Cellulose Nanocrystals as an Alignment Layer for Liquid-Crystal Displays in a Circular Economy

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Abstract

We report a Liquid Crystal Display (LCD) structure employing cellulose nanocrystals (CNC) as a recyclable, non-toxic alignment layer in a twisted nematic configuration. The CNC alignment layer, fabricated via spin coating and mechanical rubbing, demonstrated comparable performance to polyimide in transparency, threshold voltage, response speed, and liquid crystal alignment. This work demonstrates the viability of CNC alignment layers, advancing LCD technology toward circular economy principles.

Author Keywords

Liquid Crystal Displays; Cellulose Nanocrystals; Alignment Layer; Circular Economy

1. Introduction

The Liquid Crystal Display (LCD) market has experienced dynamic growth over the past several decades, driven by applications ranging from consumer electronics to industrial screens. This expansion continues today, with the global LCD market valued at an estimated 142 billion USD in 2022 and projected to grow at a compound annual growth rate (CAGR) of approximately 6.28% between 2023 and 2030 [1]. However, this growth has also raised significant environmental concerns due to the waste generated throughout the manufacturing and disposal processes. With most LCD consumer products having a lifespan of less than 10 years, tens of thousands of square kilometers of waste LCDs are produced annually [2].

LCDs operate by manipulating the orientation of liquid crystal molecules sandwiched between two alignment layers under an applied electric field, which modulates light transmission to produce images. Materials used in LCDs, such as polyimide alignment layers and Diamond-Like Carbon (DLC) films, exacerbate environmental degradation due to their nonrecyclable and chemically intensive nature. Existing waste management strategies, including incineration and landfill disposal, are insufficient to address these challenges and often contribute to further environmental harm. Recycling approaches for LCD panels, such as crushing, dismantling, and acid leaching, have been developed to recover critical raw materials [3, 4]; however, these methods remain resource-intensive and focus primarily on material separation rather than waste prevention. As sustainability becomes an urgent priority for the display industry, there is a pressing need for alternative materials that align with circular economy principles. This study investigates cellulose nanocrystals () as a sustainable replacement for conventional alignment layers, highlighting their potential as a recyclable, non-toxic, and environmentally friendly solution.

Cellulose is emerging as a versatile and sustainable material, typically derived from plant-based sources such as wood, agricultural residues, and cotton through processes involving delignification, purification, and hydrolysis. This process yields a recyclable and biodegradable material with minimal environmental impact [5, 6]. As one of the most abundant polymers on Earth, with annual production exceeding 7.5×10^{10} tons [6], cellulose offers a unique combination of environmentally friendly, renewable, and non-toxic properties. Its excellent optical transparency, low birefringence, high tensile strength, and thermal stability make it a promising candidate for use as an alignment layer in LCDs. These properties enable cellulose to guide liquid crystal alignment, facilitating light transmission through perpendicular polarizers in the "on" state.

Studies have demonstrated the potential of cellulose-based materials to induce uniform liquid crystal alignment. For example, microphotographs of 5CB liquid crystal droplets on ethyl cellulose films reveal that 5CB molecules align parallel to the banded-texture structure of the cellulose film [7]. Additionally, LCD pixels fabricated with cellulose alignment layers exhibit transparency levels comparable to polyimide and superior thermal stability, maintaining functionality even after 300°C heat treatment [8].

This study focuses on cellulose nanocrystals (CNC), which are 1D chiral nanorods derived from cellulose [9]. CNC retain all the inherent advantages of cellulose, including its sustainability and low carbon footprint, while offering unique nanoscale benefits such as ease of deposition, smooth suspension, and minimal chemical modification requirements. Furthermore, CNC enable straightforward fabrication processes and seamless integration with other recyclable, carbon-based printed backplane technologies, such as thin-film transistors (TFTs) [10, 11].

In this work, we present a novel method for integrating CNC as an alignment layer in a twisted-nematic LCD fabrication process. Electro-optical characterization and comparative analyses between CNC and polyimide-based LCD cells highlight the potential of CNC as a sustainable and high-performance alignment layer for LCD technologies in a circular economy.

2. Methodology

LC Cell Assembly: The fabrication steps and final device structure for the LC cell are illustrated in Figure 1. Indium tin oxide (ITO)-coated glass substrates (Lumtec, LT-G001, 50 mm × 50 mm, 0.7 mm thick, ~15 Ω/sq) were first solvent-cleaned and subsequently treated with UV ozone to ensure thorough cleaning and to render the surface hydrophilic. Cellulose nanocrystals (CNC) (Cellulose Lab, CNC-Slurry-DS) were diluted with deionized (DI) water to the desired concentration and deposited onto the substrates via spin coating. The coated substrates were then baked at 70°C for 5 minutes to ensure uniform film formation. The polyimide (PI) reference sample was prepared using a polyimide solution from HD Microsystems. The CNC film was gently rubbed with a flannel cloth five times to induce alignment. A 5μm PET-based spacer was positioned between two ITO-CNC-coated slides, and the cell was sealed with epoxy to maintain the desired cell gap. Finally, the assembled cell was filled with liquid crystal material (Sigma-Aldrich, 5CB) and fixed between two polarizer sheets oriented at 90° to each other.

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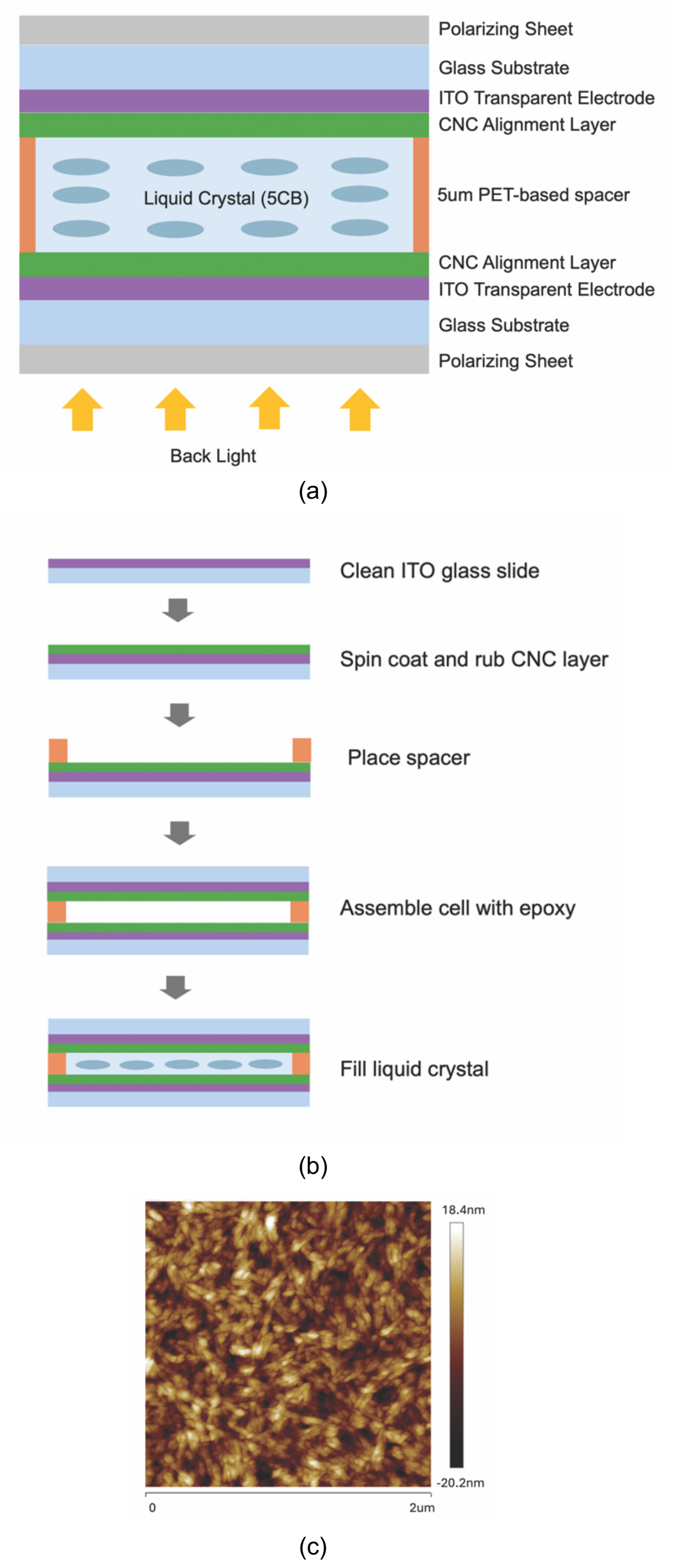

(a)

(b)

(c)

Figure 1. LCD cell incorporating CNC as the alignment layer. (a) Schematic representation of the final device structure. (b) Fabrication process flowchart for the LCD cell. (c) AFM topography image of the CNC film prior to rubbing.

Characterization and Instrumentation: The electro-optical properties of the fabricated LC cells were characterized using a setup comprising a light source (Newport, Oriel Apex Illuminator), a monochromator (Princeton Instruments, Acton SP-2150), a photodiode (Thorlabs, S120VC), and a power and energy meter (Thorlabs, PM100USB). To minimize interference, environmental light was effectively blocked by a cover. The output from the monochromator served as the backlight, and the transmitted light was measured by the photodiode. The photodiode output was configured to low-bandwidth mode to reduce noise in the collected data. Voltage-dependent behavior and temporal response were examined by driving the device with a 1 kHz square wave at varying peak-to-peak voltages to toggle the cell between on and off states.

Optical transmittance of the samples was assessed using UV-Vis spectroscopy (Agilent 8453 UV/Vis Spectrophotometer), enabling analysis of the CNC-based LCD cell's transmission across the visible spectrum.

The surface morphology of the unrubbed CNC layer was evaluated using atomic force microscopy (Bruker Dimension Fast Scan AFM) operated in contact mode to assess film uniformity and surface texture.

Response times were determined by measuring the transition durations of light transmission. The rise time (t_r) was defined as the time required for light transmission to decrease from 90% to 10% of its maximum range, while the fall time (t_f) corresponded to the time needed for light transmission to increase from 10% to 90% of its maximum range.

3. Results

Electro-optical characterization was performed at 550 nm and 560 nm to compare the performance of LCD cells fabricated with CNC and polyimide alignment layers. Figure 2(a) presents images of the fabricated LCD cells, demonstrating comparable brightness levels for both polyimide and CNC-based cells. This indicates the functionality of CNC as an alignment layer and suggests that the two types of cells exhibit qualitatively similar performance to the observer. Figure 2(b) further supports this observation, showing the voltage-dependent transmission curves for cells constructed with both polyimide and CNC at varying concentrations. Both types of cells exhibit a sharp transition in transmission between 2 and 5 Vpp, highlighting their effective operation. The observed difference in threshold voltage is attributed to variations in alignment layer thickness, as a thicker alignment layer generally increases the threshold voltage.

Figure 3 illustrates the spectral transmission profiles of both CNC and polyimide (PI) samples across the visible spectrum. Both samples exhibit similar turn-on behavior, demonstrating comparable optical performance. The spectral transmission shape is primarily influenced by the polarizers, which dominate the modulation of transmitted light. The observed oscillations in the transmission curves are likely attributable to second-order cavity effects inherent to the cell structure.

The response speeds of the LCD cells, summarized in Table 1, are comparable between samples with CNC (1.6 wt%) and traditional polyimide alignment layers at 650nm. The transition edges depicted in Figure 4 exhibit similar shapes, further confirming that the CNC alignment layer achieves dynamic performance on par with the conventional polyimide layer.

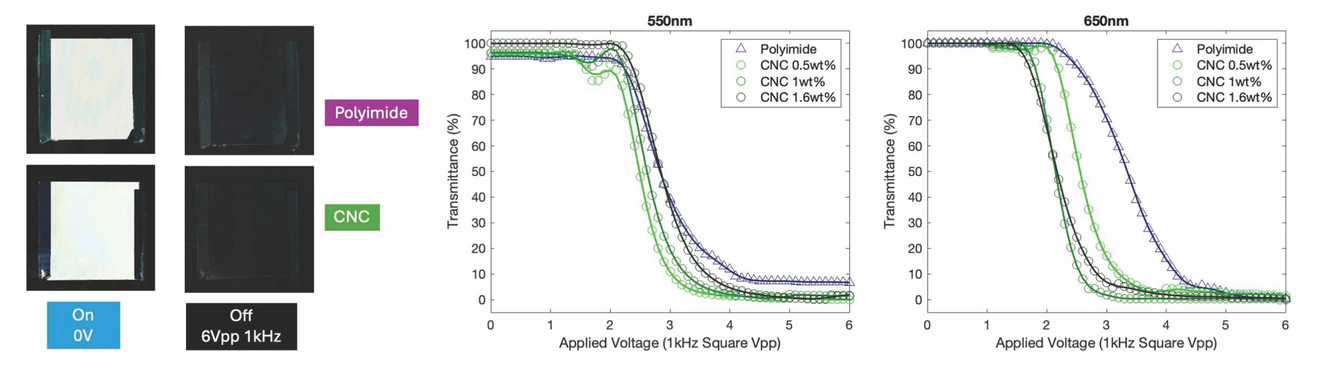

Figure 2. Electro-optical characterization of LCD cells with CNC compared to polyimide. (a) Images of LCD cells in their bright and dark states. (b) Light transmission versus voltage curves, with the polyimide-LCD sample represented in blue and CNC-LCD samples fabricated using different spin-coating solution concentrations represented in varying shades of green.

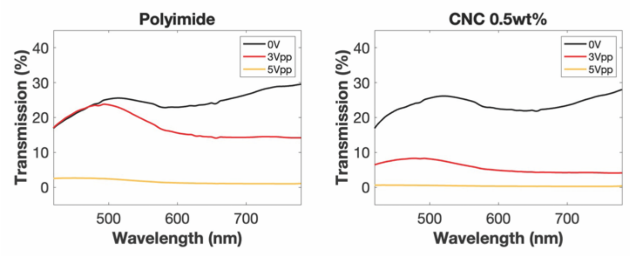

Figure 3. Spectral transmission of CNC and PI samples across the visible range (420–780 nm).

Table 1. Response Time at 650nm

Vpp	Rise Time t_r (ms)		Fall Time t_f (ms)	
	PI	**CNC**	**PI**	**CNC**
10	16.5	15.6	22.8	16.7
6	22	18.3	21.8	18.7

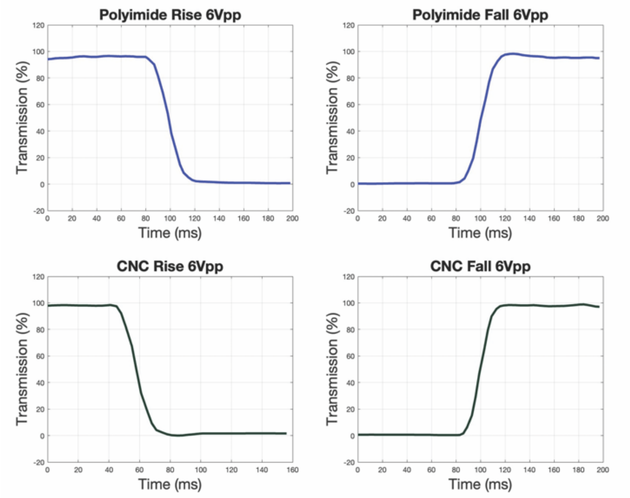

Figure 4. On-off transition edges for polyimide (PI) and CNC cells driven by a 6 Vpp, 1 kHz square wave.

Minor variations in the measured response times are likely due to slight inconsistencies in the cell gap during fabrication, which influence the overall capacitance of the cell. The rise time (t_r) is strongly influenced by the applied voltage, with higher peak-to-peak voltages accelerating the rise time by exerting greater driving forces on the liquid crystal molecules. In contrast, the fall time (t_f) is primarily governed by the intrinsic relaxation dynamics of the liquid crystals and exhibits minimal dependence on the driving voltage amplitude.

4. Conclusions and Future Work

This study demonstrates the functionality of cellulose nanocrystals (CNC) as a novel alignment layer for liquid crystal displays (LCDs). Electro-optical characterization show that the performance of CNC-based alignment layers is comparable to that of traditional polyimide layers, establishing CNC as a viable alternative for sustainable LCD manufacturing. The successful implementation of CNC in LCD cells paves the way for integrating this recyclable material into a fully sustainable display system, potentially in combination with other carbon-based recyclable components.

While the results highlight CNC's promise as an alignment layer, careful control and characterization of critical fabrication parameters, such as cell gap and alignment film thickness, are essential. Variations in these parameters can influence device performance, and addressing these inconsistencies is necessary for reliable and reproducible outcomes. Additionally, future studies should isolate the effects of the alignment films themselves, eliminating confounding influences from other cell components to provide a more accurate assessment of their optical properties. These efforts will help establish CNC as a key material for recyclable display technologies, contributing to a sustainable and environmentally responsible electronics industry.

Building on the demonstrated functionality of CNC as an alignment layer, current efforts are directed toward integrating CNC-based LCD cells with printable, recyclable thin-film transistors (TFTs). The feasibility of combining CNC alignment layers with carbon-based recyclable TFT backplanes has already been demonstrated [11]. We are also exploring the use of sustainable materials for additional LCD components, such as electrodes, optical filters, and substrates. These advancements emphasize the potential of CNC and recyclable electronics in display technology, offering a path forward that aligns performance with sustainability.

5. Acknowledgements

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6. References

1. Zion Market Research. Liquid Crystal Display (LCD) Market Size, Share, Trends, 2023-2030 [Internet]. Zion Market Research. Available from: https://www.zionmarketresearch.com/report/liquid-crystal-display-lcd-market
2. Liu Z, Xu Z, Huang H, Li B. A study of waste liquid crystal display generation in mainland China. Waste Management & Research. 2015 Nov 5;34(1):58–66.
3. Amato A, Becci A, Mariani P, Carducci F, Ruello ML, Monosi S, et al. End-of-Life Liquid Crystal Display Recovery: Toward a Zero-Waste Approach. Applied Sciences. 2019 Jul 25;9(15):2985.
4. Zhang K, Wu Y, Wang W, Li B, Zhang Y, Zuo T. Recycling indium from waste LCDs: A review. Resources, Conservation and Recycling. 2015 Nov;104:276–90.
5. Klemm D, Heublein B, Fink HP, Bohn A. Cellulose: Fascinating Biopolymer and Sustainable Raw Material. Angewandte Chemie International Edition. 2005 May 30;44(22):3358–93.
6. Habibi Y, Lucia LA, Rojas OJ. Cellulose Nanocrystals: Chemistry, Self-Assembly, and Applications. Chemical Reviews. 2010 Jun 9;110(6):3479–500.
7. Yan L, Zhu Q, Ikeda T. Ethyl cellulose films as alignment layers for liquid crystals. Journal of Applied Polymer Science. 2001 Oct 1;82(11):2770–4.
8. Kang H, Lee JC, Nam B, Bae JW. Liquid crystal alignment behavior on transparent cellulose films. RSC Advances. 2015;5(48):38654–9.
9. Duan C, Cheng Z, Wang B, Zeng J, Xu J, Li J, et al. Chiral Photonic Liquid Crystal Films Derived from Cellulose Nanocrystals. 2021 May 28;17(30):2007306–6.
10. Williams NX, Bullard G, Brooke N, Therien MJ, Franklin AD. Printable and recyclable carbon electronics using crystalline nanocellulose dielectrics. Nature Electronics. 2021 Apr;4(4):261–8.
11. Doherty JL, Zhang Y, Smith BN, Hobbie HA, Ioannis Kymissis, Franklin AD. Liquid Crystal Displays with Printed Carbon-based Recyclable Transistor Backplanes. IEEE Electron Device Letters. 2024 Jan 1;1–1.