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Chiral Sensing of Amino Acids under Visible Light via Hydroxypropyl Cellulose Gels

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The identification of Chiral molecules is essential in pharmaceutical and food science. However, conventional methods are complex and cost-prohibitive. This study introduces a sustainable method using hydroxypropyl cellulose (HPC) gel to identify amino acids enantiomers, such as phenylalanine and alanine, through visible light. By integrating the structural color properties of HPC, this research demonstrates the HPC gel's capability to distinguish L (Levo)-phenylalanine (L-Phe), D (Dextro)-phenylalanine (D-Phe), and DL (racemic mixture)-phenylalanine (DL-Phe) supplemented with visible circular dichroism (CD) spectra or hydrochloric acid (HCl) as visual indicators. Similar chiral sensing results are observed with D-alanine, L-alanine, and DL-alanine. Unlike traditional UV-based detection requiring expensive equipment, this approach simplifies the process while maintaining sensitivity. Varying phenylalanine concentrations altered the CD response without disrupting the gel's helical structure, and color changes in response to HCl addition facilitated visual identification of enantiomers. Furthermore, adding various salts generates colorful HPC/Phe gels, demonstrating their suitability for 3D printing. Meanwhile, the HPC gels remained functional for three months, indicating long-term stability. These advancements are significant for pharmaceutical and biotechnological industries, facilitating efficient low-concentration chirality detection (0.2 wt.%). Continued development and refinement of this technology are expected to expand its applications and improve analytical capabilities for future chirality-related studies and photonic gel 3D printing.

1. Introduction

Chiral molecules are characterized by their non-superimposable mirror images, akin to left and right hands.[1] Enantiomers are paired left (L) and right (D) chiral molecules, forming mirror images of each other, with the only difference in the spatial arrangement of the chemical bond. Detecting and sorting these molecules is crucial as they often display distinct chemical and biological activities, leading to varying effects in pharmaceuticals, agrochemicals, and food additives.[2] The significance of identifying chiral molecules is particularly pronounced in the pharmaceutical sector. For instance, L-phenylalanine (L-Phe) is an indispensable amino acid utilized in L-Phe supplements and injections for appetite suppression in weight management programs,[3] while D-phenylalanine (D-Phe) acts as an enzyme enkephalinase inhibitor and a pain-relieving agent.[4,5] Therefore, precise detection and isolation are imperative to ensure the safety and efficacy of the drug.[6]

Achieving low detection limits is critical for advancing chiral detection technologies in commercial applications, including pharmaceuticals, food production, and biotechnology. For example, in pharmaceutical manufacturing, regulatory standards mandate the detection of enantiomeric impurities at concentrations below 1% to ensure drug efficacy and safety.[1] Similarly, in the food industry, the ability to detect trace levels of chiral additives such as amino acids is essential for maintaining product quality and meeting nutritional compliance standards.[7] In biotechnology, monitoring low concentrations of metabolic byproducts or intermediates is vital for optimizing chiral biosynthesis processes.

Current methods for detecting chiral molecules include chromatography techniques such as high-performance liquid chromatography (HPLC) and gas chromatography (GC), which utilize chiral stationary phases to differentiate enantiomers based on their interactions with the chiral environment.[8] Traditional common optical techniques like ultraviolet circular dichroism (UV-CD) spectroscopy and vibrational circular dichroism (VCD) spectroscopy analyze optical activity to detect chiral molecules, offering non-destructive and structural insights.[9] Nuclear magnetic

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resonance (NMR) with chiral derivatizing agents provides detailed molecular environment information, making it highly accurate for enantiomer differentiation.[10] Additionally, mass spectrometry (MS) with chiral selectors or reagents distinguishes enantiomers based on mass-to-charge ratios.[7] While effective, conventional methods for UV CD detection require complex instrumentation and are cost-intensive, posing a challenge for rapid and affordable chiral detection. Recent advancements, such as improved CD sensitivity, have enhanced the precision and efficiency of chiral analysis.[11] However, since the CD peaks of chiral molecules typically occur in the UV range, these methods rely on expensive, specialized spectrometers. Therefore, exploring the potential of utilizing CD spectra in the visible range—compatible with most standard spectrometers—is crucial for advancing efficient enantiomer characterization. Some research groups have proposed to enhance the CD signals at optical wavelengths by using plasmonic[12] or dielectric[13–15] nanostructures. Regrettably, the majority of enantiomers exhibit minimal or weak intrinsic CD signals in the visible range, leading to a scarcity of direct and convenient methods for assessing chirality in this field. Therefore, utilizing reagent detection sensors emerges as a commendable alternative.

Hydroxypropyl cellulose (HPC) is a natural cellulose derivative and a versatile water-soluble polymer, contributing to its distinctive gel-forming properties. Research into HPC emphasizes its structural color, stemming from its cholesteric liquid crystal phases. These phases selectively reflect visible light, giving rise to vibrant, rainbow-like colors. By adjusting key factors such as gel concentration,[16] temperature,[17] and polarity,[18] the cholesteric pitch can be finely tuned, resulting in color shifts across the visible spectrum. Significantly, this color modulation occurs without the need for external dyes or pigments, making HPC an appealing material for applications in photonic devices, optical sensors, and decorative coatings. Beyond its optical properties, HPC's biocompatibility—due to its abundant hydroxyl groups—allows it to bind effectively with other molecules, making it an excellent platform for molecular detection in pharmaceutical and chemical research. Its ability to both exhibit tunable structural colors and serve as a detection medium for compounds underscores HPC's significance in materials science and analytical chemistry, positioning it as a promising subject for further exploration.

This study focused on detecting the chirality of phenylalanine enantiomers by monitoring the chiroptical responses through HPC-phenylalanine gel mixtures. Specifically, we developed a structural color gel capable of distinguishing between L-Phe, D-Phe, and DL-Phe based on their varying intensities in the CD spectra. We also discovered, for the first time, that adding HCl caused the HPC/Phe gel to show an even more distinct color change and thus be distinguished straightforwardly. The stability of the samples exhibited a remarkable resistance to degradation, with a projected lifespan extending up to three months. Furthermore, our experiments underscored the viability of HPC gel for detecting exceedingly low concentrations of phenylalanine (as low as 0.2 wt.%), signifying promising potential for commercial applications in distinguishing enantiomers. In addition to phenylalanine, we further tested alanine, another amino acid, to demonstrate the universality of the method. Finally, we demonstrated the versatility of HPC/Phe gels by producing structural color variations using different salts and confirmed their printability through the creation of vivid patterns.

2. Results and Discussion

The phenomenon of chiroptical enhancement and attenuation is a crucial aspect in the study of molecular chirality, serving as a significant factor in characterizing chiral molecules. As illustrated in **Figure 1a**, HPC exhibits right-handed chirality, which is evident in the negative value present in the CD spectrum of the experiment. CD measurements are commonly used to reflect the differential absorption of left-handed circularly polarized (LCP) and right-handed circularly polarized (RCP) light. When phenylalanine, containing amino and hydroxyl groups, is combined with HPC, a homogenous solution is achieved due to hydrogen bonding between the two compounds.[19] Small-molecule amino acids are further categorized into left-handed and right-handed forms, as depicted in Figure 1b,c. The mixture of HPC and chiral amino acids, which have unique peaks in the CD spectrum, shows promise as a rapid detecting method. By analyzing the CD response between the HPC-phenylalanine mixture under circularly polarized light, we can engineer the functionality of chiral molecules for a multitude of purposes, beyond its original application. The goal of this study seeks to uncover the intricacies of molecular chirality and its ramifications on interactions with light as illustrated in Figure 1d. By clarifying the structure of chiral compounds and examining their optical properties, researchers can advance understanding of chirality and pave the way for innovative solutions in diverse scientific and technological domains.

We first measured the CD spectra of the three isomers of phenylalanine and HPC- phenylalanine mixture within the UV region. The results show that phenylalanine exhibits a prominent CD peak in this range, as depicted in **Figures 2a** and S1 (Supporting Information). Conversely, HPC does not display characteristic peaks within the UV region, and due to the high concentration of HPC molecules in the mixture, the CD peaks from phenylalanine are notably reduced. In the visible light region, however, the CD signals showed distinct variations, as seen in Figure 2b. CD measurements, which characterize the differential absorption of LCP and RCP light, indicate that the pure HPC gel yields greater absorption for LCP. This results in negative CD values and confirms its right-handed helical configuration.[20] The CD data for HPC gels containing different phenylalanine isomers show that L-Phe significantly reduces the CD signal intensity, while D-Phe enhances it. On the other hand, DL-Phe, being racemic and lacking net chirality, attenuates the signal in a manner similar to that of an achiral additive. It has been established that cellulose and phenylalanine form hydrogen bonds between the hydroxyl groups of cellulose and the amino groups of phenylalanine. In our study, this interaction impacts the local helical structure of HPC, thereby influencing the gel's optical activity and its absorption of circularly polarized light. Data from Figure S2 (Supporting Information) indicate that in the HPC/L-Phe gel, the absorption of LCP and RCP light is nearly identical, indicating reduced differential absorption, whereas the HPC/D-Phe gel exhibits the largest difference. Figure 2c provides a schematic of these structural changes, demonstrating how the incorporation of chiral phenylalanine affects the intensity of the CD signals. These shifts

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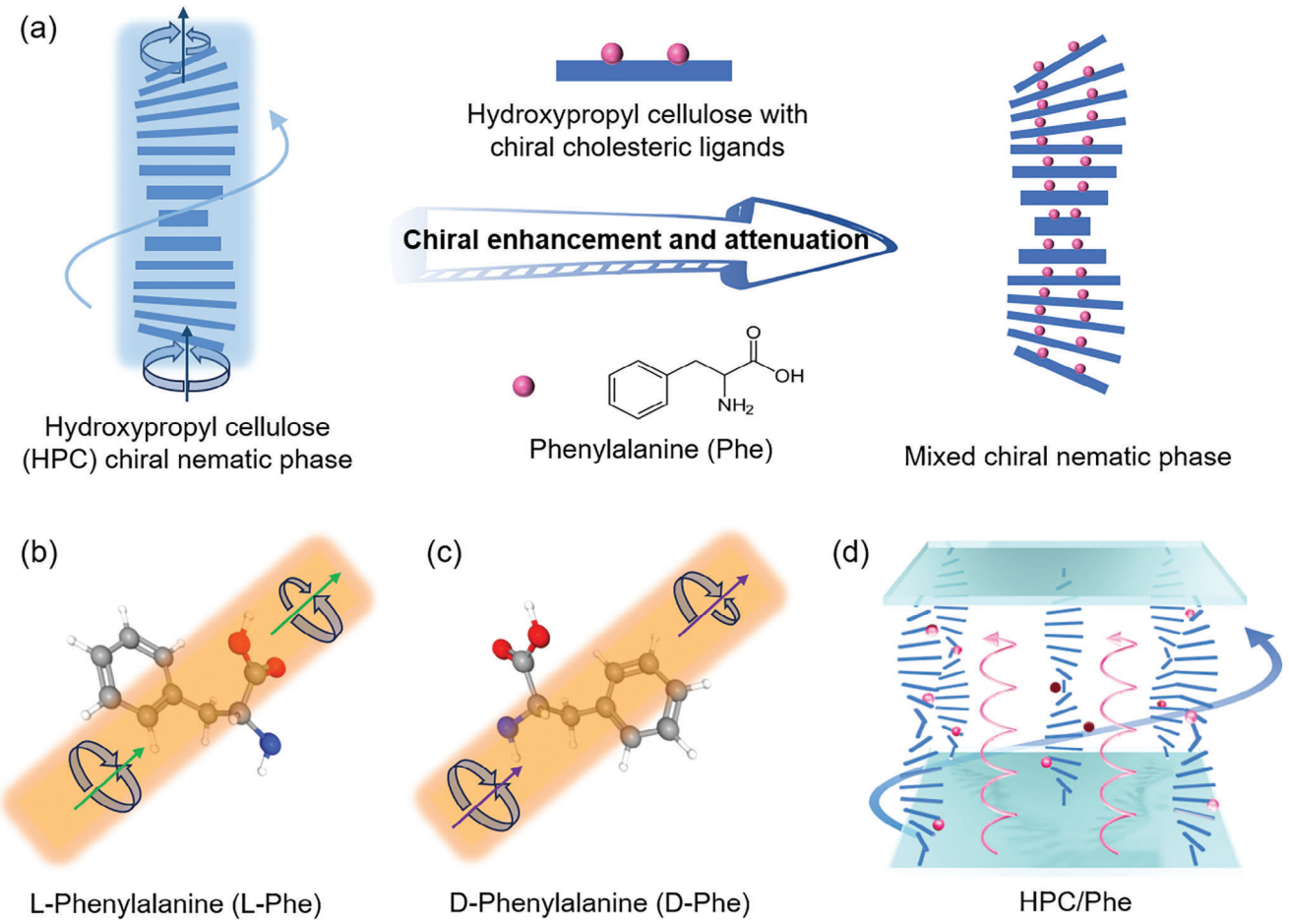

Figure 1. a) Schematic of self-assembled HPC and phenylalanine subject to the illumination of LCP and RCP light, where short blue bars indicate HPC and orange arrows represent phenylalanine molecules. b,c) Illustration of light-matter interaction of (b) L-Phe and (c) D-Phe. d) Schematic of the mixture with HPC and phenylalanine, where short blue bars indicate HPC and red dots represent phenylalanine.

highlight alterations in the local helical structure and the overall optical activity of the HPC/Phe gels, emphasizing the significance of chiral light-matter interactions. However, no observable differences were detected in the optical appearance of the HPC/Phe gels. Light passing through pure HPC gel (65% solid content) exhibited a distinct orange hue, as shown in Figure 2d. This color remained largely unchanged even after the addition of chiral (L-Phe, D-Phe) or achiral (DL-Phe) phenylalanine. This great stability is due to the low mass fraction of phenylalanine (0.2 wt.%) and its relatively small molecular weight (165.2), which is insufficient to alter the helical pitch of the HPC structure. Identical experiments were conducted using another amino acid, alanine, and showed a similar trend, Figure S3 (Supporting Information). The results indicate that HPC/Phe gels containing left-handed amino acids yield lower CD values, whereas those with right-handed amino acids produce higher CD values.

The aforementioned experiments strongly suggest the intricate balance between molecular structure and optical properties in chiral media. The introduction of another chiral compound into the HPC matrix alters the overall chiral dynamics of the mixture, a phenomenon detectable through intensity change in the CD spectra. This change serves as a reliable measure for identifying the chirality of enantiomers introduced to the HPC environment. This analysis not only enhances our understanding of chiral media interactions with light but also contributes to the broader field of photonic materials, where such phenomena can be harnessed for applications in optical filtering, sensors, and display technologies.

Moreover, discernible color changes to the naked eye offer significant convenience of detection, making the changes in these materials more intuitive and faster to perceive. Using the 65 wt.% gel concentration as an example, we observed a significant color change in the HPC/Phe gels after the addition of HCl, when the pH of the gel reached 3.5, as shown in Figure 2e. The pure HPC gel shows a tender ginger yellow color, the HPC/L-Phe gel shows a ginger yellow color, the HPC/D-Phe gel shows an olive-green color, and the HPC/DL-Phe gel shows a green color. This color change is not merely the result of a simple chemical reaction but is closely related to alterations in the molecular arrangement within the material. From the comparison presented in Table S1 (Supporting Information), we can see that our method is relatively easy and quick to operate since no extra instrument is needed. Besides, the abrupt change both in the CD peak in the spectrum and colors after mixing up, which

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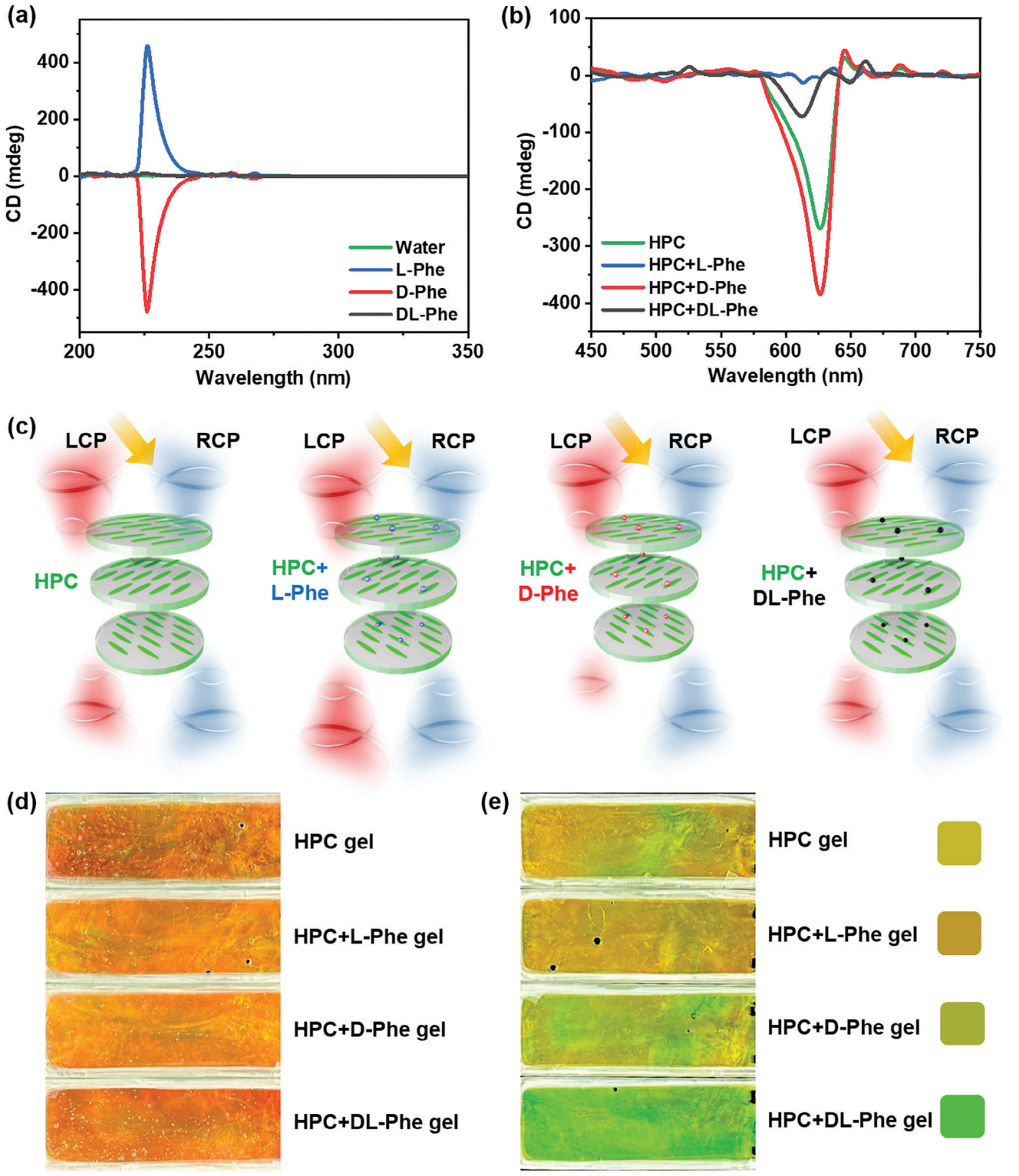

Figure 2. a) UV-CD spectrum of water, 0.2 wt.% of L-Phe aqueous solution, D-Phe aqueous solution and DL-Phe aqueous solution. b) CD spectra of pure HPC gel and HPC/Phe gels. The concentration of L-Phe, D-Phe, and DL-Phe is 0.2 wt.% in each of the 65 wt.% HPC/Phe gels. c) Schematics to illustrate the underlying light-matter interactions in different samples, where the size of the red/blue helix represents the intensity of the light. d) Optical photographs of HPC/Phe gels at 65 wt.%, and e) Optical photographs of HPC/Phe gels at 65 wt.% after the addition of HCl. From top to bottom are HPC gel, HPC/L-Phe gel, HPC/D-Phe gel, and HPC/DL-Phe gel. This demonstrated the potential for enhanced visual discrimination of chiral sensing results with the naked eye.

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is almost 50% more, indicates the high sensitivity of our application. Specifically, HPC, as a water-soluble cellulose derivative, has a unique molecular structure with hydrophilic hydroxypropyl side chains, offering good solubility in aqueous solutions and controllable gelation behavior. When HPC is mixed with chiral phenylalanine (including L-phe and D-phe), interactions such as hydrogen bonding and hydrophobic forces are likely to result in the formation of a specific molecular arrangement. It has been demonstrated that such molecular arrangements can induce structural coloration due to optical phenomena.[21,22] The structural color arises from the microstructure of the material and differs from traditional pigment or dye colors, which explains the initial orange-red appearance of the material. However, after the addition of HCl, the pH of the system changes significantly, resulting in a shift in the gel's color. The gel transitions from its initial orange-red to various shades of green. This phenomenon is not merely a pH indicator effect; rather, the pH change leads to a reorganization of the molecular arrangement within the composite material, which alters the reflection of light and, consequently, the structural color.[23]

In our system, the hydroxypropyl side chains of HPC and the functional groups of phenylalanine, such as the amino and carboxyl groups, are likely to undergo protonation under acidic conditions. The addition of HCl increases the concentration of hydrogen ions (H^+) in the solution, directly affecting the ionization state of phenylalanine. This ionization process may weaken the interactions between phenylalanine and HPC molecules, leading to changes in the overall molecular arrangement of the system. Specifically, as the pH decreases, the amino groups of phenylalanine become protonated, reducing the strength of hydrogen bonding and electrostatic interactions, which may induce a reorganization of the gel's internal microstructure. These rearrangements in molecular alignment result in a change in structural color. The color shift induced by pH-induced molecular rearrangement is not only evident in our HPC/Phe gels but also corresponds to similar phenomena reported in the literature.[24] It is the change of molecular alignment in the HPC/Phe gels under acidic conditions that results in the transition of structural color. It is worth noting that the color shift is not solely dependent on the interactions between HPC and phenylalanine but may also be influenced by factors such as ionic strength and the solvent environment. Under acidic conditions, the increase in ionic strength in the solution could further affect the intermolecular forces and solubility, thereby altering the microstructure and optical properties of the gel. Future studies could explore the effects of ionic strength and solvent conditions on the structural color changes in HPC composites, providing a deeper understanding of the underlying mechanisms. That is, the HPC/Phe gels exhibit significant structural color changes under different pH conditions, primarily due to the reorganization of molecular alignment in acidic environments. This phenomenon suggests that HPC/Phe gels not only have potential applications like structural color sensing materials for pH monitoring but also hold promise for developing stimuli-responsive smart materials.

To gain deeper insight into the structural properties of these gels, we utilized scanning electron microscopy (SEM) images of pure HPC and HPC/Phe mixtures to investigate their structures. The samples were prepared using a 65 wt.% concentration of the gel as a precursor. As shown in **Figure 3**, both the pure HPC and HPC/Phe films exhibit a homogeneous and dense structure, free from any discernible defects or irregularities. This indicates that phenylalanine molecules interacted effectively with the HPC substrate, resulting in a cohesive and uniform film. Therefore, it can be inferred that the observed changes in the CD signal intensity are due to the influence of chiral phenylalanine on light polarization, rather than any alteration in the overall structural arrangement of the HPC matrix. Furthermore, the addition of phenylalanine did not compromise the homogeneity of the HPC matrix, as the chiral molecules are uniformly dispersed within the polymer. All HPC/Phe films exhibit a consistent periodic structure and maintain a similar helical pitch, suggesting that the incorporation of chiral phenylalanine has minimal impact on the inherent helical periodicity of HPC. This observation implies the resilience and structural stability of the hydroxypropyl cellulose matrix, even when interacting with molecules of different chirality.

Additionally, we examined the influence of different HPC concentrations on the gel's structural properties. It is known that HPC concentrations ranging from 60 to 70 wt.% exhibit distinct structural colors. To ensure the study's rigor, mixed gels with HPC concentrations of 67 wt.%, and 70 wt.% were prepared and tested as substrates. Their corresponding phenylalanine concentration in all 63 wt.%, samples of 0.2 wt.% represents a low level. As depicted in **Figures** 4a,c,e, the mixed gel hues correspond to dark red, green, and blue, respectively. Once again, the findings indicate that varying chirality or the absence of chirality in phenylalanine minimally impacts the interlayer pitch of HPC. Subsequently, the CD spectra of HPC/L-Phe, HPC/D-Phe, and HPC/DL-Phe chiral compound mixtures were measured, revealing a consistent trend across different HPC concentrations, as shown in Figure 4b,d,f. Some minor wavelength shift was observed for HPC/Phe gels at 70 wt.% due to the bubbles in the sample. Those bubbles resulted in different outputs when light passed through in the experiment. Specifically, the inclusion of L-Phe generally results in an attenuation of CD signal intensity, whereas D-Phe tends to enhance these signals. This intriguing phenomenon suggests that the molecular chirality of additives can significantly influence the chiral optical properties of HPC gels. This observed dependency of CD signal modulation on the chirality of the phenylalanine isomer introduces stereochemical interaction within polymeric systems. Further, the ability to systematically alter the CD response by varying the stereochemistry of the incorporated additives opens a pathway for engineering advanced materials tailored for specific optical functionalities. This could have significant implications in the fields of photonics and bio-sensing, where such materials can be utilized for enantioselective optical filters or chiral light waveguides, potentially enhancing the performance and specificity of optical systems.

We have further examined the long-term stability of the hybrid gels. As shown in Figure 4g, the samples retain their green color, with a slight blue shift due to water loss during storage. Despite this, the CD measurements reliably reflect the optical properties, as depicted in Figure 4h. Furthermore, the entire process is highly efficient, requiring ≈10 min in total. Specifically, it involves mixing the sample for ≈5 min, allowing it to stand for another 5 min, and acquiring the CD signal in just 30 s. Even after three months of storage at room temperature without special

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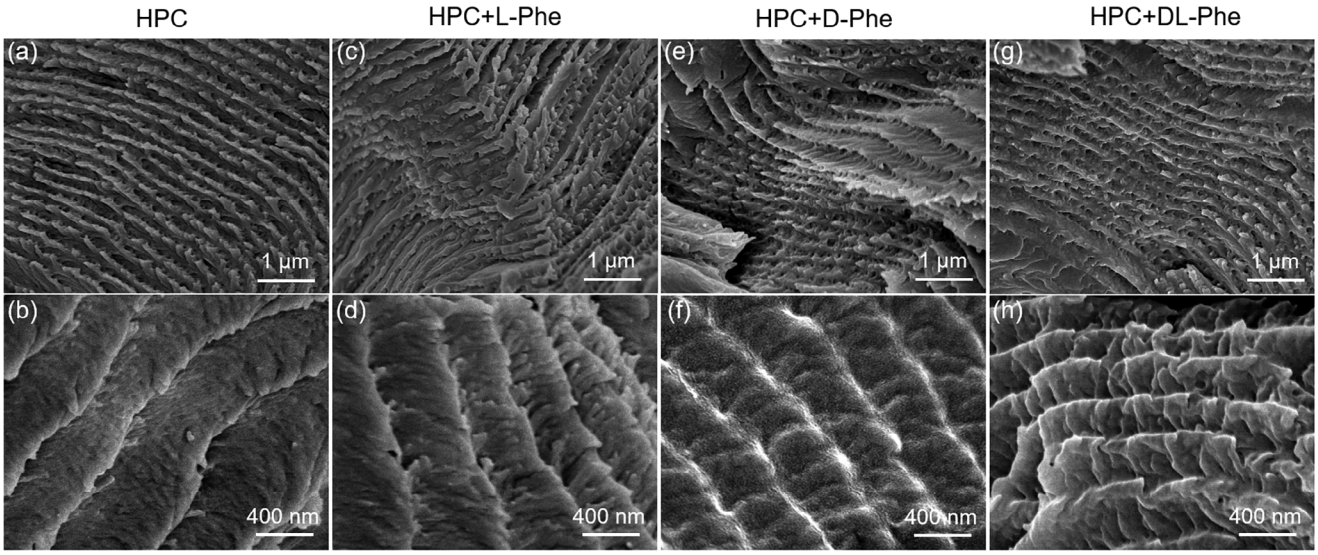

Figure 3. The Cross-section a) and surface b) of HPC. Cross-section c) and surface d) of HPC/L-Phe. Cross-section e) and surface f) of HPC/D-Phe. Cross-section g) and surface h) of HPC/DL-Phe.

conditions, the HPC/Phe gels (taken as an example for a series of samples with an HPC concentration of 67 wt.%) showed a consistent trend in their ability to absorb LCP and RCP at different scales. This sustained result indicates that the structural integrity and chiral properties of the gel remain intact over time. Such stability is crucial for applications in optical devices and sensors, where reliable and robust performance is necessary.

Furthermore, to enrich the structural colors of the HPC/Phe gels, we introduced various salts, resulting in a range of vivid colors. As shown in **Figure** 5a–f, HPC/Phe gels at a concentration of 65 wt.% displayed dark red, orange, green, light green, cyan, and blue hues following the addition of 0.5 M LiI, 0.5 M $LiNO_3$, 0.5 M KNO_3, 0.5 M LiCl, 0.8 M LiCl, and 1.0 M LiCl, respectively. Salts are known to regulate hydrophobic interactions within cellulose polymer matrices.[25,26] The chaotropic effect of different salts (following the order $Cl^- < Br^- < NO_3^- < I^- < SCN^-$ for anions and $Cs^+ < K^+ < Na^+ < Ca^{2+} < Li^+ \leq Mg^{2+} < Al^{3+}$ for cations) modifies the hydrophobic interactions

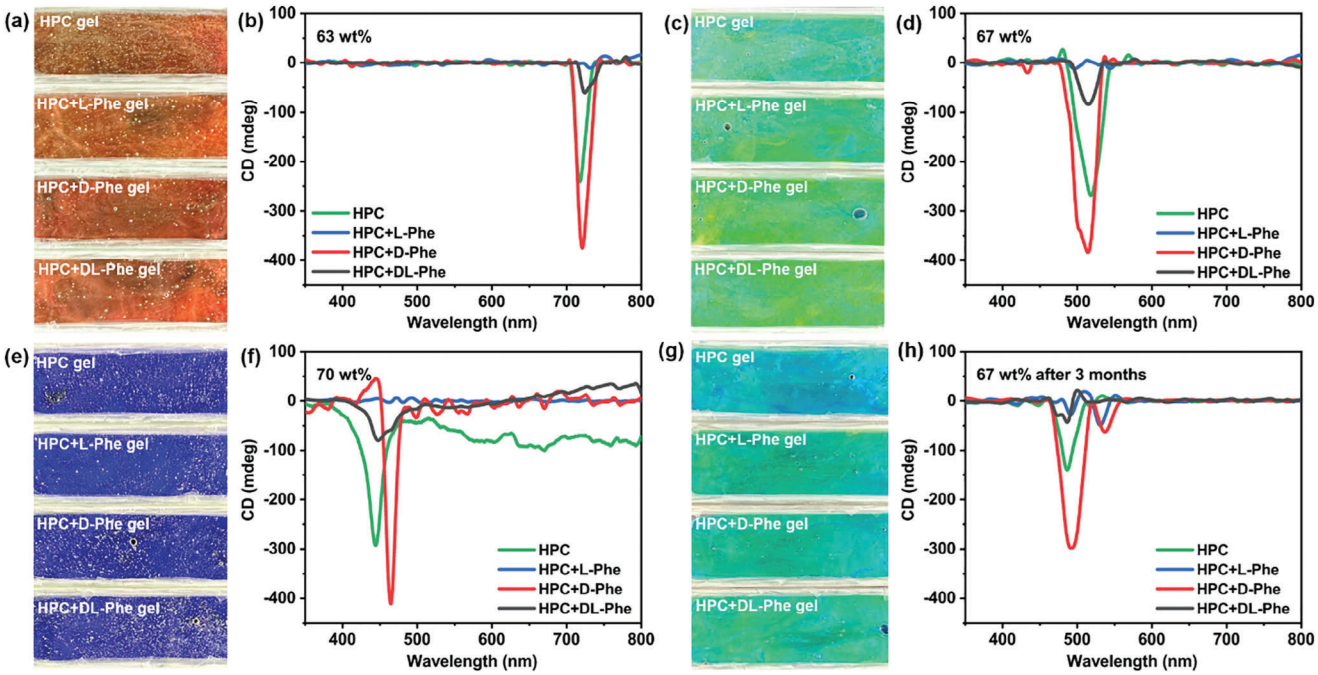

Figure 4. HPC/Phe gels at 63 wt.% a) and their CD spectra b), HPC/Phe gels at 67wt.% c) and their CD spectra d), HPC/Phe gels at 70 wt.% e) and their CD spectra f). Experiment on the longevity of the samples. HPC/Phe gels at 67 wt.% after 3 months g) and their CD spectra h).

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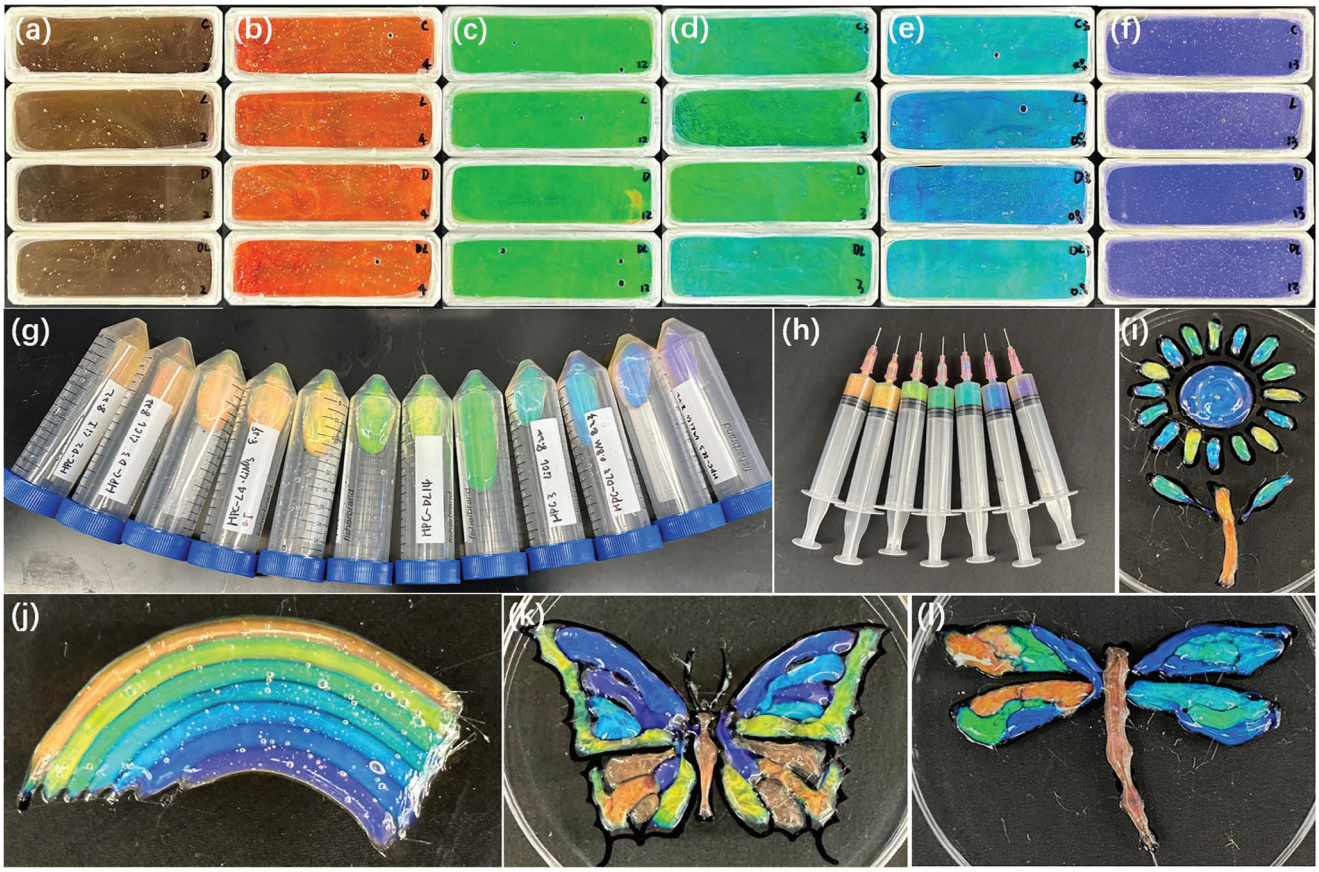

Figure 5. HPC gel and HPC/ Phe gels at a concentration of 65 wt.% were added with a) 0.5 M LiI, b) 0.5 M $LiNO_3$, c) 0.5 M KNO_3, d) 0.5 M LiCl, e) 0.8 M LiCl, and f) 1.0 M LiCl. Individual plots are shown from the top to the bottom. g) HPC gel, HPC/L-Phe gel, HPC/D-Phe gel, and HPC/DL-Phe gel prepared colorful photonic gels; h) photonic gel loaded in a syringe; and further injection printing the photonic gels to form different patterns as i) flower; j) rainbow; k) butterfly and l) dragonfly.

of HPC molecules, which changes their molecular conformation and thus the cholesteric pitch, without disturbing the molecular orientation within the liquid crystal layers.[27,28] Interestingly, the addition of salts to the HPC/Phe gels introduced a similar diversity in coloration, attributable to these interactions. Certainly, different salt concentrations make the gels show color differences, and this behavior can be explained by the increase in ionic strength.[29] Some adjustment reduces repulsive forces, therefore reducing the helical pitch and causing a blue shift in the visible signals, as seen in Figure 5c,d,e,f. However, 0.5 M LiI and 0.5 M $LiNO_3$ increased the repulsive forces, thereby increasing the helical spacing and causing a red shift in the visible signals, as shown in **Figure** 5a,b. In addition, the practical applicability of the prepared colored HPC/Phegels was evaluated by loading different colored gels into a syringe to test their printability, as shown in **Figure** 5g,h. The photonic gels retained their vivid, structural colors during the printing process, with different gels used to create detailed images of a sunflower, rainbow, butterfly, and dragonfly, as presented in Figure 5i–l. These results demonstrate excellent printing adaptability and stable color development of the HPC gels. This adaptability, coupled with the material's inherent structural coloration properties, positions HPC gels as a promising candidate for applications in pharmaceutical quality control, the food industry, and environmental monitoring of chiral pollutants. These characteristics, especially their potential for integration into smart and wearable materials, highlight the versatility and future potential of HPC gels in advanced sensing and detection technologies.

3. Conclusion

In this work, we have successfully demonstrated that HPC is an accessible and effective material for chiral detection, specifically targeting phenylalanine enantiomers. The research highlights that HPC gels provide distinguishable chiroptical responses in the CD visible spectrum for L-phenylalanine, D-phenylalanine, and DL-phenylalanine at concentrations as low as 0.2 wt.%. This capability is further enhanced through pH-induced colorimetric changes triggered by HCl addition, enabling straightforward naked-eye recognition. To validate that this method is also suitable for other materials, we further tested D-alanine, L-alanine, and DL-alanine, which demonstrated similar trends to those observed with phenylalanine. This phenomenon, reported for the first time to the best of our knowledge, offers a simple and innovative method for chiral detection that is both cost-effective and easily accessible. Moreover, the HPC matrix maintains its chiral detection capabilities for up to 3 months, making it suitable for long-term analytical applications. Additionally, we have

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developed vibrant structural colors in cellulose-based polymers to enhance the visual differentiation of chiral amino acids, further broadening the functional versatility of HPC gels. These optical analyses illustrate how chiral molecules uniquely alter light intensity and polarization when interacting with HPC. Such insights hold extensive implications for fields ranging from chemistry and physics to biology and materials science. Overall, this work introduces a novel and sustainable method for the rapid, accurate detection of enantiomers using visible light, representing a significant advancement in the field of chiral analysis.

4. Experimental Section

Materials: Hydroxypropyl cellulose (HPC, molecular weight 40 000, Molar Substitution (MS) 3.6, Degree of Substitution (DS) 2.2[30,31]) was obtained from NIPPON SIDA CO., LTD. L-phenylalanine (L-Phe, molecular weight 165.2), D-phenylalanine (D-Phe, molecular weight 165.2), DL-phenylalanine (DL-Phe, molecular weight 165.2), L-Alanine (L-Ala, molecular weight 89.1), D-Alanine (D-Ala, molecular weight 89.1), DL-Alanine (DL-Ala, molecular weight 89.1), glutaraldehyde (50%), hydrochloric acid (HCl, 37%), lithium iodide (LiI), lithium nitrate ($LiNO_3$), potassium nitrate (KNO_3) and lithium chloride (LiCl) were purchased from Fisher Scientific and used as received. All water was DI water.

Gel Preparation: To prepare a mixed gel with an HPC concentration of 65 wt.%, 0.01683 g of phenylalanine (L-Phe, D-Phe, or DL-Phe) was dissolved completely in 2.3529 g of water. Subsequently, 4.3697 g of HPC was added to the solution, and the mixture was homogenized using a mixer at 3500 rpm for 5 min. The mixture was then centrifuged at 4000 rpm for 1 h. Centrifugation accelerates the removal of air bubbles from the gel mixture, resulting in a uniform and homogeneous gel structure. While similar results could be achieved without centrifugation, this process would require significantly more time for the bubbles to dissipate naturally, potentially compromising the consistency of the gel preparation. Additionally, air bubbles, if present, could interfere with the optical and chiroptical measurements, affecting the reliability of the results. As a comparison, non-centrifuged samples are provided in Figures S4, S5 (Supporting Information). The preparation of pure HPC gel was carried out without the addition of phenylalanine. Similarly, HPC gels with concentrations of 63, 67, and 70 wt.% were prepared following the same procedure, with the respective amounts of HPC, phenylalanine, and water adjusted accordingly. An identical method was used to prepare mixtures containing alanine, the result of which is shown in Figure S3 (Supporting Information).

To prepare HPC/Phe gels abundant in structural colors, different salts were incorporated into the gels. As an example, an HPC gel containing 0.5 M LiCl at a concentration of 65 wt.% was prepared. Specifically, 0.04987 g LiCl was added to the above-prepared gel, and the mixture was homogenized using a mixer at 3500 rpm for 5 min, followed by centrifugation at 4000 rpm for 1 h.

HCl solution was added to the HPC/Phe gel to achieve color enrichment and to distinguish chirality. An appropriate amount of HCl was added to the above 65 wt.% concentration of the freshly prepared mixed gel, and the mixture was homogenized at 3500 rpm for 5 min to ensure that the pH of all the gels reached 3.5. and then centrifuged in a centrifuge at 4000 rpm for 1 h. Similarly, gels containing 0.5 M LiI, $LiNO_3$, KNO_3, LiCl, 0.8 M LiCl, and 1.0 M LiCl were prepared using the same procedure, with only adjustments to the respective amounts of the salt types and masses.

For further testing, each gel sample was placed between two glass plates and encapsulated with a parafilm primarily composed of polycaprolactone to prevent water evaporation. These prepared samples were then used for both photographic visualization and circular dichroism (CD) measurements in the visible spectrum.

Characterization—Circular Dichroism: The expression to retrieve CD spectra is given by[32]

$$CD = \arctan\left(\frac{T_{LCP} - T_{RCP}}{T_{LCP} + T_{RCP}}\right) \quad (1)$$

where T_{LCP} and T_{RCP} are the transmittance of LCP and RCP light through the sample, respectively. We used a tungsten lamp as the white light source. The light beam was then collimated by 2 lenses and 2 irises, which formed a 4f system. One linear polarizer was used to generate linearly polarized light. It then passed through a quarter waveplate to generate left- and right-handed circularly polarized light. Then it was focused on the sample with a convex lens and collected with the same lens. A mirror directed the transmitted light to the collection path of the setup, and a spectrometer (Horiba iHR550) was used to obtain the spectra. All experiments were conducted three times separately for left- and right-handed circularly polarized light.

For the CD measurements within the ultraviolet (UV) regime, a state-of-the-art Jasco J-1500 spectrophotometer was employed to ensure precise and reliable readings. The process began by carefully preparing the gel mix, which was then meticulously loaded into a small quartz cuvette with a lateral dimension of 1 cm by 1 cm. This cuvette size is standard for such experiments and allows for optimal light path and sample interaction, crucial for accurate CD spectral analysis. Once the sample was loaded in the cuvette, it was inserted into the spectrophotometer. The spectrophotometer was then set to scan across a predetermined range of UV wavelengths.

Scanning Electron Microscopy: To examine the internal structure of HPC/Phe, a gel was formed into a thin film using a cross-linking method. Initially, Glutaraldehyde (0.4 g) was diluted in an aqueous solution of hydrochloric acid (0.5 mL, 3.6 g). Subsequently, three different phenylalanine molecules (L-Phe, D-Phe, and DL-Phe) were introduced into each of these acidic glutaraldehyde solutions and mixed instantly using a planetary centrifuge. Following this dried HPC powder (6.0 g) was added to the solution and further mixed in a planetary centrifuge under the same conditions. The resultant mixture was degassed by centrifugation at 4000 × g for 1 h. Subsequently, the gel was spread on glass slides and held at 70 °C for 2 h.

Supporting Information

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

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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

amino acids, chiral molecule detection, hydroxypropyl cellulose, phenylalanine, structural color

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