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Editorial Article

3D Printed Ocular Drug Delivery Systems: Recent Progress and Future Perspectives

Debjyoti Adak[1], Bikash Ranjan Jena[1], Surya Kanta Swain[2*]

[1]School of Pharmacy, The Neotia University, Sarisha, D.H Road, Kolkata - 743368, West Bengal, India.
[2]Amity Institute of Pharmacy, Amity University Kolkata, Major Arterial Road, AA II, Newtown, Kadampukur, Kolkata 700135, West Bengal, India.

[*]**Correspondence**
Surya Kanta Swain
swain_suryakant@yahoo.co.in

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The three-dimensional (3-D) printing model has been recognized as an ideal platform through which ocular drug delivery vehicles can bypass the natural anatomical and physiological barriers that limit the performance of traditional eye drops, suspensions, and injections. Through the ability to provide geometrical precision in regulating space and volume for drug loading, 3D printing can be used to create personalized, location-specific ocular dosage geometries capable of sustaining drug release, decreasing dosing frequency, and improving patient compliance and comfort. Rational design of 3D-printed devices has enabled the development of ocular inserts, microneedles, contact lenses, and microfluidic systems (Giri et al., 2024; Tan et al., 2022). Extrusion has been widely used in anterior segment therapy, in which ocular inserts capable of extending residence time and providing controlled drug release have been fabricated. More recently, sodium hyaluronate-derived hydrogel inserts loaded with liposomal moxifloxacin (SL:MOX) were printed as multilayered structures with consistent size and thickness. FTIR and SEM analyses demonstrated the successful production of liposomes (~150 nm) with an encapsulation efficiency of approximately 80%, while maintaining uniform drug content and avoiding destructive drug–polymer interactions. In vivo, 10-layer SL:MOX inserts achieved approximately 71% drug release with a near zero-order release profile and slower release than non-liposomal MOX inserts and conventional eye drop formulations, resulting in improved ocular retention and bioavailability (Duman et al., 2024; Giri et al., 2024; Alzahrani et al., 2023). The treatment challenges associated with posterior segment diseases have stimulated the development of 3D-printed intraocular implants capable of prolonged drug delivery. Homogeneous dispersion of triamcinolone acetonide (TA) within a polycaprolactone (PCL) matrix has been achieved with loading efficiencies approaching 100% through precise geometry control, while eliminating residual organic solvents that may irritate ocular tissues. Implants with higher surface-area-to-volume ratios demonstrated the greatest cumulative drug release over 180 days in vitro, and release kinetics followed the Korsmeyer–Peppas diffusion model. Cytocompatibility exceeded 90% cell viability, highlighting the potential of customizable implants to provide sustained steroid delivery while reducing the need for repeated intravitreal injections (Annuryanti et al., 2023; Ioannou et al., 2023).

Methodology

Extrusion-based methods such as fused deposition modeling (FDM) and semi-solid extrusion have been extensively applied over the past five years to fabricate polymeric ocular inserts using materials such as polycaprolactone (PCL) and hydrogels. These techniques provide precise control over thickness, surface area, and internal architecture, which directly influence drug loading and release characteristics. Duman et al. (2024) demonstrated that liposomal moxifloxacin-loaded ocular inserts fabricated by 3D printing exhibited uniform drug distribution, high structural reproducibility, and a slower near zero-order release profile than conventional inserts (Annuryanti et al., 2023; Duman et al., 2024; Fitaihi et al., 2024). A biodegradable 3D-printed conjunctival insert developed by Garg et al. (2025) demonstrated sustained drug release. By

enabling accurate dosing while minimizing systemic absorption, biodegradable polymer implants positioned within the conjunctival fornix offer a promising strategy for localized long-term drug delivery. Vat photopolymerization techniques, including stereolithography (SLA) and digital light processing (DLP), have enabled the fabrication of transparent, high-resolution hydrogel contact lenses suitable for ocular applications. Mohamdeen et al. (2022) demonstrated that drug-eluting contact lenses loaded with timolol or azithromycin could be customized by modifying monomer concentration and post-curing conditions, allowing sustained antimicrobial or antiglaucoma therapy from a single lens (Mohamdeen et al., 2022). This concept has recently been extended to smart contact lenses, where functionalized hydrogels are printed directly onto commercial lenses to incorporate therapeutic or diagnostic features. Furthermore, ex vivo 3D-printed ocular models have been developed to evaluate periocular drug delivery and lateral diffusion, thereby reducing reliance on animal experimentation and improving physiological relevance during pharmacokinetic studies (González-Fernández et al., 2025).

Current Challenges and Future Scope

Although 3D-printed ocular drug delivery systems show significant promise, several barriers remain before widespread clinical implementation can be achieved. One major challenge is the limited availability of ophthalmically safe printable polymers and bioinks, as many printable formulations require harsh extrusion temperatures or photocurable monomers that may degrade drugs or leave toxic residues. Mechanical and optical limitations also remain, since printed corneal and implantable devices often lack the strength, transparency, and curvature of native tissues. Biological integration presents another challenge because implanted constructs may induce fibrosis, haze, neovascularization, or permanent changes in cellular phenotype, reducing long-term functionality (Tan et al., 2022). The future of sustained drug-eluting glaucoma implants remains promising; however, long-term in vivo stability, GMP-compliant manufacturing, real-time quality control, regulatory approval, and scalable personalized production must still be established. Addressing these material, biomechanical, biological, and regulatory challenges will be essential for successful clinical translation (Swain et al., 2025). Future developments are expected to integrate nanomedicine with stimuli-responsive polymers to create multifunctional, closed-loop ocular drug delivery systems capable of sensing disease biomarkers and adjusting drug release accordingly. Point-of-care manufacturing may eventually allow ophthalmologists to customize implant geometry and drug dosage using patient-specific imaging data. Additionally, standardized 3D-printed ocular models and quality-by-design manufacturing approaches will facilitate regulatory approval while reducing risks associated with personalized ocular drug delivery (Tan et al., 2022; Swain et al., 2025). Continued advances in polymer science are anticipated to produce ophthalmic-grade printable materials possessing intrinsic mucoadhesion, biodegradability, and antifouling properties, thereby extending 3D printing applications from anterior segment diseases to posterior segment disorders such as uveitis, diabetic retinopathy, and age-related macular degeneration (Ioannou et al., 2023).

Conclusion

Overall, 3D printing has emerged during the past five years as a transformative technology for ocular drug delivery, with successful proof-of-concept demonstrations including drug-eluting contact lenses, conjunctival inserts, microneedle patches, and ex vivo testing platforms. These innovations have improved drug bioavailability, reduced dosing frequency, and enabled personalized ocular therapy (Annuryanti et al., 2023; Swain et al., 2025). Nevertheless, successful clinical translation will depend on overcoming challenges related to ophthalmically safe printable materials, process standardization, regulatory approval, and patient acceptance. Once these challenges are addressed, 3D-printed ocular drug delivery systems are expected to transition from experimental technologies to routine clinical applications for the treatment of both anterior and posterior ocular diseases (Mohamdeen et al., 2022).

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All authors contributed equally.

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Ethics approval

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AI tool usage declaration

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