

Advanced Preparation Techniques for High-Performance Liquid Crystal Cells: A Review on the Last Decade

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ABSTRACT

Fabricating high-performance liquid crystal (LC) cells has changed considerably over the past decade, driven by pressure to lower power consumption, speed up switching, accommodate flexible form factors, and improve colour accuracy in display and photonic applications. This review surveys the main preparation techniques reported between 2015 and 2025, covering substrate cleaning and pre-treatment, electrode deposition, alignment layer engineering, cell-gap control, LC filling, and sealing. Particular attention goes to photo-alignment methods, polymer-stabilised blue-phase LCs, atomic-layer-deposited oxide electrodes, graphene-based transparent conductors, and AI-assisted process optimisation. Performance data are compiled in structured tables to allow direct comparison across methodological generations. The review also identifies persistent fabrication difficulties most notably, defect density control at sub-nanometre scales and outlines directions the field is likely to pursue through the 2030s.

Keywords- Liquid Crystal Cells; Photo-Alignment; Blue-Phase LC; Graphene Electrode; Polymer Network; Cell-Gap Uniformity; Alignment Layer; Fabrication Review.

I. INTRODUCTION

Liquid crystal devices are used throughout modern optical technologies. Flat-panel displays in consumer electronics, precision optical modulators in adaptive optics, telecommunications equipment — the performance of any LC-based system depends directly on the quality of the cell that contains it. At its most basic, an LC cell is a precisely engineered sandwich: a thin film of anisotropic fluid held between two substrates, each carrying an electrode and a surface treatment that sets the preferred molecular orientation of the adjacent LC layer. That description understates the engineering difficulty. Every interface, every deposited film, and every process parameter affects the electro-optical behaviour of the finished device, sometimes in ways that are not linear or immediately obvious.

The decade from 2015 to 2025 has been an active one. Several pressures converged: the spread of

high-pixel-density displays, the arrival of augmented and virtual reality headsets with strict latency requirements, and growing commercial demand for flexible and rollable display formats. These pushed researchers and engineers to revisit practices that, in some areas, had gone largely unchanged for twenty years. New analytical tools — aberration-corrected transmission electron microscopy, synchrotron X-ray nano-diffraction, and machine-learning-assisted process control made possible a level of diagnostic precision and feedback-driven optimisation that simply was not available earlier.

This review is organised to take the reader from the substrate inward: substrate preparation first, then electrode and alignment-layer deposition, then cell assembly, LC filling, and post-fill treatments. Where preparation requirements differ across mesophase types, the discussion distinguishes between nematic, cholesteric, and smectic LC systems. Figure 1 shows a cross-sectional schematic of a canonical LC cell for reference throughout the paper.

SUBSTRATE (Glass)
TRANSPARENT ELECTRODE (ITO)
ALIGNMENT LAYER (Polyimide / Photo-aligned)
LIQUID CRYSTAL BULK (Nematic / Cholesteric / SmA)
ALIGNMENT LAYER (Polyimide / Photo-aligned)
TRANSPARENT ELECTRODE (ITO)
SUBSTRATE (Glass)

Figure 1. Layer Stack of a Canonical LC Cell

Figure 1. Schematic cross-sectional layer stack of a canonical liquid crystal cell. Layers are shown in greyscale to indicate typical refractive-index contrast between structural components. Thickness ratios are illustrative, not to scale.

II. SUBSTRATE PREPARATION AND
SURFACE PRE-TREATMENT

2.1 Glass and Flexible Polymer Substrates

Borosilicate and alkali-free aluminosilicate glass remain the substrate materials of choice for high-performance LC cells, largely because of their dimensional stability, low coefficients of thermal expansion (< 4 ppm/°C), and well-understood surface chemistry. Over the decade under review, however, research effort has shifted substantially toward flexible substrates polyethylene naphthalate (PEN), polyethylene terephthalate (PET), and cyclo-olefin polymer (COP) films driven by demand for wearable and conformal-display applications.

Substrate surface cleanliness at the start of processing is not a procedural formality; it determines alignment quality and long-term device reliability. Standard protocols call for sequential ultrasonic cleaning in acetone, isopropanol, and deionised water, followed by dehydration baking. Studies published after 2018 have shown that UV-ozone treatment at wavelengths below 200 nm can remove organic contaminants to levels undetectable by X-ray photoelectron spectroscopy, without the mechanical risks that ultrasonic agitation poses for ultra-thin flexible substrates. Plasma-based cleaning using O₂ or Ar/O₂ mixtures has also been revisited, with RF power and treatment durations calibrated to raise surface energy without inducing micro-cracking in brittle oxide-coated polymers.

2.2 Surface Energy Optimisation

The influence of substrate surface energy on alignment-layer adhesion received renewed quantitative attention during this period. Contact-angle goniometry combined with the Owens-Wendt-Rabel-Kaelble (OWRK) decomposition has been used routinely to separate polar and dispersive components of surface energy on treated glass and PEN surfaces. Research groups in East Asia and Europe independently found that a surface energy window of roughly 40–60 mN/m with the polar component held below 15 mN/m — produces

good adhesion of polyimide alignment layers while limiting dewetting pinholes during spin-coating. Surfaces outside this range consistently showed higher defect densities in finished cells, as measured by polarised optical microscopy and Mueller-matrix polarimetry.

III. ELECTRODE DEPOSITION
TECHNIQUES

3.1 Indium Tin Oxide: Persistent Workhorse and Its Limitations

Indium tin oxide (ITO) has been the transparent electrode of choice in LC cells for decades. Between 2015 and 2025, its deposition was refined incrementally while the field also accumulated a growing body of evidence about its limitations. RF- and DC-magnetron sputtering remain the dominant deposition routes; better control over target composition and working-gas partial pressure has pushed sheet resistances reliably below 8 Ω/sq at transmittances above 90% across the visible spectrum. Low-temperature ITO deposition — needed for flexible polymer substrates — was advanced through pulsed DC sputtering combined with mild substrate heating (60–80°C), producing films with carrier concentrations above 10²¹ cm⁻³ on PEN without exceeding the substrate’s thermal limit.

That said, indium supply-chain risk, ITO’s brittleness under repeated flexion (cracks appear at strains of about 1–2%), and the cost of high-purity sputtering targets kept the search for alternatives alive throughout the decade, particularly after 2017.

3.2 Graphene and Carbon Nanotube Electrodes

Chemical-vapour-deposited (CVD) graphene as a transparent electrode for LC cells moved from proof-of-concept demonstrations to process-engineering investigations during this period. The main technical hurdles transferring large-area graphene from copper foil to glass or polymer without wrinkles, tears, or polymeric residues from the PMMA transfer layer were tackled through dry transfer, roll-to-roll lamination, and electrochemical delamination. By 2023, sheet resistances of 150–300 Ω/sq with optical transmittances above 97% had been demonstrated on 150 mm wafer-scale substrates, and LC cells using graphene electrodes performed comparably to ITO-based reference cells, with slightly lower switching hysteresis.

Carbon nanotube (CNT) networks, while geometrically less uniform than graphene, offered tunable sheet resistance through density control and held up well under repeated bending, with resistance changes below 3% after 10,000 flexion events at a 5 mm radius.

3.3 Atomic-Layer-Deposited Oxide Films

Atomic layer deposition (ALD) of zinc oxide (ZnO) and indium-gallium-zinc oxide (IGZO) thin films emerged as a practical route to ultra-uniform, pinhole-free electrodes and gate insulators in active-matrix LC backplanes. The self-limiting surface-reaction

mechanism of ALD gives thickness control at the sub-angstrom level across substrates with complex topography something conventional sputtering cannot achieve. Research from 2016 to 2022 established ALD-ZnO as a viable ITO replacement in cells where electrode planarity and conformality over pixelated TFT topography matter most. The chief remaining limitation, deposition throughput, is being addressed through spatial ALD reactor designs, which exceeded 10 nm/min by 2024.

IV. ALIGNMENT LAYER ENGINEERING

4.1 Conventional Mechanical Rubbing

Mechanical rubbing of polyimide films using a velvet-covered roller traversing the cured alignment layer at a controlled speed, load, and pile-length penetration depth — remained widespread in large-area TFT-LCD manufacturing throughout this decade. Studies published after 2015 applied more rigour to the rubbing parameter space, relating pretilt angle to rubbing density (a compound parameter combining roller speed, substrate speed, and pile length) through empirical models and molecular-dynamics simulations. Pretilt angles of 2–5° for standard nematic displays, and up to 85° for vertically aligned modes, were achieved reliably. The mechanism by which rubbing orients the polyimide surface layer remained under active study, with evidence pointing to both mechanical deformation and the exposure of anisotropic sub-surface domains.

The main problems with mechanical rubbing electrostatic charge build-up, particulate contamination, and incompatibility with non-planar or pre-patterned substrates sustained continued development of non-contact alternatives.

4.2 Photo-Alignment

Photo-alignment, in which polarised light exposure creates directional anisotropy in a photosensitive polymer, was the alignment development of greatest industrial consequence during this decade. It eliminates all mechanical contact with the substrate, removes the risk of electrostatic discharge damage to TFT circuits, and most usefully allows multiple in-plane alignment directions to be patterned on a single substrate through sequential masked exposures. This last capability proved indispensable for lenticular lens arrays, multi-domain LC cells for wide viewing angles, and holographic waveguide combiners in augmented-reality systems.

The photosensitive materials used fall into three main chemical families: cinnamate-based polymers, in which [2+2] cycloaddition under polarised UV creates anisotropic crosslinks; azo-dye-doped polymers, in which repeated trans-cis isomerisation cycles under polarised irradiation drive anisotropic dye orientation that is then transferred to the polymer backbone; and linear photopolymerisable polymers (LPP), in which

polarised exposure directly generates anisotropy in side-chain chromophores without post-exposure thermal treatment. Anchoring energies from photo-alignment layers were, for some time, lower than those of rubbed polyimide; advances in LPP chemistry between 2018 and 2023 narrowed the gap to within a factor of two, which is acceptable for most display applications.

4.3 Laser and Nanoscale Patterning Approaches

Femtosecond laser ablation to create periodic surface-relief gratings on glass substrates — groove depths of 5–50 nm, periods of 200–800 nm — was demonstrated as an alignment technique capable of setting pretilt angles with sub-degree precision. Unlike rubbed polyimide, laser-textured glass needs no polymer coating, which simplifies the stack and may improve thermal stability. Atomic force microscopy (AFM)-based nano-rubbing with the probe tip traversing the alignment layer in a raster pattern at applied forces of 100–500 nN has been used as a research tool to study the relationship between groove geometry and LC anchoring energy at length scales that conventional rubbing characterisation cannot access.

Two-dimensional materials, notably molybdenum disulphide (MoS₂) deposited by chemical vapour deposition, were also investigated as alignment layers in their own right. In 2025, the in-plane crystal anisotropy of hexagonal MoS₂ was shown to orient LC molecules along crystallographic directions without additional surface treatment an avenue toward atomically thin, chemically stable alignment layers.

V. CELL-GAP CONTROL AND SPACER TECHNOLOGIES

The cell gap the distance between the two substrates directly controls the birefringence-thickness product that governs electro-optical response and colour behaviour, making it arguably the most critical dimensional parameter in LC cell fabrication. Tolerances of ±0.1 µm or better are required for high-performance applications.

Conventional ball spacers dispersed by spray or wet-coating remained in use for cost-sensitive products, but were progressively supplemented, and in premium products replaced, by lithographically defined column spacers. Column spacers, formed from negative-tone photoresists by photolithographic patterning and soft-baking, are placed only in non-active pixel regions, provide height uniformity better than ±0.05 µm across 300 mm × 400 mm substrates, and can be tuned mechanically through resin formulation and bake conditions. Inkjet-printing of photo-curable spacer arrays, reported by several groups between 2019 and 2023, combined the positional flexibility of column spacers with a maskless deposition process suited to rapid prototyping and non-rectangular cell geometries.

White-light interferometry deployed in-line at multiple stages became standard for cell-gap

measurement at leading manufacturing facilities. Closed-loop gap control, where measured deviations from target trigger real-time adjustments to pressing force during seal cure, cut finished-cell gap standard deviations from 0.3 μm to below 0.08 μm in documented industrial implementations.

Figure 2. Decade Timeline of Key LC Cell Preparation Milestones (2015–2025)

Year	Milestone / Technique	Significance
2015	Roll-to-roll photo-alignment on flexible substrates	Enabled flexible LC displays
2016	Atomic-layer-deposited ZnO gate insulators	Improved TFT uniformity
2017	Reactive-mesogens for self-assembled polymerised LC	Solid-state optic films
2018	Femtosecond laser surface texturing for anchoring	Sub-micron alignment control
2019	Inkjet-printed spacer arrays	Reduced cell-gap non-uniformity
2020	Plasma-free dry photo-alignment (DUV)	Contamination-free process
2021	Atomic-force-microscopy rubbing with <5 nm grooves	Ultra-fine pretilt tuning
2022	Blue-phase LC stabilised by polymer network	Fast switching, wide temperature range
2023	Graphene transparent electrodes replacing ITO	Improved flexibility and conductivity
2024	AI-assisted assembly optimisation for mini-LED backlit cells	Defect rate < 0.01%
2025	2D-material (MoS_2) alignment layers	Atomically thin anchoring control

Figure 2. Key preparation milestones in liquid crystal cell fabrication, 2015–2025. Entries are selected based on demonstrated impact on device performance or on industrial adoption.

VI. LIQUID CRYSTAL FILLING AND SEALING PROCESSES

6.1 One-Drop Fill

The one-drop fill (ODF) process in which a precisely metered volume of LC is dispensed onto one substrate before cell assembly has dominated flat-panel display manufacturing since the mid-2000s. Between 2015 and 2025, it was refined in dispensing precision, LC material characterisation, and environmental control during assembly. The dispensed volume per cell, typically 1–200 μL depending on cell area, must be

calculated from the gap target and the LC’s anisotropic compressibility. Gravimetric feedback systems with 0.01 μL resolution became standard, and bulk modulus characterisation of LC mixtures as a function of temperature and composition was revisited to support dispensing calculations for new LC formulations.

Environmental control during ODF assembly particularly humidity and particulate levels remained a persistent concern. Residual moisture in the LC bulk contributes to ionic impurity and long-term image sticking. ISO Class 4 or better cleanroom conditions are consistently cited in the literature as necessary for reliable ODF assembly of displays intended for extended field lifetimes.

6.2 Vacuum Injection

For smaller, higher-value devices LC spatial light modulators, variable retarders for adaptive optics, and research cells vacuum injection from a reservoir remains the preferred filling method. It allows tighter control over the thermal and temporal conditions of LC introduction. Injection at temperatures within the isotropic phase, followed by slow cooling at 0.1–0.5°C/min through the clearing point, promotes uniform macroscopic alignment. Faster cooling rates correlate with higher defect densities, particularly in smectic systems where layer formation requires a contaminant-free environment.

6.3 Sealant Materials and Processes

The sealant that bonds the two substrates and defines the cell perimeter is a more complex engineering problem than it appears. It must maintain mechanical strength under temperature cycling, exhibit negligible out gassing into the LC volume, adhere to both glass and alignment-layer surfaces, and cure without generating ionic contaminants. Epoxy-acrylate formulations cured by sequential UV and thermal exposure so-called dual-cure sealants progressively displaced single-cure epoxies during this period, because the UV pre-cure step locks the seal geometry before thermal cure is complete, preventing flow during the elevated-temperature hold. Ion chromatography measurements of LC extracted from test cells showed that state-of-art dual-cure sealants released fewer than 3 ppm of ionic species into the LC volume after 1000 hours at 60°C, a tenfold improvement over formulations in use at the start of the decade.

VII. ADVANCED AND EMERGING FABRICATION TECHNIQUES

7.1 Polymer-Stabilised and Blue-Phase Liquid Crystals

Blue-phase liquid crystals (BPLCs) exist in a self-organised, optically isotropic cubic lattice at temperatures between the chiral nematic and isotropic phases. Their sub-millisecond electro-optical response a direct consequence of the absence of a persistent macroscopic director that must be reoriented attracted sustained interest throughout the decade. The main obstacle to practical use has been the inherently narrow

temperature range of the blue phase (typically a few Kelvin). Polymer networks formed by UV-initiated crosslinking of reactive mesogen monomers dissolved in the LC host address this limitation; polymer-stabilisedBPLCs with temperature ranges above 60°C were demonstrated by 2022, and driving voltages were reduced to below 15 V through electrode geometry optimisation using interdigital electrodes with sub-5-μm gaps defined by electron-beam lithography.

7.2 Reactive Mesogen Films and Solid-State Optics

Reactive mesogens (RMs) — polymerisable LC monomers offer a distinct fabrication route in which LC alignment and polymerisation are combined to produce solid-state optical films with fixed retardation profiles. Deposited by spin-coating or inkjet printing onto photo-aligned LPP layers, RM films crosslink under UV irradiation to form polymer networks that permanently lock in the desired director configuration. Applications include patterned retarders for 3D display systems, achromatic waveplates, and compensation films for wide-viewing-angle LC panels. Spin-coated RM films achieve thickness uniformity better than ±2 nm across 200 mm substrates under well-controlled process conditions, which is adequate for single-wavelength retardation work. Broadband achromatic performance requires stacked layers with orthogonal slow axes, adding process complexity.

7.3 Artificial Intelligence in Process Optimisation

The most structurally novel development of the decade has been the integration of machine learning into LC cell fabrication process control. Convolutional neural networks trained on polarised microscopy images of partially assembled cells classified domain boundaries, disclination lines, and dust-induced alignment defects with sensitivity and specificity above 95%, matching or exceeding experienced human inspectors while operating at line speeds where manual inspection is not feasible. Reinforcement learning frameworks were also applied to multi-parameter optimisation of rubbing and photo-alignment processes, where the high-dimensional interactions among tool speed, exposure dose, film thickness, and cure temperature make exhaustive empirical search impractical. Published results from 2024 documented a reduction in alignment defect density to below 5 cm⁻², down from a baseline of roughly 50–100 cm⁻², achieved through AI-guided adjustment of fifteen concurrent process parameters on a pilot manufacturing line.

Figure 3. Comparative Performance Matrix: Three Alignment Methodologies

Performance Metric	Conv. Rubbing	Photo-alignment	Blue-Phase LC
Switching Speed	5/10	7/10	9/10
Anchoring Energy	8/10	7/10	4/10

Uniformity	6/10	9/10	7/10
Thermal Stability	7/10	6/10	9/10
Scalability	7/10	8/10	6/10

Figure 3. Comparative performance matrix for three principal alignment methodologies across five electro-optical and process metrics on a normalised ten-point scale. Values are derived from mean published figures across at least five independent studies per technique.

VIII. INTEGRATED PROCESS FLOW FOR HIGH-PERFORMANCE LC CELLS

The advances surveyed in preceding sections do not operate in isolation; they fit into a fabrication sequence in which each step constrains what is achievable in all subsequent steps. Figure 4 shows a stage-sequenced process flow that reflects current best practice for high-performance LC cell fabrication, synthesised from published process accounts and patent disclosures reviewed for this paper.

Figure 4. Annotated Process Flow for High-Performance LC Cell Fabrication

S.N	Stage	Process Details
01	Substrate Preparation	Ultrasonic cleaning, UV-ozone treatment, dehydration bake at 120°C
02	Electrode Deposition	RF-magnetron sputtering of ITO or graphene CVD transfer; sheet resistance < 10 Ω/sq
03	Alignment Layer Coating	Spin-coating / inkjet deposition of polyimide or photosensitive polymer at 500–3000 rpm
04	Curing & Alignment	Thermal imidisation at 200°C OR polarised UV exposure (λ = 313 nm, 50–300 mJ/cm²)
05	Spacer Dispensing	Ball-spacer spray or lithographic column spacers; cell gap ±0.1 μm tolerance
06	Sealant Dispensing	UV-curable or thermally cured epoxy sealant via micro-dispensing robot
07	Cell Assembly & LC Fill	Vacuum injection or one-drop-fill (ODF); bubble-free fill at controlled temperature
08	Final Sealing & Test	UV + thermal cure of seal; EO characterisation (V-T curve, response time, contrast ratio)

Figure 4. Annotated process flow for high-performance liquid crystal cell fabrication, reflecting current best practice as synthesised from the literature and patent record of 2015–2025.

One particularly important feature of contemporary practice is the increasing use of in-line metrology between stages. Spectroscopic reflectometry after ITO deposition, atomic force microscopy after alignment-layer curing, and white-light interferometry after cell assembly each provide feedback that allows process correction before the next, irreversible step is taken. Multiple independent industrial benchmarking studies have identified this shift from end-of-line inspection to distributed in-process measurement as the single most impactful change in yield management practice during the decade.

IX. PERFORMANCE
BENCHMARKING:
CONVENTIONAL VERSUS
STATE-OF-ART

Translating the qualitative advances described above into quantitative terms is necessary for objective evaluation. Figure 5 compiles representative values of six key cell performance parameters as reported for conventional processes before 2015 and for state-of-art processes at the close of the decade. The data draw on a systematic review of peer-reviewed publications, conference proceedings from the Society for Information Display and the International Display Workshop, and patent disclosures with quantitative performance claims.

Figure 5. Quantitative Benchmarking: Conventional vs. State-of-Art LC Cell Fabrication

Parameter	Conventional (Pre-2015)	State-of-Art (2020–2025)	Improvement Factor
Cell Gap Tolerance (μm)	±0.5	±0.05–0.1	~5–10×
Alignment Uniformity (σ, °)	0.8–1.2	0.1–0.3	~4–8×
Response Time (ms)	4–8	0.3–1.5	~5–20×
Contrast Ratio	500:1–1000:1	5000:1–15000:1	~10–15×
Defect Density (cm ⁻²)	50–200	< 5	>10×
Sealant Outgassing (ppm)	20–80	< 3	>25×
Throughput (cells/hr)	50–120	400–800	~5–7×

Figure 5. Quantitative benchmarking of liquid crystal cell performance parameters: conventional

fabrication (pre-2015) versus state-of-art processes (2020–2025). Values represent medians of published figures; improvement factors are ratios of median conventional to median state-of-art values, rounded to the nearest integer.

The data in Figure 5 show consistent improvement across all metrics. Switching response time, which determines suitability for high-frame-rate and low-persistence applications, has fallen most sharply by a factor of five to twenty depending on the specific LC mode driven by blue-phase and polymer-stabilised LC materials, reduced cell gaps, and optimised electrode fringe-field geometries. Contrast ratio improvements of roughly an order of magnitude reflect advances in alignment uniformity (which reduces light leakage in the dark state) as well as in polariser and optical compensation film technology, though the latter falls outside the scope of this review.

X. PERSISTENT CHALLENGES AND
OUTLOOK

10.1 Scaling to Extreme Format Sizes and Pixel Densities

Achieving uniform cell-gap and alignment quality simultaneously across substrates exceeding 2 m × 2 m (Generation 10.5 glass) remains unsolved. Thermal gradients during cure introduce systematic cell-gap variation; gravity-induced substrate deflection between support points requires sophisticated compensation in press design; and extending photo-alignment exposure systems to such areas while keeping dose variation within ±2% is a difficult optical engineering problem. At the other extreme, micro-LC cells with pixel pitches below 5 μm required for near-eye display waveguide combiners push lithographic patterning, alignment, and electrical addressing into regimes where surface and quantum phenomena begin to matter more than bulk LC behaviour.

10.2 Ionic Contamination and Long-Term Stability

Despite advances in sealant formulation and substrate cleaning, ionic contamination within the LC bulk remains a primary cause of long-term performance degradation, manifesting as image sticking, DC offset accumulation, and threshold voltage drift. The sources are multiple and interact: residual impurities in the LC material itself, outgassing from the sealant and alignment layer, and ion generation through photodegradation of LC molecules under UV-rich backlight exposure. Developing standardised accelerated-lifetime test protocols — calibrated against field failure data to quantify contamination contributions from different process steps would benefit the field considerably.

10.3 Sustainability and Material Supply

Roughly two-thirds of global indium production is concentrated in China, giving indium supply-chain risk a practical urgency that has sustained interest in

electrode alternatives. Beyond indium, many LC mixtures contain fluorinated compounds with persistent environmental profiles; regulatory pressure in the European Union, and analogous frameworks developing elsewhere, will require reformulation of certain high-performance mixtures over the coming decade. Developing thermally stable, high-birefringence LC materials that avoid both environmental hazards and supply-chain dependencies is a materials-chemistry challenge with direct implications for fabrication process design.

10.4 Outlook

The trajectory evident in the 2023–2025 literature suggests a few directions likely to shape fabrication practice in the near term. In-situ, real-time characterisation particularly Mueller-matrix polarimetry and micro-Raman spectroscopy integrated with closed-loop control systems will further close the gap between laboratory-demonstrated and production-achieved performance. Two-dimensional material alignment layers, starting in specialised photonic devices, are expected to benefit from higher-throughput deposition methods that could make them commercially viable at scale. And machine-learning process optimisation frameworks, trained on increasingly rich multi-modal datasets combining optical, electrical, and surface-analytical measurements, will reduce the empirical iteration cycles that have historically dominated process development timelines.

Looking at this decade of work as a whole, what stands out is how much advances in adjacent fields synthetic chemistry, computational materials science, precision robotics, and data analytics have shaped a discipline whose fundamental physics has been understood for more than a century. The liquid crystal cell, in that sense, reflects the broader technological ecosystem it draws from. There is good reason to expect that cross-disciplinary dynamism to sustain progress well into the 2030s.

XI. CONCLUSIONS

This review has surveyed principal advances in liquid crystal cell preparation techniques published between 2015 and 2025, with the aim of providing an evidence-based account of progress across the full fabrication sequence from substrate pre-treatment to final sealing and testing.

Photo-alignment has moved from laboratory technique to production-qualified process at leading manufacturing facilities, driven by the need to eliminate contamination and enable multi-domain patterning. Graphene and ALD-oxide electrodes have demonstrated the technical feasibility of replacing ITO in high-performance cells; what remains is throughput and cost-reduction engineering rather than further performance work. Blue-phase and polymer-stabilised LC systems have extended operating temperature ranges and pushed

switching times into the sub-millisecond regime, establishing their candidacy for next-generation display and photonic applications. Column spacer and inkjet-dispensed spacer technologies have improved cell-gap uniformity by a factor of five to ten over ball-spacer baselines. Machine learning integrated into process control has produced documented yield improvements in pilot-scale manufacturing, pointing toward broader industrial adoption.

Against these, the field carries unresolved challenges: ionic contamination at extended lifetimes, alignment uniformity at extreme format sizes and pixel densities, and materials sustainability concerns around fluorinated LC compounds and indium-dependent electrodes. These are not just incremental engineering problems. They call for the kind of foundational work in materials chemistry, surface science, and process engineering that produced the most consequential contributions of the past decade.

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