by tensile and three-point bending tests, and the obtained stress–strain plots are shown in Figure 4 while the calculated mechanical properties are presented in Table 2. The mechanical properties from both materials demonstrated their durability as glass lenses and frame materials, which is apparent when comparing them with materials employed in similar applications. The flexural properties (from three-point bending test) indicated that the frame manufactured via 3D...
printing will not break easily even if it was subjected to folding or bending. Overall, the spectacles (including both the lenses and frame) exhibited excellent durability as reviewed by Lee et al. in 2021 and performance of 3D lenses evaluated by Gawedzinski et al. in 2017.

The hardness and scratch resistance play an important role in the durability of the glasses. Vickers’ hardness was performed on the 3D-printed clear and tinted glasses and the average HV was found to be 4.11 ± 0.06, which is close to the hardness of structural polymer reported previously. There was no effect of dye mixing observed on the hardness of the tinted glasses and the similar results were obtained for all the glasses with a very little variation. Furthermore, optical polarization spectroscopic analysis of the 3D-printed tinted glasses was carried out, and the results are shown in Figure 5. The schematic diagram of the customized polarization setup for measuring the transmission spectra at different polarization angles is presented in Figure 5A. The transmission spectra of the samples were recorded at various polarization angles ranging from 0° to 90°. As the polarization angle was incremented, the overall transmitted light reduced until the polarizers became crossed at 90°, upon which light was entirely blocked. The latter trend was observed throughout the recorded spectrum for all printed glasses, thus, indicating that these glasses have no light polarization effects. Also, the level of tinting had no apparent effect on the polarization of light, suggesting that the Atto dyes, themselves,

![Figure 4](image-url)

**Figure 4.** Mechanical testing of the materials making up the glasses (Dentaclear) and frame (Gray resin). A) Tensile test specimen and B) stress–strain plots obtained from the test. C) Three-point bending test specimen and D) stress–strain calculated from bending test.

| Samples   | Strength [MPa] | Modulus [MPa] | Elongation [%] |
|-----------|----------------|---------------|----------------|
|           | Tensile        | Bending       | Tensile        | Bending       |
| Dentaclear| 21.9 ± 0.2     | 3.2 ± 0.2     | 5.56 ± 0.31    | 1.25 ± 0.02   | 11.5 ± 1.2    | 25.1 ± 4.1    |
| Gray Resin| 12.3 ± 0.4     | 3.1 ± 0.3     | 2.68 ± 0.42    | 1.01 ± 0.01   | 14.3 ± 1.8    | 33.2 ± 2.7    |

![Table 2](image-url)

**Table 2.** Mechanical properties calculated from the tensile and three-point bending tests.
have no polarization properties. Overall, the results from the optical polarization spectroscopy suggest that 3D printing is suitable for manufacturing of tinted glasses.

The optical and wavelength-filtering properties of the 3D-printed tinted glasses were compared with those of the commercially available glasses for colorblindness management; comparisons are demonstrated in Figure 6. Four glasses from different companies were utilized and compared to the in-house-made 3D-printed glasses. The transmission spectra of the Atto-dyed glasses were very much comparable to the

Figure 5. Optical polarization spectroscopic analysis of tinted glasses manufactured via 3D printing. The transmission spectra of samples at various polarization angles from 0° to 90° A) schematic representation of the setup utilized for measuring the polarization spectra, B) 0.5% Atto 565, C) 1.0% Atto 565, D) 1.5% Atto 565, E) 0.5% Atto 488, F) 1.0% Atto 488, G) 1.5% Atto 488, and H) 0.5% Atto 565 + 0.5% Atto 488. Scale bar below the digital photographs of lenses is 10.1 mm.
spectra obtained from Enchroma and BJ-5149 glasses (Figure 6C,D). In fact, the 3D-printed glasses, Enchroma, and BJ-5149 filtered out light at similar wavelengths, yet the 3D-printed glasses showed better selectivity as they had narrower transmission dips. Hence, they blocked the undesired wavelengths for CVD patients while transmitting the remaining wavelengths from the spectrum, unlike Enchroma and BJ-5149, which filtered out more of the light that CVD patients could normally distinguish. Furthermore, colorblind glasses from Pilestone exhibited lower transmission rates throughout the visible spectrum along with one transmission peak at 460–470 nm (36%). The glasses from HB-585-BL filtered out more than half of the visible light range (i.e., blocked almost 100% from 390 to 570 nm range).

For further assessment of the effectiveness of the Atto-dyed glasses, their spectra were evaluated against that of a red–green CVD patient and are presented in Figure 6E. The utilized dyes should filter out specific wavelengths from the spectrum that correspond to areas in which the cone cells are activated simultaneously, that is, the range where they intersect as indicated through the green circles. Both dyes, Atto 565 and Atto 488, exhibited transmission dips near the intersection points. Indeed, Atto 565 blocked the undesired wavelengths for
red–green patients whereas Atto 488 filtered out unwanted wavelengths for blue–yellow patients. The samples, which contained both dyes, exhibited peaks at both ranges (red–green as well as blue–yellow), suggesting their efficacy in managing both CVD types. Overall, the 3D-printed Atto-dyed glasses demonstrated superior optical properties to many of the commercially available glasses for colorblindness management.

There are various ways to detect and report the CVD type and its severity, but Ishihara test, which comprises 38 pseudoisochromatic plates, is the most common method. To assess the actual effectiveness of the dye-tinted samples, two CVD volunteers were asked to look through the 3D-printed glasses and identify the number written on the plate within a certain viewing time. The volunteers were first asked to identify the number without any glasses (clear) and then through the 3D-printed glasses. Moreover, both volunteers benefited from the Atto-dyed glasses. In fact, volunteer 1 showed good color vision enhancement with the help of glasses tinted with Atto 565 whereas volunteer 2 was able to distinguish more plates with Atto 488–tinted glasses. This indicates that volunteer 1 probably suffers from red–green CVD whereas volunteer 2 seems to be suffering from blue–yellow CVD. The 1.5% Atto 565 glasses aided volunteer 1 in recognizing 45% more plates than what volunteer 1 initially identified. For volunteer 2, his score improved by twofold upon using the 0.5% Atto 488 glasses and by almost 200% when using the mixed glasses (i.e., 0.5% Atto 565 + 0.5% Atto 488). Hence, we can conclude from the Ishihara test results that the 3D-printed tinted glasses have a great potential in colorblindness management (Figure 7).

4. Conclusions

In the current work, 3D-printed glasses, tinted with Atto dyes, were successfully developed to enhance CVD patients’ color vision distinction. Two wavelength selective dyes, Atto 565 and Atto 488, were incorporated into a transparent resin, Dentaclear, to block the undesired wavelengths (480–510 and 550–580 nm) for blue–yellow and red–green CVD patients. Three different concentrations per dye, namely 0.5%, 1.0%, and 1.5%, were utilized and added to the resin after which the glasses were fabricated via MSLA 3D printing. Results showed that 3D printing had no influence on the wavelength-filtering properties of the dyes. In fact, characteristic transmission dips of the dyes remained unchanged as they were integrated within the resin and 3D printed. Further, a commercially available flexible grey resin was utilized to 3D print the frame of the spectacles, and the mechanical properties of both resins, forming the lenses and the frame, were examined using tensile and three-point bending tests, which were performed according to ASTM standards. The properties of both materials showed acceptable strength, modulus, and deflection and were adequate compared to other products employed in similar applications. Moreover, the optical performance of the 3D-printed glasses was compared with commercial colorblind glasses; results indicated that our 3D-printed glasses were more selective in filtering undesired wavelengths than the commercially available CVD glasses. Finally, two CVD volunteers were subjected to the Ishihara test, and both had better color perception when using the glasses. Indeed, 45% and 200% improvements in identifying Ishihara test plates were recorded for volunteers 1 and 2, respectively. The aforementioned findings show that these 3D-printed tinted glasses have great potential in combating colorblindness, owing to their ease of fabrication and customization, which can be tailored to the patient’s need.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements

The authors acknowledge Khalifa University of Science and Technology (KUST) for the Award No. RCII-2019-003 and KU-KAIST Joint Research Center (Project code: 8474000220-KKJRC-2019-Health1) research funding in support of this research. We also acknowledge Sandooq Al Watan LLC and Aldar Properties for the research funding (SWARD Program—AWARD, Project code: 8434000391-EX2020-044).

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available in the supplementary material of this article.
Keywords
colorblindness, 3D printing, photocurable resin, wavelength

Received: February 11, 2022
Revised: March 31, 2022
Published online: April 29, 2022

[1] F. Alam, A. E. Salih, M. Elsherif, A. K. Yetisen, H. Butt, Addit. Manuf. 2021, 49, 102464.
[2] J. Birch, Diagnosis of defective colour vision, 2001.
[3] A. E. Salih, M. Elsherif, M. Ali, N. Vahdati, A. K. Yetisen, H. Butt, Adv. Mater. Technol. 2020, 5, 1901134.
[4] E. Welby, J. Lakowski, V. Di Foggia, D. Budinger, A. Gonzalez-Cordero, A. T. L. Lun, M. Epstein, A. Patel, E. Cuevas, K. Kruczek, A. Naeem, F. Minneci, M. Hubank, D. T. Jones, J. C. Marioni, R. R. Ali, J. C. Sowden, Stem Cell Rep. 2017, 9, 1898.
[5] A. Grzybowski, K. Kupidura-Majewski, Clin. Dermatol. 2019, 37, 392.
[6] Z. El Moussawi, M. Boueiri, C. Al-Haddad, Int. Ophthalmol. 2021, 41, 1917.
[7] H. Lee, E. Lee, G. S. Choi, J. Inter. Des. 2020, 45, 35.
[8] D. Taylor, Causes of Color Blindness: Function and Failure of the Genes that Detect Color, 2020.
[9] J. H. Clark, American Journal of Physiological Optics, 1924, 5, 269.
[10] J. Birch, Ophthalmic Physiol. Opt. 1997, 17, 403.
[11] A. Simionato, O. E. Pecho, A. Della Bona, J. Esthetic Restorat. Dent. 2021, 33, 865.
[12] F. Iqbal, H. Ali Khan, J. Ophthalmol. Res. 2019, 2, 10.
[13] N. H. Salimian, A. Belli, R. J. Blanch, J. Neurotrauma 2021, 38, 2778.
[14] D. Farnsworth, JOSA 1943, 33, 568.
[15] M. P. Simunovic, Eye 2010, 24, 747.
[16] Y. Zhao, S. Sziro, L. Shi, S. Azenkot, ACM Trans. Accessible Comput. (TACCESS) 2019, 12, 1.
[17] Y. Wong, Y. Xu, L. Kang, K. Y.-L. Yap, Int. J. Bioprinting 2020, 6, 276.
[18] M. M. Schornack, W. L. Brown, D. W. Siemsen, Optometry – J. Am. Optometric Assoc. 2007, 78, 17.
[19] A. E. Salih, A. Shanti, M. Elsherif, F. Alam, S. Lee, K. Polychronopoulou, F. Almaskari, H. AlSafar, A. K. Yetisen, H. Butt, Phys. Status Solidi A 2021, 219, 2100294.
[20] A. E. Salih, M. Elsherif, F. Alam, A. K. Yetisen, H. Butt, ACS Nano 2021, 15, 4870.
[21] EnChroma, https://enchroma.com/ (accessed: November, 2021).
[22] J. H. Lee, H. Kim, J.-Y. Hwang, J. Chung, T.-M. Jang, D. G. Seo, Y. Gao, J. Lee, H. Park, S. Lee, H. C. Moon, H. Cheng, S.-H. Lee, S.-W. Hwang, ACS Appl. Mater. Interfaces, 2020, 12, 21424.
[23] A. Laude, E. Y. S. Tan, S. Wang, W. Y. Yeong, Invest. Ophthalmol. Visual Sci. 2016, 57, 5324.
[24] M. M. Prabhakar, A.K. Saravanan, A. Haider Lenin, I. Jerin Leno, K. Mayandi, P. Sethu Ramalingam, Mater. Today: Proc. 2021, 45, 6108.
[25] O. Ayyildiz, Clin. Exp. Optometry, 2018, 101, 747.
[26] D638-14, A., Standard Test Method for Tensile Properties of Plastics, ASTM International, West Conshohocken, PA, www.astm.org, 2014.
[27] D790-17, S., Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials, ASTM International, West Conshohocken, PA, www.astm.org, 2017.
[28] M. Elsherif, F. Alam, A. E. Salih, B. Alqattan, A. K. Yetisen, H. Butt, Small 2021, 17, 2102876.
[29] A.-R. Badawy, M. U. Hassan, M. Elsherif, Z. Ahmed, A. K. Yetisen, H. Butt, Adv. Healthcare Mater. 2018, 7, 1800152.
[30] D. W. Abueidda, M. Bakir, R. K. Abu Al-Rub, J. S. Bergström, N. A. Sobh, I. Jasiuk, Mater. Des. 2017, 122, 255.
[31] J. Verdu, J. Macromol. Sci. Pure Appl. Chem. 1994, 31, 1383.
[32] N. Saba, M. Jawaid, J. Ind. Eng. Chem. 2018, 67, 1.
[33] L. Lee, A. M. Burnett, J. G. Panos, P. Paudel, D. Keys, H. M. Ansari, M. Yu, Clin. Exp. Optometry 2020, 103, 590.
[34] F. Alisafaei, C.-S. Han, Adv. Condens. Matter Phys. 2015, 2015, 1.
[35] M. Nishita, S.-Y. Park, T. Nishio, K. Kamizaki, Z. Wang, K. Tamada, T. Takumi, R. Hashimoto, H. Otani, G. J. Pazour, V. W. Hsu, Y. Minami, Sci. Rep. 2017, 7, 1.
[36] Coblis, Color Blindness Simulator. https://www.color-blindness.com/ coblis-color-blindness-simulator/, (accessed: November 2021).
[37] M. Elsherif, A. E. Salih, A. K. Yetisen, H. Butt, Adv. Mater. Technol. 2021, 6, 2000797.