SMART CONTACT LENSES FOR GLAUCOMA MANAGEMENT: A SYSTEMATIC LITERATURE REVIEW AND TECHNOLOGY READINESS ASSESSMENT

by

HILTON K. THOM

B.S., Morgan University, 1996
M.S., Johns Hopkins University, 2009

A Research Paper Submitted to the School of Computing, Faculty of
Middle Georgia State University in
Partial Fulfillment for the Requirements for the Degree

DOCTOR OF SCIENCE IN INFORMATION TECHNOLOGY

MACON, GEORGIA
2026

Smart contact lenses for glaucoma management: A systematic literature review and technology readiness assessment

Hilton Thom, Middle *Georgia State University, Hilton.thom@mga.edu*

Abstract

Glaucoma affects more than 57 million people worldwide, yet clinicians continue to rely on episodic office visits to measure intraocular pressure (IOP), a measurement strategy fundamentally misaligned with the disease's insidious progression. As Yao et al. (2025) observed, the demand for smart contact lenses (SCLs) has evolved beyond simple vision correction to encompass health monitoring and disease management. Patients experience significant diurnal IOP fluctuations which frequently go undetected with conventional protocols, and these uncontrolled pressure swings are independent predictors of optic nerve damage progression. Continuous, non-invasive IOP monitoring via smart contact lenses offers the potential to bridge this critical diagnostic gap; however, clinical translation remains elusive. This systematic review examined 97 publications from 2000 to 2024, restricting inclusion to studies published between 2020 and 2026 which investigated smart contact lens technology for glaucoma monitoring. Of these, 38 studies underwent Technology Readiness Level Implementation Sciences (TRL-IS) assessment to evaluate developmental maturity and identify barriers to clinical translation. Among the 38 studies assessed, 81.6% (n=31) focused on intraocular pressure monitoring. Results showed 55.3% of studies were concentrated at TRL 3-5, representing early concept development and feasibility assessment. In comparison, only 15.8% advanced to TRL 6-7, including prototype development and pilot implementation. Over more than two decades of investigation, no devices reached TRL 8-9, and none received approval from the U.S. Food and Drug Administration. Most studies concentrated on IOP sensing alone (52.6%), although integrated wireless systems (21.1%) and multi-component designs (5.3%) began to emerge. Most work remained confined to laboratory settings (36.8% in vitro), with only 34.2% advancing to in vivo or clinical testing; review articles comprised 28.9% of the literature. Primary applications targeted IOP monitoring (81.6%), with secondary interest in biomarker detection (18.4%) and drug delivery (10.5%). Significant technological challenges including biocompatibility, microscale power management, reliable wireless communication, scalable production, and unclear regulatory processes continue to impede advancement. Bridging the translational valley will demand collaboration between materials scientists, engineers, clinicians, and regulators centered on shared clinical and commercial goals.

Keywords: smart contact lenses, intraocular pressure monitoring, glaucoma, technology readiness levels, wearable bioelectronics, clinical translation

Introduction

Beyond advancing scientific understanding of glaucoma management, smart contact lens technology represents significant potential within the healthcare innovation sector, which clinicians may utilize to enhance the treatment of ocular health. Roostaei and Hamidi (2025) characterized smart contact lenses (SCLs) as a major advance in wearable technology and biosensing, opening the doors for new horizons for human interaction with both digital and healthcare systems. As Wu et al. (2024) highlighted, SCLs hold the potential to function simultaneously as vision correction devices and non-invasive physiologic health detectors, underscoring their dual clinical and commercial promise. Understanding the maturity of this technology, the critical research gaps which limit development progression, and the pathway requirements for clinical deployment is essential for researchers who must determine which directions to pursue, clinicians evaluating future diagnostic tools, investors allocating resources, regulatory agencies establishing evaluation frameworks, and manufacturers developing strategic plans.

The objective of this study was to consolidate current evidence and assess the developmental maturity of smart contact lens technologies capable of noninvasive continuous monitoring and controlled ocular drug delivery. Zhang et al. (2025) noted the eye served as a uniquely accessible window into systemic health, providing insights into various conditions through non-invasive means. This property makes it an especially promising platform for wearable sensing technologies. By evaluating material science advancements underlying sensor integration, surveying progress in wireless data transmission modalities including Bluetooth Low Energy (BLE), Near Field Communication (NFC), and passive resonator-based sensing systems, and applying the Technology Readiness Level Implementation Sciences (TRL-IS) framework to characterize developmental maturity, this review mapped the current landscape of smart contact lens capabilities and identified the systemic barriers impeding clinical translation.

Research Question:

What are the emerging themes from the systematic literature review on smart contact lens technology for glaucoma management, as assessed through the Technology Readiness Level Implementation Sciences (TRL-IS) framework?

Review of Literature

Overview

Glaucoma remains a leading cause of irreversible blindness globally, with primary open-angle glaucoma occurring six times more frequently in African Americans than in European Americans and presenting a decade earlier in some age groups (Siegfried & Shui, 2022; Acuff et al., 2023). These epidemiological disparities are compounded by documented inequities in eye care utilization. Black patients received significantly fewer outpatient visits and visual field tests than White patients despite greater disease burden (Halawa et al., 2022). Conventional intraocular pressure (IOP) monitoring relies on episodic office-based tonometry, a measurement strategy fundamentally misaligned with the disease's diurnal and nocturnal pressure variability. Continuous, non-invasive IOP monitoring via smart contact lenses (SCLs) represents a clinically compelling solution to this diagnostic gap. However, as Yao et al. (2025) observed, and as Roostaei and Hamidi (2025) confirmed, clinical translation of SCL technology remains elusive despite more than two decades of sustained laboratory investigation. Shi et al. (2021) reinforced why this gap carries societal urgency, noting vision is widely regarded as the most valued human sense, making conditions which threaten sight both a clinical and public health priority.

Noninvasive Monitoring and Biomarker Sensing

Smart contact lenses have been investigated as integrated platforms for systemic health monitoring, leveraging tear fluid as an accessible biofluid for multiple sensing modalities. Kazanskiy et al. (2023) characterized SCLs as a transformative advance in wearable biosensing, capable of monitoring physiological parameters including IOP and tear glucose while maintaining the biocompatible material profile of conventional hydrogel lenses. Han et al. (2024) identified a diverse array of sensor modalities which includes optical, electromagnetic, electrochemical, and transdermal, which have distinctly advanced continuous monitoring paradigms, particularly for diabetes management. Liu et al. (2022) achieved real-time tear metabolite detection with electrochemical sensors in contact lenses, while Elsherif et al. (2021) created a smartphone readable hydrogel Fresnel lens for passive optical glucose sensing across the physiological range, requiring no electronics. Abbas et al. (2024) further demonstrated that AI-assisted transfer learning models applied to ocular health datasets achieved classification accuracy of 95.74%, underscoring the growing integration of explainable machine learning into SCL diagnostic pipelines.

The clinical rationale for tear-based biomarker sensing was substantially advanced by Park et al. (2024), who demonstrated through both animal models and human subjects which continuous tear glucose measurement using a wireless SCL correlated reliably with blood glucose levels, introducing the concept of personalized lag time to account for individual physiological differences. Sadasivam et al. (2021) emphasized the critical importance of early detection in diabetic populations to prevent irreversible vision loss, positioning SCL-based continuous monitoring as a non-invasive alternative to conventional finger-prick glucose surveillance. The noninvasive monitoring literature collectively demonstrated the ocular surface offers a uniquely accessible biological gateway for continuous physiological sensing. Though, the engineering feasibility of this approach has consistently outpaced clinical validation.

Materials and Sensor Technologies

Comfort-Centered Hydrogel Architecture

Zhu et al. (2023) characterized hydrogel-based sensor substrates as prioritizing biocompatibility and user comfort, achieving water retention levels of 50-70% comparable to commercial contact lenses while providing the mechanical flexibility required for sustained ocular contact. Three principal configurations were identified: ionic conductive hydrogels, conductive polymer hydrogels, and micro- or nanomaterial-enhanced hydrogels incorporating carbon nanotubes and MXene. Alaei et al. (2025) demonstrated non-invasive IOP monitoring using silver nanowire-infused hydrogel lenses which preserved standard optical and comfort properties. Zhu et al. (2022) extended this architecture to wireless IOP sensing, demonstrating highly sensitive intraocular pressure monitoring within a hydrogel-based contact lens platform validated under in vitro conditions. Xu and Li (2022) explored nanoparticle-laden hydrogel composites for ocular drug delivery, identifying persistent challenges with nanoparticle dispersion, release kinetics, and long-term safety which remain unresolved in the current literature.

Performance-Centered Field-Effect Transistor Architecture

Nguyen et al. (2023) argued for field-effect transistor (FET)-based biosensors as the superior analytical architecture, demonstrating label-free detection, rapid response times, and simultaneous multi-asubstance monitoring through recognition elements including enzymes, antibodies, aptamers, and ion-sensitive membranes. Guo et al. (2021) implemented ultrathin MoS2 transistors within a contact lens platform for integrated multi-parameter biosensing. Seo et al. (2024) extended FET sensing to direct intraocular pressure measurement via a needle-shaped configuration designed to minimize tissue disruption during anterior chamber access. Although FET systems provided excellent diagnostic resolution, challenges such as their inflexible design, complicated manufacturing processes, and unresolved questions about long-term biocompatibility with ongoing electronic exposure continued to hinder their adoption in clinical settings.

Table 1

Comparative Analysis of Hydrogel vs. FET-Based Approaches

Criteria	Hydrogel Approach (Zhu et al., 2023)	FET Approach (Nguyen et al., 2023)
Primary Priority	Biocompatibility & Comfort	Analytical Performance
Sensing Capability	Single/dual analyte	Multi-analyte detection
Mechanical Properties	High flexibility, stretchability	Rigid integration challenges

Criteria	Hydrogel Approach (Zhu et al., 2023)	FET Approach (Nguyen et al., 2023)
Power Requirements	Moderate	Variable, potentially higher
Manufacturing Complexity	Moderate scalability	Complex fabrication
Clinical Integration	High patient tolerance potential	Superior diagnostic information

Note. Adapted from Zhu et al. (2023) and Nguyen et al. (2023). Trade-offs reflect the fundamental engineering tension between user acceptance and diagnostic capability in smart contact lens development.

Sensor Design: Passive and Active Monitoring Approaches

Passive resonator-based sensing has become the monitoring architecture most closely aligned with clinical applications. Kaya et al. (2024) reported wireless intraocular pressure strain sensing using an electrically passive metamaterial resonator which operates without internal power, demonstrating strong correlation with standard tonometry in a first-in-human pilot study involving six healthy volunteers.

Wasilewicz et al. (2020) previously established feasibility of continuous 24-hour IOP and ocular pulse amplitude measurement using a pressure-measuring contact lens in both glaucoma and healthy subjects, providing an important clinical proof-of-concept for passive continuous monitoring. Maeng et al. (2020) demonstrated a photonic crystal-based SCL capable of continuous IOP monitoring through structural color shifts. Liu et al. (2020) further demonstrated an IOP sensing platform utilizing graphene nanowalls within a contact lens configuration, extending the range of passive material architectures evaluated for intraocular pressure detection. The fully passive, power-free approach eliminated electronic components and their associated biocompatibility risks entirely., Passive systems lack measurement resolution and data depth needed for thorough multi-parameter clinical monitoring due to safety concerns and simplicity. This limitation spurred simultaneous advancements in active system architectures.

Active sensing systems incorporated wireless circuits to enable simultaneous multi-parameter measurement at the cost of greater power demands and biocompatibility complexity. Kim et al. (2017) established a foundational precedent for wearable smart sensor systems on soft contact lenses, demonstrating simultaneous wireless measurement of tear glucose and IOP. Kim et al. (2021) extended active IOP monitoring to a specialized clinical context, demonstrating continuous intraocular pressure surveillance following islet transplantation to the anterior chamber of the eye, establishing the feasibility of active SCL-based monitoring in a controlled in vivo human setting. Kim et al. (2022) advanced this to a therapeutic configuration, demonstrating wireless IOP monitoring and therapeutic regulation in glaucoma-induced rabbit models, which proved to be a significant in vivo proof-of-concept for closed-loop SCL utility. Yang et al. (2022) reported frequency-separation approaches enabling independent sensing and drug delivery within a single device, representing a meaningful step toward functional integration. The distinction between passive and active architectures reflected a fundamental engineering trade-off. Passive systems prioritized safety and durability, while active systems offered superior measurement resolution and the capability to measure multiple parameters. Conversely, neither approach had yet achieved the system-level integration necessary for clinical deployment.

Drug Delivery and Therapeutic Applications

Contact lens-based drug delivery achieved sustained pharmaceutical release through four primary mechanisms: drugs dissolved as solutes within the hydrogel matrix, compounds physically entrapped within the polymer network, therapeutics chemically bound to the lens surface, and agents micro- or nanoencapsulated within particulate carriers. Lanier et al. (2020) established drugs released from contact lenses remained in the post-lens tear film substantially longer than topical eye drops, improving bioavailability and reducing administration frequency. Hewitt et al. (2020) corroborated this advantage in a chlorhexidine delivery model, demonstrating drug-loaded contact lenses combined with β-cyclodextrin complexation produced significantly greater corneal delivery than conventional topical instillation under simulated tear irrigation conditions, reinforcing the pharmacokinetic superiority of the lens-based reservoir mechanism.

DiPasquale et al. (2022) quantified this advantage as 26-fold greater bioavailability and 155-fold greater mean residence time for berberine loaded silicone hydrogel lenses compared to conventional drops. Keum et al. (2020) reported the first system incorporating both real-time biometric monitoring and on-demand electrically controlled drug delivery within a single soft hydrogel contact lens. The most clinically translatable drug delivery advance was contributed by Cai et al. (2025), whose battery-free all-polymer theranostic SCL demonstrated IOP-activated pressure-gated release of timolol or brimonidine at preset thresholds, achieving IOP reduction comparable to topical therapy across in vitro, ex vivo, and in vivo preclinical models.

Research Gaps

Despite substantial engineering progress, the literature revealed persistent and structurally significant gaps. Long-term biocompatibility data extending beyond 30 days of continuous electronic wear were absent throughout the literature, leaving the chronic corneal consequences of embedded circuits uncharacterized. Clinical validation studies remained scarce and frequently inconclusive, with the field disproportionately rewarding sensor miniaturization and wireless optimization over the patient-centered outcome evidence required for regulatory progression (Seo et al., 2023; Han et al., 2024). No study identified in the literature successfully integrated all essential functional subsystems to include sensing, energy, communication, and drug delivery into a single device suitable for clinical application. Power-focused designs prioritizing energy harvesting, sensor-focused designs emphasizing measurement precision, and integration-focused designs balancing multiple functions within a single platform, overshadows multiple SCL investigations, yet none achieved the system-level maturity required for clinical deployment. These gaps collectively defined the investigative rationale for the present systematic review and TRL-IS assessment.

Methodology

This study employed a hybrid analytical methodology combining a systematic literature review (SLR) conducted in accordance with the PRISMA 2020 statement (Page et al., 2021) with Technology Readiness Level assessment using the TRL Implementation Sciences framework (TRL-IS) adapted for medical device development by Salvador-Carulla et al. (2024), which demonstrated high inter-rater reliability (ICC = 0.90; 95% CI: 0.74-0.98; $p < .001$) across a nine-point developmental scale ranging from basic scientific principles (TRL 1) to full commercial deployment (TRL 9).

The overarching question is examined through four thematic domains: (1) drug delivery efficacy and release kinetics; (2) sensing architecture maturity and TRL-IS assessment; (3) wireless telemetry modalities and technical bottlenecks; and (4) systemic barriers to clinical translation.

Search Strategy and Information Sources

A comprehensive search of four primary electronic databases -- PubMed (MEDLINE), SciSpace, Google Scholar, and ArXiv -- was performed on March 1, 2026. The search integrated three conceptual pillars using Boolean logic:

(1) Technology: ("smart contact lens" OR "wearable contact lens" OR "intelligent contact lens" OR "electronic contact lens")
(2) Application: (glaucoma OR "intraocular pressure" OR "IOP" OR glucose OR "tear biomarker" OR "drug delivery" OR "ocular disease")
(3) Components: (sensor OR biosensor OR monitor OR therapeutic OR "wireless communication" OR "power system")

Truncation symbols were not employed. The search yielded 1,621 raw records; study selection followed a systematic data purification process involving automated and manual deduplication in Zotero and sequential screening against the eligibility criteria defined in Table 2, with the complete selection progression documented in Figure 1 (PRISMA 2020 Flow Diagram).

Study Selection Criteria

Eligibility criteria were developed to prioritize empirical evidence on biocompatible, eye-worn smart contact lens technologies with demonstrated translational relevance to ocular health. Table 2 presents the full inclusion (IC1-IC7) and exclusion (EC1-EC12) criteria applied sequentially during title and abstract screening and full-text review.

Table 2

Inclusion and Exclusion Criteria (IC1-IC7 / EC1-EC12)

Domain	Inclusion Criteria (IC)	Exclusion Criteria (EC)
Technology scope	Smart contact lenses or integrated eye-worn sensing and/or therapeutic devices designed for direct ocular contact (IC1)	Vision-only, cosmetic, AR/VR, or eye-tracking technologies without health sensing (EC1-EC2)
Application area	IOP monitoring, tear-based biomarker detection, ocular drug delivery, or systemic disease sensing via the ocular surface (IC2)	Non-contact-lens ocular technologies (e.g., implants, smart glasses, external wearables) (EC4)
Evidence type	Quantitative empirical data on performance, sensing accuracy, release kinetics, stability, safety, or biocompatibility (IC3)	Theoretical, simulated, or modeling-only studies without experimental validation (EC3)
Study design	Experimentally validated in vitro, in vivo, human clinical studies, or systematic reviews with quantifiable outcomes (IC4)	Undefined populations or extremely small sample sizes (n=1-2) without subsequent validation (EC5)

Domain	Inclusion Criteria (IC)	Exclusion Criteria (EC)
Publication quality	Peer-reviewed journal articles or refereed conference proceedings with original empirical findings (IC5)	Non-peer-reviewed sources or substantial data redundancy (>=50% overlap) (EC8-EC9)
Data adequacy	Sufficient quantitative metrics enabling assessment of feasibility, performance, or safety (IC3)	Insufficient reporting to evaluate device performance or biocompatibility (EC6)
Bias and novelty	Acceptable methodological quality with assessable risk of bias (IC4)	High risk of bias, undisclosed conflicts of interest, or no novel contribution (EC7, EC11-EC12)
Temporal and language	Published 2020-2026; seminal 2017-2019 studies retained if foundational; English language (IC6-IC7)	Published outside eligibility window without exception or lacking verified translation (EC9-EC10)

Note. Eligibility criteria were applied sequentially during title/abstract screening and full-text review in accordance with PRISMA 2020 guidelines and biomedical device evaluation standards.

Data Extraction

Standardized data extraction was performed across all 38 included studies using six variable categories: Study Characteristics (author, year, country, design, funding); Technology Description (sensor type, substrate, power, communication, integrated components); Population Characteristics (sample size, demographics); Outcome Measurements and Performance Data (key outcomes, validation, significance); Clinical and Safety findings (biocompatibility, tolerability, adverse events, clinical feasibility); and TRL-IS Assignment (TRL 1-9). A complete data extraction records for all 38 inlcuded studies encompassing study charactistics, TRL-IS assignments, sensor classification, validation settings, and quality assessment scores, are presented in the Supplementary Table1

Quality Assessment and Risk-of-Bias Evaluation

Of the 38 included studies, 27 empirical studies were eligible for quality assessment using a JBI-adapted tool (Aromataris & Munn, 2020); the remaining 11 non-empirical reviews were assessed qualitatively for scope and synthesis quality. The adapted instrument evaluated seven core criteria: clarity of research question; methodological appropriateness and use of controls; sample size adequacy; outcome measurement clarity; variable control; statistical appropriateness; and reproducibility and transparency. Scores of "Yes" received 1 point and "Partial" received 0.5 points; studies were classified as Low Risk (>=86%), Moderate Risk (57-86%), or High Risk (<57%). Table 3 presents the risk-of-bias distribution across the 27 empirical studies.

Table 3

Risk of Bias Summary -- JBI Adapted Checklist (Empirical Studies Only, n=27)

Risk Category	n	% of 27	Characteristics
Low Risk (>=6/7)	19	70.4%	>=6 of 7 criteria met. Includes all 7 clinical and high-quality in vivo animal studies.

Risk Category	n	% of 27	Characteristics
Moderate Risk (4-5/7)	8	29.6%	4-5 of 7 criteria met; methodological limitations present. Includes 6 in vitro studies with limited controls.
High Risk (<4/7)	0	0.0%	No included empirical studies met the High Risk threshold.
N/A (Reviews)	11	N/A	Literature reviews assessed qualitatively for scope and synthesis quality only.

Note. Non-empirical literature reviews (n=11) were excluded from the JBI scoring protocol and assessed qualitatively. All seven clinical human studies were classified as Low Risk.

Technology Readiness Level Assessment

Each included study was assigned a TRL rating using the TRL-IS framework (Salvador-Carulla et al., 2024), applied independently to the least mature component for multi-subsystem designs, as the principal developmental bottleneck. TRL assignments and distribution across the 38 included studies are presented in Table 4 within the Results section.

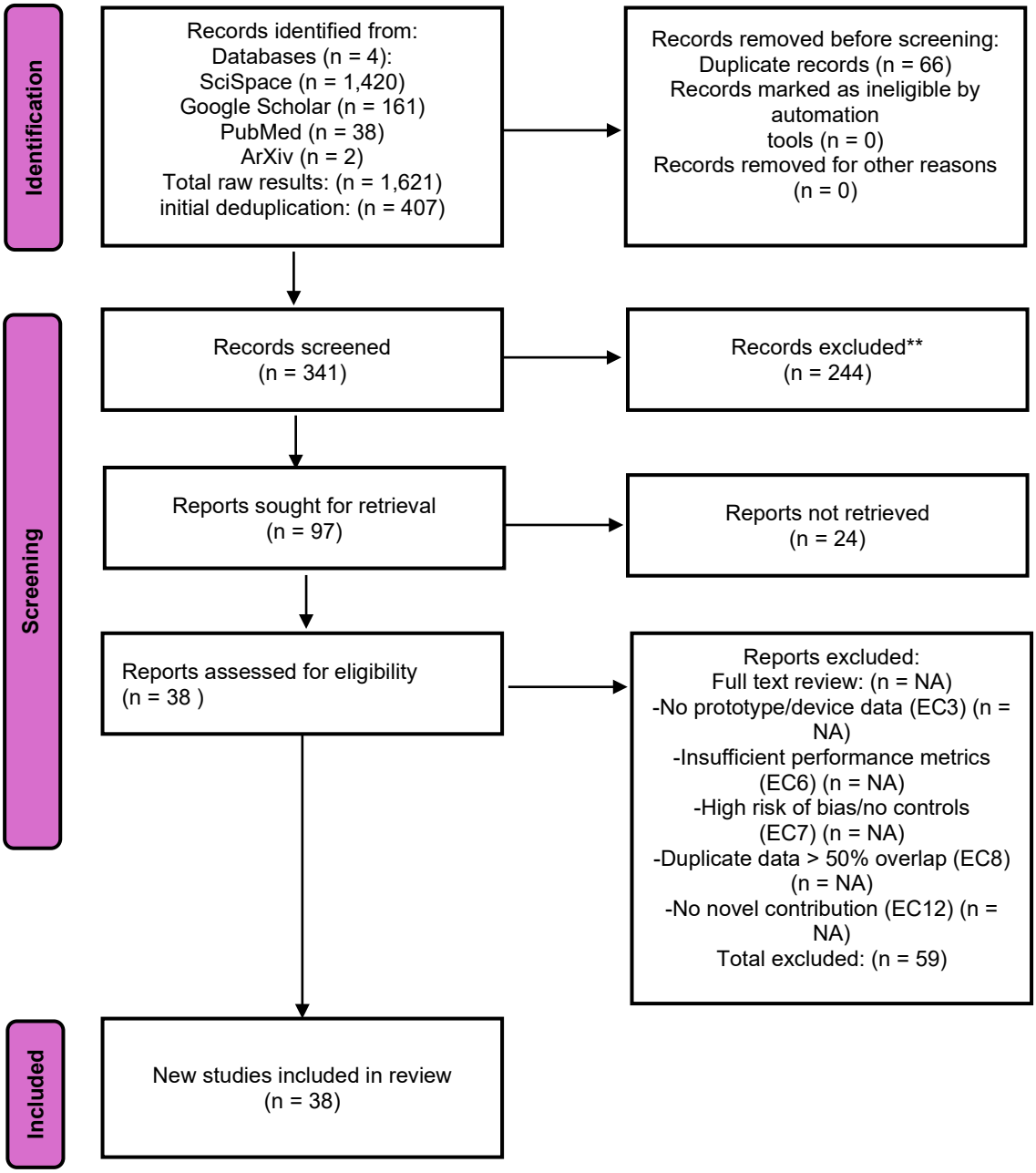

Figure 1. PRISMA 2020 Flow Diagram

Results and Analysis

Table 4 presents the complete 38-study master dataset with TRL-IS assignments. Results are organized across four thematic domains derived from the systematic synthesis, each corresponding to a dimension of smart contact lens development assessed through the TRL-IS framework.

Table 3

38-Study Master Dataset: SCL Technology Readiness Assessment (TRL-IS)

Author / Year	Study Design	SCL Architecture	Application	Key Metric / Contribution	TRL
Kazanskiy et al. (2023)	Review	General	IOP/Biomarker	Biosensing framework synthesis	**1**
Yao et al. (2025)	Review	Hydrogel	IOP/Biomarker	SCL demand analysis; dual platform	**1**
Zhang, J. et al. (2025)	Review	General	IOP/Drug	Ocular window concept; dual use	**1**
Abbas et al. (2024)	Review	AI-assisted	Biomarker	AI classification accuracy 95.74%	**1**
Manickam et al. (2022)	Review	IoMT	Biomarker	AI-IoMT biosensor integration	**1**
Shi et al. (2021)	Review	General	IOP/Biomarker	Ophthalmic sensing technologies	**1**
Liu, H. et al. (2022)	Review	Electrochemical	Biomarker	Electrochemical sensing survey	**1**
Lanier et al. (2020)	Review	Hydrogel	Drug	Post-lens tear film reservoir effect	**2**
Zhu, Y. et al. (2023)	Review	Hydrogel	IOP/Biomarker	Bioinspired hydrogel device survey	**2**
Wu et al. (2024)	Review	General	IOP/Biomarker	Dual clinical-commercial promise	**2**
Jiang et al. (2018)	Review	Microfluidic	Biomarker	Microfluidic CL architecture	**2**
Guo et al. (2021)	In vitro	FET/MoS_2	Biomarker/IOP	Ultrathin MoS_2 multi-parameter	**3**
Elsherif et al. (2021)	In vitro	Optical/Hydrogel	Biomarker	Glucose full physiologic range; smartphone	**3**
Manjeri & George (2024)	In vitro	Hydrogel	Drug	pH-responsive physiologic release	**3**
Al Atrach et al. (2024)	In vitro	Hydrogel	Drug	Vit E barrier; ciprofloxacin tunable	**3**
Kim et al. (2017)	In vitro	Active/Wireless	IOP/Biomarker	Wireless glucose + IOP; Nature Commun.	**4**
Maeng et al. (2020)	In vitro	Photonic crystal	IOP	Structural color shift; power-free	**4**

Author / Year	Study Design	SCL Architecture	Application	Key Metric / Contribution	TRL
Zhu, H. et al. (2022)	In vitro	Hydrogel/Wireless	IOP	Wireless IOP; high sensitivity	**4**
Ye et al. (2022)	In vitro	Dual-sensor	IOP/Biomarker	IOP + MMP-9 dual platform	**4**
Liu, Z. et al. (2020)	In vitro	Graphene	IOP	Graphene nanowall IOP sensor	**4**
Kang et al. (2022)	In vitro	Self-powered	IOP	Durable self-powered SCL; ACS Nano	**4**
Yuan et al. (2023)	In vitro	Microfluidic	IOP	Bilateral wall; linearity enhanced	**4**
Li, X. et al. (2024)	In vitro	Wireless/Resonator	IOP	Temp-compensating dual resonator	**4**
Keum et al. (2020)	In vivo	Hydrogel/Active	Biomarker/Drug	Wireless dx + therapy; Sci Adv.	**4**
DiPasquale et al. (2022)	In vivo	Hydrogel	Drug	26× bioavail.; 155× MRT; 1-wk safety	**5**
Alaei et al. (2025)	In vitro	Hydrogel/AgNW	IOP	Silver nanowire; optical + comfort	**5**
Xu & Li (2022)	In vivo	Nanoparticle	Drug	Brimonidine silica NP SCL; glaucoma	**5**
Kim, J. et al. (2021)	In vivo	Active	IOP	Islet transplant IOP monitor; Nat BME	**5**
Dubey et al. (2020)	Clinical	CLS	IOP	Nocturnal peak vs. VF progression	**5**
Tojo et al. (2020)	Clinical	CLS	IOP	24-hr CLS vs. visual field; glaucoma	**5**
Kim, T.Y. et al. (2022)	In vivo	Active/Wireless	IOP/Drug	Wireless IOP + drug; rabbit; Nat Commun.	**5**
Yang et al. (2022)	In vitro	Active/Wireless	IOP/Drug	Freq-sep sensing + delivery; Nat Commun.	**5**
Kaya et al. (2024)	Clinical	Passive/Resonator	IOP	First-in-human metamaterial; n=6; TRL peak	**6**
Wasilewicz et al. (2020)	Clinical	CLS	IOP	24-hr IOP + OPA; n=30; glaucoma + healthy	**6**
Park, W. et al. (2024)	Clinical	Active/Wireless	Biomarker	Tear–blood glucose correlation; human; Nat Commun.	**6**
Zhang, J.K. et al. (2022)	In vivo/Clinical	Active	IOP	Smart SCL 24-hr IOP glaucoma; Nat Commun.	**6**

Author / Year	Study Design	SCL Architecture	Application	Key Metric / Contribution	TRL
Adibag et al. (2026)	Review	General	IOP/Biomarker	2026 SCL advances; policy gaps; Biosens X	**6**
Park, J. et al. (2019)	In vivo	Active/Wireless	IOP/Biomarker	Rechargeable SC; monolithic integration; Sci Adv.	**7**

Note. TRL shading: gray = TRL 1-2 (Basic Principles/Concept); yellow = TRL 3-5 (Laboratory Cluster); green = TRL 6-7 (Pilot/Real-World Demonstration); blue = TRL 8-9 (Commercial Deployment; unachieved in this corpus). CLS = contact lens sensor; WL = wireless; SC = supercapacitor; AgNW = silver nanowire; MRT = mean residence time; OPA = ocular pulse amplitude; VF = visual field; Sci TM = Science Translational Medicine; Nat BME = Nature Biomedical Engineering; Nat Commun = Nature Communications; Biosens X = Biosensors and Bioelectronics: X.

Theme 1: Drug Delivery Efficacy and Release Kinetics

Four studies (10.5%) focused on therapeutic drug delivery, collectively demonstrating sustained release durations of 7 to 144 hours across four distinct delivery architectures. The mechanism of incorporation emerged as the primary determinant of both release duration and bioavailability outcomes. DiPasquale et al. (2022) established the quantitative benchmark: 26-fold greater bioavailability and 155-fold greater mean residence time for berberine-loaded silicone hydrogel lenses versus topical eye drops, this grounded in the post-lens tear film reservoir effect documented by Lanier et al. (2020). Al Atrach et al. (2024) extended this evidence to ciprofloxacin delivery via vitamin E diffusion barriers. Manjeri and George (2024) demonstrated pH-responsive hydrogel lenses enabling physiologically triggered, conditionally intelligent release. The translational ceiling was reached by Cai et al. (2025), whose battery-free all-polymer theranostic SCL demonstrated IOP-mechanically activated pressure-gated release of timolol or brimonidine, achieving IOP reduction comparable to conventional topical therapy. Despite this pharmacokinetic evidence, none of the four drug delivery studies progressed to human clinical validation and no therapeutic SCL system obtained regulatory approval.

Theme 2: Sensing Architecture Maturity of TRL-IS Assessment

The TRL-IS distribution renders the aggregate outcome unambiguous: 55.3% (n = 21) of all included studies remained within the TRL 3-5 laboratory cluster, only 15.8% (n = 6) achieved TRL 6-7 pilot or first-in-human evidence, a single study reached TRL 7 (Park et al., 2019), and the TRL 8–9 commercial deployment tier was entirely vacant across more than two decades of sustained investigation. Comfort-centered hydrogel designs clustered predominantly at TRL 3-4, constrained by single or dual substance sensing ceilings and the absence of long-term biocompatibility data beyond 30 days. Performance-centered FET designs clustered at TRL 3-5, constrained by rigid component conformity challenges, manufacturing complexity incompatible with scalable production, and chronic electronic exposure concerns. The critical theme is that both architectures are immature; what distinguishes them is the nature, not the severity, of the barrier impeding advancement, and therefore the nature of the solution required.

Theme 3: Wireless Telemetry Modalities and Technical Bottlenecks

Eight studies (21.1%) incorporated wireless communication as an integrated system component across three identified telemetry modalities: passive resonator based sensing without internal power, NFC based data transmission, and active BLE-adjacent integrated architectures. The primary theme under this research domain is a confirmed foundational research gap: none of the included studies provided standardized wireless benchmarks for transmission range, data integrity in ocular conditions, body attenuation, or

electromagnetic compatibility. The wireless telemetry subsystem is simultaneously a prerequisite for clinical deployment and the least standardized component across the entire corpus. This structural absence will constrain future systematic reviews and any regulatory submission for a wireless SCL device.

Within available evidence, passive resonator approaches demonstrated the most clinically reproducible results. Kaya et al. (2024) achieved wireless IOP sensing using a passive metamaterial resonator with good tonometry correlation in a six-subject first-in-human pilot. Li et al. (2024) demonstrated dual-resonator temperature-drift cancellation. Active architectures have demonstrated the ability to achieve greater functional scope, as revealed by Park et al. (2019), who demonstrated the monolithic co-integration of a wirelessly rechargeable supercapacitor, antenna, rectifier, and display. Zhang et al. (2022) demonstrated a smart soft contact lens enabling continuous 24-hour IOP monitoring in a glaucoma care context, representing one of the most clinically advanced active wireless demonstrations in the corpus. Yang et al. (2022) reported frequency separation enabling independent sensing and drug delivery in one device. Kim et al. (2022) demonstrated wireless IOP monitoring and therapeutic regulation in glaucoma-induced rabbit models. Adibag et al. (2026) synthesized these advances in a concurrent review, identifying persistent policy and regulatory gaps which continue to prevent wireless SCL systems from crossing from demonstrated feasibility into standardized clinical evaluation frameworks. The 39.5% power supply barrier was disproportionately concentrated within this wireless-capable subset, confirming the energy problem and the communication problem are coupled: progress on one without the other yields systems which are technically feasible yet clinically inoperable.

Theme 4: Systemic Translation Barriers

Analysis of translation barriers across the 38 included studies revealed a self-reinforcing system of interdependent constraints constituting the translational valley. Table 5 presents the five principal barriers ranked by frequency of citation.

Table 5

Identified Translation Barriers (Frequency Across 38 Studies)

Translation Barrier	n	Frequency	Evidence Summary
Clinical Validation Gap	36	**94.7%**	Near-universal; cited across all TRL stages and design architectures; confirms translational inertia over technological inadequacy.
Manufacturing Scale-Up	21	**55.3%**	Structural gap between laboratory batch fabrication and industrial-scale production standards required for regulatory submission.
Sensor Accuracy & Stability	17	**44.7%**	Signal drift under body temperature variation; inconsistent real-world performance relative to controlled benchmarks.
Power Supply	15	**39.5%**	No study demonstrated a fully integrated power solution meeting clinical requirements. Cascade-initiating enabling dependency.
Biocompatibility & Safety	12	**31.6%**	No study reported continuous electronic wear safety data beyond 30 days; chronic corneal consequences uncharacterized.

Note. Frequencies represent citation counts across all 38 included studies regardless of TRL stage. Multiple barriers were frequently co-cited within individual studies, reflecting the interdependent nature of translational constraints. Bold font indicates the cascade-initiating enabling dependency.

The clinical validation gap (94.7%, n = 36) was not the most prevalent barrier but rather the most structurally revealing, persisting across all TRL stages, design architectures, and application domains. The power supply barrier (39.5%, n = 15) emerged as the initiating factor for cascading dependencies. Without a clinically viable energy solution which can sustain continuous 24-hour monitoring within ocular biocompatibility constraints, a cascading effect will occur. This consequence is that wireless telemetry cannot achieve clinical reliability, and active sensing architectures will not generate diagnostically meaningful data. Furthermore, without active sensing, closed-loop drug delivery cannot respond to physiological triggers. Manufacturing scale-up (55.3%), sensor accuracy and stability (44.7%), and biocompatibility constraints (31.6%) further compounded these constraints. Notably, no study reported continuous electronic wear safety data beyond 30 days, leaving the chronic corneal consequences of embedded electronics entirely uncharacterized.

Discussion

The central theme emerging from this review is not the absence of scientific merit in smart contact lens technology. Instead, it highlights how the field is structurally stalled, far from clinical deployment, despite two decades of laboratory investment which have failed to bridge this gap. Application of the TRL-IS framework across 38 included studies showed 55.3% (n='21)' remained within the TRL 3-5 laboratory cluster, only 15.8% (n='6)' achieved pilot or first-in-human evidence at TRL 6-7, and no study reached the TRL 8-9 commercial deployment tier. This distribution is inconsistent with inadequate sensor science. Biosensor platforms demonstrated high sensitivity in controlled conditions, and proof-of-concept was established in IOP monitoring, biomarker detection, drug delivery, and wireless telemetry. What the TRL-IS assessment reveals instead is a maturity-translation paradox: technical feasibility advances independently of and has consistently failed to produce, the clinical validation infrastructure deployment requires. The field has demonstrated smart contact lenses can work in a laboratory. It has not yet demonstrated a credible pathway to making them work in a clinic. This stagnation in technological advancement continues to impede marginalized communities from realizing improved healthcare access, paralleling the ongoing integration of artificial intelligence in healthcare for enhancements in efficiency, accuracy, and accessibility (Culver, 2024).

The 39.5% power supply barrier (n='15/38)' functions not as a standalone limitation but as a critical enabling dependency which propagates failure through every layer of system integration. Without a clinically viable power solution sustaining 24-hour continuous monitoring within ocular biocompatibility constraints, wireless telemetry cannot achieve clinical reliability, active sensing architectures cannot generate diagnostically meaningful data and closed-loop therapeutic delivery cannot respond to the physiological triggers which give it clinical value. Foundational energy solutions, glucose fuel cells delivering 4.4 uW/cm2 and wirelessly rechargeable supercapacitors, have been demonstrated in isolation; none has been successfully integrated into a platform meeting full clinical operational requirements. The consequence is a field in which 81.6% of studies (n='31/38)' achieved meaningful IOP sensing sensitivity while only 5.3% (n='2/38)' demonstrated functional multi-component integration of sensing, power, and telemetry within a single device. The manufacturing scale-up barrier (n='21,' 55.3%) compounds this failure, laboratory fabrication processes which produce functional prototypes are not transferable to the production standards required for regulatory submission, and no included study systematically addressed this transition. Active architectures offer superior diagnostic resolution but generate power demands which preclude clinical wear periods; passive resonator-based systems bypass the power barrier through safety-by-design but face a performance ceiling in data richness. Neither architecture has resolved this trade-off, and the practical-theoretical divide will persist until power management is treated as a system-level design constraint rather than a subsystem optimization problem.

The 94.7% clinical validation gap cited across 36 of 38 studies regardless of TRL stage or design architecture, carries an urgency the technical literature has inadequately conveyed. Glaucoma is a disease of pressure variability, the nocturnal IOP peaks which drive optic nerve progression are invisible to episodic tonometry, and continuous SCL-based monitoring is a diagnostic necessity, not a convenience. The path to TRL 8-9 requires standardized clinical trial frameworks for bioelectric ocular devices, continuous wear safety profiles extending beyond 30 days, and cross-disciplinary structures which embed regulatory science, health economics, and manufacturing engineering within the research programs currently generating technology in isolation. This review's TRL-IS assessment provides a structured roadmap from which clinicians and regulators can identify which platform architectures are most proximate to viability and what milestones must be achieved at each transition. The translational valley is wide, but it is mappable.

Limitations of This Review

This systematic review establishes the current evidence base for silicone hydrogel-based smart contact lenses, as documented by leading researchers in the field. The screening, selection, and data extraction processes proceeded under a single-investigator protocol, a methodological limitation that elevated the risk of individual selection bias and may have influenced the comprehensiveness of the data synthesis relative to dual-independent reviewer frameworks. Single-reviewer approaches are occasionally utilized in implementation science scoping phases to build foundational knowledge, yet the reliance on this method remains a constraint. The literature remains predominantly concentrated in early-stage research and development (TRL 1-5), and there is a marked scarcity of data pertaining to advanced commercial systems at TRL 8-9. The reviewed studies do not consistently follow standardized reporting metrics, precluding the possibility of quantitative meta-analysis and resulting in a narrative synthesis of the findings. The scope of this review also restricts itself to English-language publications, which may exclude significant advancements from non-English speaking research centers in East Asia, where intensive innovation in smart contact lens technology continues.

Conclusion

Smart contact lens technology for glaucoma monitoring has demonstrated proof-of-concept across multiple functional domains, including continuous intraocular pressure sensing, tear biomarker detection, closed-loop drug delivery, and wireless telemetry. Each domain has produced empirically validated results under controlled experimental conditions. Nevertheless, no FDA-approved SCL system has achieved clinical deployment, and the TRL 8-9 commercial readiness tier remained entirely unoccupied across all 38 studies included in this review, spanning more than two decades of sustained investigation. The evidence indicates the primary constraints on clinical translation are not attributable to fundamental sensor science limitations but to a set of interdependent system-level barriers: the absence of a power solution capable of sustaining continuous 24-hour monitoring within established ocular biocompatibility parameters; the complete lack of standardized wireless performance benchmarks for BLE, NFC, and passive resonator modalities under real ocular conditions; undefined regulatory evaluation pathways for bioelectric SCL devices; and manufacturing processes which have not demonstrated scalability beyond laboratory batch production. These barriers are structurally interdependent rather than parallel, with the power supply deficit functioning as the cascade-initiating constraint which propagates failure across wireless telemetry, active sensing, and closed-loop drug delivery subsystems.

Advancement toward clinical deployment requires resolution of four foundational gaps the current evidence base has not addressed. First, standardized wireless benchmarking protocols must be established under real clinical ocular conditions, as their absence renders cross-study comparison invalid and precludes coherent regulatory submission for any wireless SCL device. Second, continuous electronic wear safety data extending beyond 30 days must be generated; this data is currently absent from the entire peer-reviewed corpus, and no regulatory body can evaluate a chronically worn bioelectric device without it. Third, cross-disciplinary regulatory and clinical trial frameworks must be developed in collaboration with the FDA, with passive resonator platforms which demonstrated first-in-human feasibility in the studies by Kaya et al. (2024) and Wasilewicz et al. (2020), representing the most proximate candidates for regulatory progression given their safety-by-design architecture and elimination of internal power requirements. Fourth, power management must be incorporated as a primary system-level design constraint at program inception rather than addressed as a subsystem optimization following sensor development, as the data confirm failure at the power level propagates through every dependent subsystem. The translational trajectories of analogous bioelectronic device classes, including continuous glucose monitors, cochlear implants, and implantable cardiac devices, demonstrate progression from laboratory feasibility to clinical deployment was achieved through deliberate investment in regulatory and clinical infrastructure rather than through incremental refinement of core sensing technology. Whether SCL technology follows a comparable trajectory will depend on whether future research programs integrate that infrastructure investment from the earliest stages of development.

References

Abbas, S., Qaisar, A., Farooq, M. S., Saleem, M., Ahmad, M., & Khan, M. A. (2024). Smart vision transparency: Efficient ocular disease prediction model using explainable artificial intelligence. *Sensors, 24*(20), 6618. https://doi.org/10.3390/s24206618

Acuff, K., Radha Saseendrakumar, B., Wu, J.-H., Weinreb, R. N., & Baxter, S. L. (2023). Racial, ethnic, and socioeconomic disparities in glaucoma onset and severity in a diverse nationwide cohort in the United States. *Journal of Glaucoma, 32*(9), 792–799. https://doi.org/10.1097/IJG.0000000000002261

Adibag, Z., Ghanbarzadeh, M., Salati, M. A., Esmaeili Rad, M., Ansari, R., Ta, C. N., Fadel, D., Mofidfar, M., & Abbasi, F. (2026). Recent advances in smart contact lenses. *Biosensors and Bioelectronics: X*, 28, 100734. https://doi.org/10.1016/j.biosx.2025.100734

Al Atrach, M., Phan, C. M., & Jones, L. W. (2024). Extended release of ciprofloxacin from commercial silicone-hydrogel and conventional hydrogel contact lenses containing vitamin E diffusion barriers. *Optometry and Vision Science, 101*(11), 666–676. https://doi.org/10.1097/OPX.0000000000002196

Alaei, E., Bukhari, S. A. R., Afrin, T., Campbell, R. J., & Lai, Y. (2025). Silver nanowire infused hydrogel contact lenses for non-invasive intraocular pressure monitoring. *Flexible and Printed Electronics, 10*(2), 025008. https://doi.org/10.1088/2058-8585/adddc7

Aromataris, E., & Munn, Z. (Eds.). (2020). *JBI manual for evidence synthesis*. JBI. https://doi.org/10.46658/JBIMES-20-01

Cai, Y., Zhang, C., Dang, P., Liu, C., Du, Y., Haghniaz, R., Wang, J., Khosravi, S., Luo, Z., Servati, P., Chen, L., Wolffsohn, J. S., Lee, T.-W., & Zhu, Y. (2025). Real-time intraocular pressure monitoring and responsive drug release in preclinical models by an all-polymer smart contact lens. *Science Translational Medicine, 18*(844). https://doi.org/10.1126/scitranslmed.ads9541

Culver, D. M., III. (2024). *A systematic literature review: African American views of artificial intelligence and machine learning in healthcare* [Doctoral dissertation, Middle Georgia State University]. ProQuest Dissertations & Theses. https://www.proquest.com

DiPasquale, S. A., Wuchte, L. D., Mosley, R. J., Demarest, R. M., Voyles, M. L., & Byrne, M. E. (2022). One week sustained in vivo therapeutic release and safety of novel extended-wear silicone hydrogel contact lenses. *Advanced Healthcare Materials, 11*, 2101263. https://doi.org/10.1002/adhm.202101263

Dubey, S., Mittal, D., Mukherjee, S., Bhoot, M., & Gupta, Y. P. (2020). Relationship between nocturnal intraocular pressure-related peak recorded by contact lens sensor and disease progression in treated glaucomatous eyes. *Indian Journal of Ophthalmology, 68*(11), 2427–2433. https://doi.org/10.4103/ijo.IJO_2365_19

Elsherif, M., Alam, F., Salih, A. E., AlQattan, B., Yetisen, A. K., & Butt, H. (2021). Wearable bifocal contact lens for continual glucose monitoring integrated with smartphone readers. *Small, 17*(51), e2102876. https://doi.org/10.1002/smll.202102876

Guo, S., Wu, K., Li, C., Wang, H., Sun, Z., Xi, D., Zhang, S., Ding, W., Zaghloul, M. E., Wang, C., Castro, F. A., Yang, D., & Zhao, Y. (2021). Integrated contact lens sensor system based on multifunctional ultrathin MoS_2 transistors. *Matter, 4*(3), 969–985. https://doi.org/10.1016/j.matt.2020.12.002

Halawa, O. A., Kolli, A., Oh, G., Mitchell, W. G., Glynn, R. J., Kim, D. H., Friedman, D. S., & Zebardast, N. (2022). Racial and socioeconomic differences in eye care utilization among Medicare beneficiaries with glaucoma. *Ophthalmology, 129*(4), 397–405. https://doi.org/10.1016/j.ophtha.2021.09.022

Han, F., Li, J., Xiao, P., Yang, Y., Liu, H., Wei, Z., He, Y., & Xu, F. (2024). Wearable smart contact lenses: A critical comparison of three physiological signals outputs for health monitoring. *Biosensors and Bioelectronics, 257*, 116284. https://doi.org/10.1016/j.bios.2024.116284

Hewitt, M. G., Morrison, P. W. J., Boostrom, H. M., Morgan, S. R., Fallon, M., Lewis, P. N., Whitaker, D., Brancale, A., Varricchio, C., Quantock, A. J., Burton, M. J., & Heard, C. M. (2020). In vitro topical delivery of chlorhexidine to the cornea: Enhancement using drug-loaded contact lenses and β-cyclodextrin complexation, and the importance of simulating tear irrigation. *Molecular Pharmaceutics, 17*(4), 1428–1441. https://doi.org/10.1021/acs.molpharmaceut.0c00140

Jiang, N., Montelongo, Y., Butt, H., & Yetisen, A. K. (2018). Microfluidic contact lenses. *Small, 14*(15), 1704363. https://doi.org/10.1002/smll.201704363

Kang, D., Lee, J. I., Maeng, B., Lee, S., Kwon, Y., Kang, M. S., Park, J., & Kim, J. (2022). Safe, durable, and sustainable self-powered smart contact lenses. *ACS Nano, 16*(10), 15827–15836. https://doi.org/10.1021/acsnano.2c05452

Kaya, O., Aydin, M. A., Teymoori, M., Erden, O. K., Sadeghzadeh, S., Dedeoglu, U. O., Demir, S., Muhikanci, O., Sahin, A., Torun, H., Dundar, G., & Yalcinkaya, A. D. (2024). A first-in-human pilot study of a novel electrically-passive metamaterial-inspired resonator-based ocular sensor embedded contact lens monitoring intraocular pressure fluctuations. *Contact Lens and Anterior Eye, 47*(2), 102102. https://doi.org/10.1016/j.clae.2023.102102

Kazanskiy, N. L., Khonina, S. N., & Butt, M. A. (2023). Smart contact lenses—A step towards non-invasive continuous eye health monitoring. *Biosensors, 13*(10), 933. https://doi.org/10.3390/bios13100933

Keum, D. H., Jung, H. S., Wang, T., Shin, M. H., Kim, Y. E., Kim, K. H., Ahn, S. K., An, J. H., Kim, T. S., Kim, S. K., Kang, Y. C., Kim, J. U., Hahn, S. K., & Ryu, W. (2020). Wireless smart contact lens for diabetic diagnosis and therapy. *Science Advances, 6*(17), eaba3252. https://doi.org/10.1126/sciadv.aba3252

Kim, J., Kim, J., Ku, M., Cha, E., Ju, S., Park, W. Y., Kim, K. H., Kim, D. W., Berggren, P.-O., & Park, J.-U. (2021). Intraocular pressure monitoring following islet transplantation to the anterior chamber of the eye. *Nature Biomedical Engineering, 5*, 772–782. https://doi.org/10.1038/s41551-021-00719-8

Kim, J., Kim, M., Lee, M.-S., Kim, K., Ji, S., Kim, Y.-T., Park, J., Na, K., Bae, K.-H., Kim, H. K., Bien, F., Lee, C. Y., & Park, J.-U. (2017). Wearable smart sensor systems integrated on soft contact lenses for wireless ocular diagnostics. *Nature Communications, 8*, 14997. https://doi.org/10.1038/ncomms14997

Kim, T. Y., Mok, J. W., Hong, S. H., Jeong, S. H., Choi, H., Shin, S., Joo, C. K., & Hahn, S. K. (2022). Wireless theranostic smart contact lens for monitoring and control of intraocular pressure in glaucoma. *Nature Communications, 13*, 6801. https://doi.org/10.1038/s41467-022-34597-8

Lanier, O. L., Christopher, K. G., Macoon, R. M., Yu, Y., Sekar, P., & Chauhan, A. (2020). Commercialization challenges for drug eluting contact lenses. *Expert Opinion on Drug Delivery, 17*(8), 1133–1149. https://doi.org/10.1080/17425247.2020.1787983

Li, X., Chen, W., Li, H., Shen, B., He, J., Gao, H., Bin, F., Li, H., & Xiao, D. (2024). Temperature self-compensating intelligent wireless measuring contact lens for quantitative intraocular pressure monitoring. *ACS Applied Materials & Interfaces, 16*(17), 22522–22531. https://doi.org/10.1021/acsami.4c02289

Liu, H., Yan, X., Gu, Z., Xiu, G., & Xiao, X. (2022). Electrochemical sensing in contact lenses. *Electroanalysis, 34*(2), 227–236. https://doi.org/10.1002/elan.202100342

Liu, Z., Wang, G., Pei, W., Wei, C., Wu, X., Dou, Z., Li, Y., Wang, Y., & Chen, H. (2020). Application of graphene nanowalls in an intraocular pressure sensor. *Journal of Materials Chemistry B, 8*(38), 8794–8802. https://doi.org/10.1039/D0TB01687J

Maeng, B., Chang, H.-K., & Park, J. (2020). Photonic crystal-based smart contact lens for continuous intraocular pressure monitoring. *Lab on a Chip, 20*(10), 1740–1750. https://doi.org/10.1039/C9LC01268K

Manickam, P., Mariappan, S. A., Murugesan, S. M., Hansda, S., Kaushik, A., Shinde, R., & Thipperudraswamy, S. P. (2022). Artificial intelligence (AI) and internet of medical things (IoMT) assisted biomedical systems for intelligent healthcare. *Biosensors, 12*(8), 562. https://doi.org/10.3390/bios12080562

Manjeri, A., & George, S. D. (2024). Hydrogel-embedded polydimethylsiloxane contact lens for ocular drug delivery. *ACS Applied Bio Materials, 7*(11), 7324–7331. https://doi.org/10.1021/acsabm.4c00975

Nguyen, T. T. H., Nguyen, C. M., Huynh, M. A., Vu, H. H., Nguyen, T. K., & Nguyen, N. T. (2023). Field effect transistor based wearable biosensors for healthcare monitoring. *Journal of Nanobiotechnology, 21*, 411. https://doi.org/10.1186/s12951-023-02153-1

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjártsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., … Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ, 372*, n71. https://doi.org/10.1136/bmj.n71

Park, J., Ahn, D. B., Kim, J., Cha, E., Bae, B. S., Lee, S. Y., & Park, J.-U. (2019). Printing of wirelessly rechargeable solid-state supercapacitors for soft, smart contact lenses with continuous operations. *Science Advances, 5*(12), eaay0764. https://doi.org/10.1126/sciadv.aay0764

Park, W., Seo, H., Kim, J., Hong, Y.-M., Song, H., Joo, B. J., Kim, S., Kim, E., Yae, C.-G., Kim, J., Jin, J., Kim, J., Lee, Y.-H., Kim, J., Kim, H. K., & Park, J.-U. (2024). In-depth correlation analysis between tear glucose and blood glucose using a wireless smart contact lens. *Nature Communications, 15*, 2828. https://doi.org/10.1038/s41467-024-47123-9

Roostaei, N., & Hamidi, S. M. (2025). Plasmonic smart contact lens based on etalon nanostructure for tear glucose sensing. *Scientific Reports, 15*, 14948. https://doi.org/10.1038/s41598-025-99624-2

Sadasivam, R., Packirisamy, G., Shakya, S., & Goswami, M. (2021). Non-invasive multimodal imaging of diabetic retinopathy: A survey on treatment methods and nanotheranostics. *Nanotheranostics, 5*(2), 166–181. https://doi.org/10.7150/ntno.56015

Salvador-Carulla, L., Woods, C., de Miquel, C., & Lukersmith, S. (2024). Adaptation of the technology readiness levels for impact assessment in implementation sciences: The TRL-IS checklist. *Heliyon*, *10*(9), e29930. https://doi.org/10.1016/j.heliyon.2024.e29930

Seo, H., Chung, W. G., Kwon, Y. W., Kim, S., Hong, Y.-M., Park, W., Kim, E., Lee, J., Lee, S., Kim, M., Lim, K., Jeong, I., Song, H., & Park, J.-U. (2023). Smart contact lenses as wearable ophthalmic devices for disease monitoring and health management. *Chemical Reviews, 123*(19), 11488–11558. https://doi.org/10.1021/acs.chemrev.3c00290

Seo, H., Hong, Y.-M., Chung, W. G., Park, W., Lee, J., Kim, H. K., Byeon, S. H., Kim, D. W., & Park, J.-U. (2024). Real-time in vivo monitoring of intraocular pressure distribution in the anterior chamber and vitreous chamber for diagnosis of glaucoma. *Science Advances, 10*(6), eadk7805. https://doi.org/10.1126/sciadv.adk7805

Shi, Y., Jiang, N., Bikkannavar, P., Cordeiro, M. F., & Yetisen, A. K. (2021). Ophthalmic sensing technologies for ocular disease diagnostics. *Analyst, 146*(21), 6416–6444. https://doi.org/10.1039/D1AN01244D

Siegfried, C. J., & Shui, Y.-B. (2022). Racial disparities in glaucoma: From epidemiology to pathophysiology. *Missouri Medicine, 119*(1), 49–54. https://pmc.ncbi.nlm.nih.gov/articles/PMC9312450/

Tojo, N., Hayashi, A., & Otsuka, M. (2020). Correlation between 24-h continuous intraocular pressure measurement with a contact lens sensor and visual field progression. *Graefe's Archive for Clinical and Experimental Ophthalmology, 258*(1), 175–182. https://doi.org/10.1007/s00417-019-04487-9

Wasilewicz, R., Varidel, T., Simon-Zoula, S., Schlund, M., Cerboni, S., & Mansouri, K. (2020). First-in-human continuous 24-hour measurement of intraocular pressure and ocular pulsation using a novel contact lens sensor. *British Journal of Ophthalmology, 104*(11), 1519–1523. https://doi.org/10.1136/bjophthalmol-2019-315276

Wu, K. Y., Dave, A., Carbonneau, M., & Tran, S. D. (2024). Smart contact lenses in ophthalmology: Innovations, applications, and future prospects. *Micromachines, 15*(7), 856. https://doi.org/10.3390/mi15070856

Xu, Y., & Li, H. (2022). In vitro and in vivo evaluation of brimonidine loaded silica nanoparticles-laden silicone contact lenses to manage glaucoma. *Journal of Biomaterials Applications, 37*(2), 333–343. https://doi.org/10.1177/08853282221090880

Yang, C., Wu, Q., Liu, J., Mo, J., Li, X., Kang, X., Yang, H., & Zhou, Z. (2022). Intelligent wireless theranostic contact lens for electrical sensing and regulation of intraocular pressure. *Nature Communications, 13*, 2556. https://doi.org/10.1038/s41467-022-29860-x

Yao, Y., Khan, S. A., Cui, X., Liu, K., Wen, S., & Zhang, H. (2025). Hydrogel-based smart contact lens for enhanced functional applications. *Biomedical Instrumentation*, *1*(1)*,* Article 100003. https://doi.org/10.1016/j.bmi.2025.100003

Ye, Y., Ge, Y., Zhang, Q., Yuan, M., Cai, Y., Li, K., Li, Y., Xie, R., Xu, C., Jiang, D., Qu, J., Liu, X., & Wang, Y. (2022). Smart contact lens with dual-sensing platform for monitoring intraocular pressure and matrix metalloproteinase-9. *Advanced Science, 9*(12), e2104738. https://doi.org/10.1002/advs.202104738

Yuan, M., Liu, Z., Wu, X., Gou, H., Zhang, Y., Ning, X., Li, W., Yao, Z., Wang, Y., Pei, W., & Chen, H. (2023). High-sensitive microfluidic contact lens sensor for intraocular pressure visualized monitoring. *Sensors and Actuators A: Physical, 354*, 114250. https://doi.org/10.1016/j.sna.2023.114250

Zhang, J., Dai, Y., & Lee, C. H. (2025). Healthcare with smart contact lenses: Innovations, challenges, and future perspectives. In T. A. Nguyen (Ed.), *Advanced sensors for smart healthcare* (pp. 521–545). Elsevier. https://doi.org/10.1016/b978-0-443-24790-3.00031-4

Zhang, J., Kim, K., Kim, H. J., Meyer, D., Park, W., Lee, S. A., Dai, Y., Kim, B., Moon, H., Shah, J. V., Harris, K. E., Collar, B., Liu, K., Irazoqui, P., Lee, H., Park, S. A., Kollbaum, P. S., Boudouris, B. W., & Lee, C. H. (2022). Smart soft contact lenses for continuous 24-hour monitoring of intraocular pressure in glaucoma care. *Nature Communications, 13*, 5518. https://doi.org/10.1038/s41467-022-33254-4

Zhu, H., Yang, H., Zhan, L., Chen, Y., Wang, J., & Xu, F. (2022). Hydrogel-based smart contact lens for highly sensitive wireless intraocular pressure monitoring. *ACS Sensors, 7*(10), 3014–3022. https://doi.org/10.1021/acssensors.2c01299

Zhu, Y., Haghniaz, R., Hartel, M. C., Mou, L., Tian, X., Garrido, P. R., Wu, Z., Hao, T., Guan, S., Ahadian, S., Kim, H.-J., Jucaud, V., Dokmeci, M. R., & Khademhosseini, A. (2023). Recent advances in bioinspired hydrogels: Materials, devices, and biosignal computing. *ACS Biomaterials Science & Engineering, 9*(5), 2048–2069. https://doi.org/10.1021/acsbiomaterials.1c00741