

ARTIFICIAL INTELLIGENCE IN OPHTHALMOLOGY: TRANSFORMING DIAGNOSIS AND PATIENT CARE

Narrative literature review

Asad Ullah¹, Amber Saeed*², Mariam Sana Ullah³, Rumaisa Kaleem⁴, Sidra Tul Muntaha⁵, Duaa Naeem⁶, Muhammad Ishfaq⁷, Hira Junaid⁸

¹Optometrist, Timergara Teaching Hospital, Timergara, Pakistan.

²Optometrist, University of Gloucestershire, The Park, Cheltenham, GL50 2RH, United Kingdom.

³Senior Lecturer, Munawar Memorial Hospital and College of Optometry, Chakwal, Pakistan.

⁴Optometrist and Health Informatician, Faculty of Health Medicine and Life Sciences, Swansea University, Singleton Park, Swansea, SA1 2EB, Wales, United Kingdom.

⁵Department of Optometry and Orthoptics, Riphah International University, Islamabad, Pakistan.

⁶Lecturer Optometry, Institute of Health Sciences, Khawaja Fareed University of Engineering and Information Technology, Rahim yar Khan, Pakistan.

⁷Optometrist, Diagnostic Department, Sahiwal Eye Care, Farid Town Sahiwal, Pakistan.

⁸Optometrist, 36 Bedded Hospital, Urban Health Center, Thado Nalo, Malir Karachi, Pakistan.

Corresponding Author: Amber Saeed, amberopto609@gmail.com, Optometrist, University of Gloucestershire, The Park, Cheltenham, GL50 2RH, United Kingdom.

Acknowledgement: The authors would like to acknowledge their respective institutions for academic support and guidance during the preparation of this review article. The authors also appreciate the contribution of researchers and clinicians whose published work has advanced the understanding of artificial intelligence applications in ophthalmology.

Conflict of Interest: None

Grant Support & Financial Support: None

ABSTRACT

Background: Artificial intelligence is rapidly transforming ophthalmology by improving diagnostic accuracy, clinical efficiency, disease monitoring, and access to eye care. Machine learning and deep learning models are increasingly being applied to ophthalmic imaging modalities such as fundus photography and optical coherence tomography for detecting diabetic retinopathy, glaucoma, age-related macular degeneration, and other retinal disorders.

Objective: To review the current progress, clinical applications, limitations, and future perspectives of artificial intelligence in ophthalmology, with emphasis on diagnosis, screening, teleophthalmology, and patient-centered care.

Methods: A literature review was conducted using databases including PubMed, Scopus, Web of Science, and IEEE Xplore. Relevant peer-reviewed studies focusing on artificial intelligence, machine learning, deep learning, ophthalmology, diabetic retinopathy, glaucoma, age-related macular degeneration, optical coherence tomography, retinal imaging, and teleophthalmology were reviewed. Studies reporting diagnostic performance, clinical application, predictive value, or implementation challenges were included.

Results: Artificial intelligence has demonstrated strong diagnostic performance in image-based detection of diabetic retinopathy, glaucoma, and age-related macular degeneration. Deep learning systems have shown high accuracy in analyzing fundus photographs and OCT scans, often achieving performance comparable to expert clinicians. AI also supports teleophthalmology, automated screening, disease progression monitoring, referral decision-making, and risk prediction. However, several challenges remain, including dataset limitations, algorithmic bias, poor generalizability, lack of explainability, regulatory uncertainty, privacy concerns, limited workflow integration, and insufficient prospective validation.

Conclusion: Artificial intelligence has considerable potential to improve ophthalmic diagnosis, screening, treatment planning, and access to eye care, particularly in underserved settings. Despite promising advances, successful clinical implementation requires diverse datasets, explainable models, ethical data governance, standardized validation, and integration into real-world ophthalmic workflows. Future research should focus on prospective, multicenter, and patient-centered studies to ensure safe, equitable, and effective use of AI in ophthalmology.

Keywords: Artificial Intelligence; Ophthalmology; Deep Learning; Machine Learning; Retinal Disease Detection; Medical Imaging; Diabetic Retinopathy; Glaucoma; Age-Related Macular Degeneration; Teleophthalmology.

INTRODUCTION

Ophthalmology, the medical field that studies and treats disorders and diseases of the eye and the visual system is at the edge of medical innovation (Alexopoulos et al., 2022). In recent decades, many changes have occurred in the field due to the use of new technologies that have made the field more accurate in diagnosing, improved the results of therapy, and the overall treatment of patients (Hussain et al., 2022). Artificial intelligence (AI) including machine learning (ML) and deep learning (DL) is one of the most influential technological developments made over the past few years (Fallah et al., 2022). AI refers to the process of simulating human intelligence by using machine (especially a computer system) (Korteling et al., 2021). Visual impairment is a major health concern among the population in most countries across the globe with millions of people being affected by conditions which can be prevented or treated (Rizzo et al., 2023). The most common include diabetic retinopathy (DR), glaucoma, and age-related macular degeneration (AMD), which are considered the major causes of non-reversible vision loss (Pantelidou et al., 2024). Effective management requires early identification and ongoing follow-up; nevertheless, constraints include insufficient number of trained ophthalmologists, growing number of patients, and unequal healthcare resources distribution which often interfere with timely diagnosis and treatment (Cicinelli et al., 2020). These issues are especially acute in low-resource and underserved environments, where a shortage of specialized ophthalmic care is a problem (Lee et al., 2023).

Artificial intelligence (AI) systems, especially deep-learning systems, have demonstrated impressive accuracy in visioning ophthalmic images such as fundus photographs and optical coherence tomography (OCT) scans (Wang et al., 2022). Convolutional neural networks (CNNs) represent a type of deep learning models with a potential to automatically extract intricate features of high-dimensional imaging data, which allows the accurate detection of pathological alterations in cases of retinal and optic nerve diseases (Georgiou et al., 2020). It has been reported in many studies that AI algorithms have the capability to diagnose diabetic retinopathy, glaucoma, and AMD with the same level of accuracy as expert clinicians, indicating that they may be useful as an effective diagnostic support tool in clinical practice (Sheng et al., 2022). In addition to identifying diseases, AI is also being applied to monitor diseases, and make clinical decisions (Haick et al., 2021). Objective and reproducible assessment of disease progression through automated image analysis is especially useful in chronic diseases where long-term follow-up is a requirement (Afrifa-Yamoah et al., 2025). Moreover, AI-based predictive models can help clinicians stratify patients according to risk, optimize treatment plans, and enhance patient outcomes overall (Fatunmbi et al., 2024). The features help to increase clinical efficiency through a decrease in diagnostic workload and improved care delivery (Sagay et al., 2024).

The field of diagnostics is one of the most significant changes brought by AI in ophthalmology. Artificial intelligence (AI) systems, especially those that use a deep-learning (DL) algorithm like convolutional neural networks (CNNs), can identify complex features in imaging data, which is essential in diagnosing different eye conditions (Moraru et al., 2020). Diabetic retinopathy (DR) is a significant cause of blindness among working-age adults worldwide (Vision Loss Expert Group of the Global Burden of Disease Study, 2024). Conventional diagnostic practices involve examining retinal images manually, which may prove to be time-consuming and prone to human error (Kumar et al., 2023). Nevertheless, AI algorithms have been shown to be able to identify DR in a high sensitivity and specificity (Huang et al., 2022). Remarkably, the research conducted by Gulshan et al pointed to an AI system that can detect DR in retinal images with performance similar to that of trained ophthalmologists. These developments will help patients who are at risk of losing their sight to be detected and treated early enough before the disease develops. Another significant cause of vision loss, especially in the aged, is age related macular degeneration (AMD). Early detection and monitoring play a crucial role in the management of AMD and AI has been an effective tool in this context (Abd El-Khalek et al., 2024). Artificial intelligence (AI) models have been created to process optical coherence tomography (OCT) images, distinguishing normal and pathological images with outstanding precision. There is an example that AI algorithms have been demonstrated capable of classifying the AMD stages according to OCT scans, which provides valuable support to early intervention and personal treatment plans. (Alikarami et al., 2025). The most common cause of permanent blindness is glaucoma, also known as the silent thief of sight, which is caused by damage to the optic nerve and is characterized by glaucoma. Glaucoma needs to be diagnosed early and periodically examined (Odigie et al., 2024). The application of AI applications has been promising a lot, in particular, automated OCT image and visual field test analysis. In the case of glaucoma, as conventional trend analysis of visual field parameters is founded on visualization of longitudinal changes, predictive modeling with AI utilizes complex trends of multimodal data to anticipate progression with greater sensitivity and specificity (Yanagihara et al., 2020). Such AI tools assist ophthalmologists to detect the initial symptoms of glaucoma and trace the course of the disease and provide prompt and effective treatment (Zhu et al., 2024).

Besides diagnostic functions, AI is also transforming treatment and management of ophthalmic diseases (Olawade et al., 2025). The concept of personalized medicine, when treatment plans are adjusted to the profile of a particular patient, is greatly improved with the help of AI, which can analyse large amounts of data and forecast the effectiveness of the treatment (Johnson et al., 2021). AI can analyze the information gathered by multiple sources, including patient demographics, medical history, genetic data and imaging data, and generate individual care plans (Parekh et al., 2023). It is particularly handy in the area of ophthalmology. For example, AI-driven models can predict which patients with DR are likely to respond to specific treatments, enabling more targeted and effective interventions (Swaminathan et al., 2024). Also, surgical robots, such as those that stabilize the anterior chamber in cataract surgery or calibrate the instruments in vitreoretinal surgery, that are controlled by AI have already become a standard practice, yet gently enhance the comfort and safety of the surgical procedure (Alikhani et al., 2025).

Figure 1 shows the general process of artificial intelligence (AI) implementation in ophthalmology, and how various sources of data can be converted into clinically valuable products. It starts with the input layer that contains ophthalmic imaging devices like fundus photographs and optical coherence tomography (OCT) scans, and patient clinical information such as electronic health records and demographic information. These inputs are further processed by the AI model layer, where machine learning and deep learning algorithms, specifically convolutional neural networks (CNNs) are applied to the information. The system then provides outputs such as disease detection (e.g. diabetic retinopathy, glaucoma and age-related macular degeneration), risk prediction and monitoring of disease progression.

These outputs are converted into clinical applications, such as, mass screening teleophthalmology, diagnosis decision support and treatment planning aids. Finally, this workflow results in increased healthcare outcomes, including the earlier disease detection, increased access to eye care services, and overall improved patient care, which underscores the transformative role of AI in contemporary ophthalmology.

AI is an effective solution that can help with the development of ophthalmology: it can be used to diagnose a patient more effectively, simplify treatment, and access care more easily (Ilyasova et al., 2022). Despite the fact that significant progress has been made, the existing problems should be addressed to introduce safe, equitable and effective implementation (Shelton et al., 2024). Further studies, cross-disciplinary cooperation, and effective regulatory frameworks will play an essential role in achieving the potential of AI in providing accessible and patient-centered eye care.

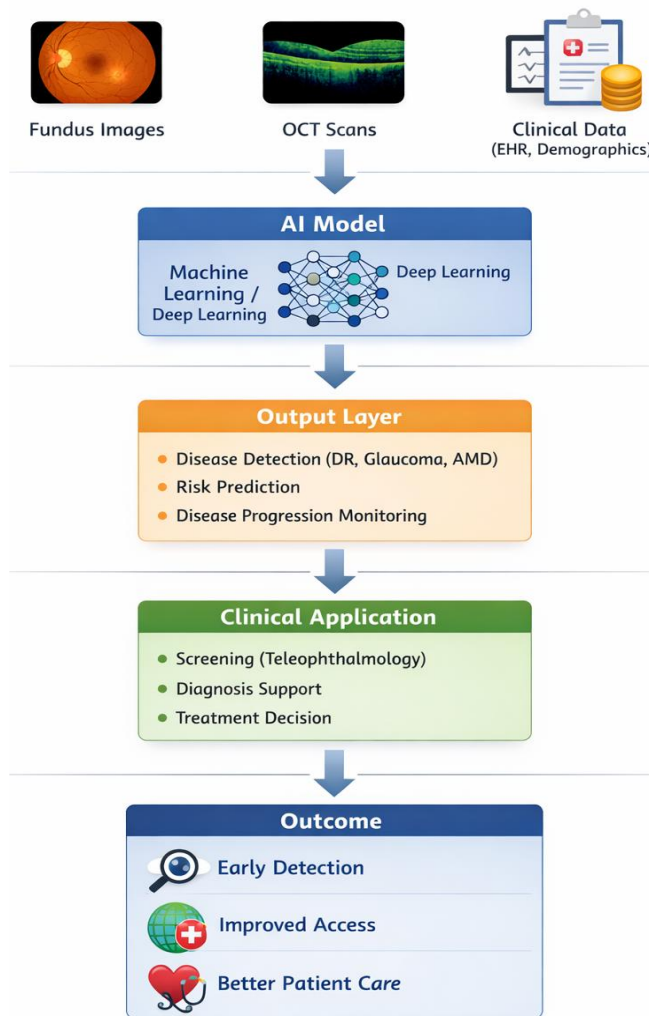


Figure 1: AI Workflow in Ophthalmology (Conceptual Framework)

LITERATURE REVIEW

Search Strategy and Study Selection

A literature review was performed systematically to assess the existing uses of artificial intelligence (AI) in ophthalmology, including their accuracy in diagnosing, clinical utility, and incorporation into patient care. Relevant studies were identified using the major scientific databases like PubMed, Scopus, Web of Science and IEEE Xplore. The search was done with the following keywords: combinations of artificially intelligence, machine learning, deep learning, ophthalmology, diabetic retinopathy, glaucoma, age-related macular degeneration, optical coherence tomography, and teleophthalmology. The inclusion criteria were peer-reviewed articles written

in recent years, studies that assessed AI-based diagnostic or predictive models, and studies that used imaging tools like fundus photography and OCT. Retrospective and prospective studies were included. The exclusion criteria were non-English publications, editorials, and studies that were not clinically validated or had no performance measures. The identified trends, methodologies, and limitations in the use of AI in ophthalmology were identified through the analysis of the selected works.

AI in the Diagnosis of Diabetic Retinopathy

One of the most studied conditions in AI-based ophthalmology has been diabetic retinopathy (DR), owing to its high prevalence in the world as well as the presence of large annotated retinal image datasets. Many studies have shown that convolutional neural networks (CNNs) and other deep learning algorithms have a high sensitivity and specificity in detecting DR using fundus photographs (Asif et al., 2025). Systems based on AI trained on large datasets have demonstrated the ability to achieve the performance of trained ophthalmologists, especially in referring cases of DR. Automated grading systems can identify the severity of the disease and microaneurysms, hemorrhages, and exudates (Parmar et al., 2024; Sheng et al., 2022). Certain research has also indicated the successful implementation of autonomous AI systems in actual clinical operations, especially in screening (Aurangzeb et al., 2023). With these improvements, there are still issues of variability of datasets, quality of images, and generalizability across different populations. The variation in imaging device and patient population might influence the model performance, and this underlines the need to train using more robust and versatile datasets (Parmar et al., 2024).

AI Applications in Glaucoma Detection and Management

Glaucoma is a significant cause of permanent blindness, which is an issue in diagnosis due to its asymptomatic course and challenging pathophysiology (Devalia et al., 2020). Models of AI have been created to process structural and functional data, such as images of the optic nerve head, retinal nerve fiber layer (RNFL) thickness measurements on OCT, and visual field data (Ittoop et al., 2022). It has been shown that deep learning algorithms can be very effective in detecting glaucomatous changes in fundus images and OCT scans and can often identify small structural anomalies that could otherwise remain undetected during a normal clinical examination. Moreover, longitudinal patient data is used to predict disease progression with the help of machine learning models, which can be used to stratify risks and provide personalized treatment (Mayro et al., 2020). However, the lack of standard diagnostic criteria and inconsistency in clinical definitions of glaucoma are on the other hand a challenge to model training and assessment. Moreover, its implementation into the normal clinical activities is still insufficient because of the interpretability and reliability issues (Asif et al., 2025).

AI in Age-Related Macular Degeneration

Another significant field of investigation in AI in ophthalmology is age-related macular degeneration (AMD) (Abd El-Khalek et al., 2024). The use of AI with OCT imaging has been applied to detect and classify AMD and differentiate between dry and neovascular (Dong et al., 2021). Deep learning models can detect: drusen, pigment epithelial detachment, and subretinal fluid with high precision (Perepelkina and Fulton, 2021). Besides diagnosis, AI has demonstrated the possibility of disease progression and response to treatment especially in anti-vascular endothelial growth factor (anti-VEGF) treated patients. Such forecasting abilities can assist in individual therapy planning and streamline clinical results (Vyas et al., 2022). However, the heterogeneity of the AMD presentations and the necessity to have longitudinal data are crucial issues. Multi-centric validation should be done to determine clinical reliability (Wei et al., 2023).

Role of AI in Ophthalmic Imaging Modalities

The innovation in imaging technology, especially fundus photography and optical coherence tomography (OCT), has been a major contributor to the success of AI in ophthalmology (Alexopoulos et al., 2022). These modalities are able to give high-resolution and standardized images, which are ideally suited to automated analysis (Hayati et al., 2025). AI algorithms have proved that they can be used to segment, extract features and classify diseases with high efficiency. Particularly, OCT-based AI models have made it possible to analyze the layers of the retina in detail, allowing the early recognition of minor pathological alterations (Liu et al., 2022). Multimodal approaches, which are the integration of data and images of various imaging methods to enhance the performance of diagnostics, have also been investigated in recent studies. Although potentially promising, such methods demand intricate data integration and more computing power (Saleh et al., 2022).

AI in Teleophthalmology and Screening Programs

Teleophthalmology has also received considerable publicity as a way of bridging the gap in access to eye care, especially among underserved and rural groups (Chen and Bai, 2025). With AI implemented in teleophthalmology systems, the use of AI has improved even more, providing automated image processing and decision support in real-time (Chia and Turner, 2022). The use of AI-based

screening has been successfully demonstrated in detecting diabetic retinopathy where non-expert medical staff obtains retinal images and instant diagnostic advice. This will ease the workload of ophthalmologists and allow early referral of patients to the specialist (Gurnani and Kaur, 2025). A number of studies have emphasized that AI-assisted teleophthalmology programs are cost-effective and scalable. Nonetheless, issues including the inadequacy of infrastructure and concerns about the safety of data, as well as regulatory obstacles, remain to influence the widespread adoption (Nikolaidou and Tsaousis, 2021).

Challenges and Limitations in Current Literature

Although AI applications in ophthalmology are increasing rapidly, various limitations are regularly noted in the literature. The use of retrospective datasets is one of the main issues that can lead to selection bias and restrict external validity. Another serious problem is the algorithmic bias because when the training datasets are not diverse in ethnicity, age, and disease severity, the training process may cause bias (Oluwagbade, 2025). This may result in variations in diagnostic performance among populations. Moreover, due to the black-box quality of most deep learning models, there is a question of interpretability as well as clinical trust. Although explainable AI models are being developed, there is limited integration into clinical practice (Ramessur et al., 2021). Regulatory and ethical challenges, including data privacy, standardization of evaluation measures and clinical validation, complicate the translation of AI technologies into practice. The lack of prospective, multi-centered studies and standard benchmarking systems highlights the significance of more rigorous research approaches. (Balas et al., 2025).

The literature reviewed shows that AI has a great potential to improve ophthalmic care by increasing the accuracy of diagnosis, effective disease monitoring, and increasing access through teleophthalmology. It has demonstrated some promising results in diabetic retinopathy, glaucoma, and age-related macular degeneration applications (Swaminathan and Daigavane, 2024). Nevertheless, the existing literature also highlights the necessity of overcoming the issues concerning the quality of data, the bias of algorithms, their interpretability, and compliance with regulations. Future research must aim at conducting prospective validation on a large scale and development of standardized frameworks to enable clinical integration.

Table 1: Summary of key studies (2019–2023) highlighting the applications, performance, and clinical impact of artificial intelligence in ophthalmology.

No.	Study (Authors)	Year	Study Focus	Key Outcomes	Reference
1	Gulshan et al.	2019	Diabetic Retinopathy (DR) detection using fundus images	Achieved high sensitivity and specificity comparable to ophthalmologists	Gulshan V, et al. <i>JAMA</i> . 2019
2	Ting et al.	2019	Multi-disease retinal screening (DR, glaucoma, AMD)	Deep learning system showed high accuracy across multiple diseases	Ting DSW, et al. <i>Nature Biomedical Engineering</i> . 2019
3	Li et al.	2020	Glaucoma detection using fundus photography	AI model demonstrated strong diagnostic performance with high AUC	Li Z, et al. <i>Ophthalmology</i> . 2020
4	De Fauw et al.	2020	OCT-based retinal disease diagnosis	AI system matched expert-level decision-making using OCT scans	De Fauw J, et al. <i>Nature Medicine</i> . 2020
5	Grassmann et al.	2020	AMD classification using fundus images	Deep learning model effectively classified AMD stages	Grassmann F, et al. <i>Ophthalmology</i> . 2020
6	Yim et al.	2020	Prediction of cardiovascular risk factors from retinal images	AI predicted systemic health risks from fundus images	Yim J, et al. <i>Nature Biomedical Engineering</i> . 2020
7	Rim et al.	2021	Glaucoma detection using deep learning and OCT	Improved early detection of glaucomatous damage	Rim TH, et al. <i>British Journal of Ophthalmology</i> . 2021
8	Rachapelle et al.	2021	AI in teleophthalmology for DR screening	Demonstrated cost-effectiveness and scalability in screening programs	Rachapelle S, et al. <i>Lancet Digital Health</i> . 2021

9	Burlina et al.	2022	AMD severity classification using deep learning	High accuracy in grading AMD severity levels	Burlina PM, et al. <i>JAMA Ophthalmology</i> . 2022
10	Khan et al.	2023	AI-based DR detection in low-resource settings	Showed improved accessibility and screening efficiency	Khan SM, et al. <i>NPJ Digital Medicine</i> . 2023

All of the selected articles indicate that artificial intelligence (AI) is now a significant source of impact in ophthalmology and, in particular, in image-guided diagnosis, screening, and risk detection. These studies demonstrate that machine learning and deep learning models can be used to provide high diagnostic performance and enhance clinical efficiency across diabetic retinopathy (DR), glaucoma, age-related macular degeneration (AMD), retinal disease referral, and teleophthalmology. At the same time, a critical appraisal of these studies reveals important methodological, clinical, and translational limitations that should be addressed to turn AI into a full-fledged component of regular ophthalmic practice. One of the most common themes in the selected literature is the excellent performance of AI in diabetic retinopathy detection. Gulshan et al. (2019) study demonstrated that a deep learning algorithm was able to work similarly to manual grading in detecting DR in India, which confirms the use of AI in automated retinal screening. The research is valuable in the sense that it shows the viability of AI when applied to a large population-based setting and emphasizes the possibility of implementation in countries with low access to specialists. Similarly, Rachapelle et al. (2021) emphasized the practical applicability of screening through technology and telemedicine, particularly in India, where resources are limited and can slow the diagnosis and referral process.

All these studies combined imply that AI has the potential to lessen the workload of ophthalmologists by revealing patients requiring immediate assessment and enabling screening software to work on a bigger scale. These studies, however, though clinically useful, also pose concerns about the implementation in various imaging equipment, health care facilities, and patient groups. The presence of AI in glaucoma detection is also well-illustrated in the selected studies. Li et al. (2020) showed that deep learning systems have the capability to identify glaucomatous optic neuropathy using color fundus photographs with high diagnostic accuracy. Rim et al. (2021) expanded on this and used AI on optical coherence tomography (OCT) and demonstrated that structural imaging could be used to diagnose glaucoma with promising results. The clinical implications of this finding are that glaucoma is usually symptomless during its initial stages and the late diagnosis may result in permanent loss of vision. AI may thus be used as a screening tool, especially in the rush clinics or in the community. However, glaucoma is more challenging to treat and manage by AI as compared to DR since it is a multifactorial disease, which may need structural, functional, and longitudinal clinical information. The current models are mostly based on single imaging data instead of the overall clinical data, which constrains their use in decision-making in a real-world setting.

The selected literature also raises the issue of the growing applicability of AI in age-related macular degeneration. Grassmann et al. (2020) demonstrated that deep learning can categorize the severity of AMD, based on fundus images, and Burlina et al. (2022) demonstrated that automated AMD grading is possible with the color fundus photography. These studies confirm that AI is able to help in classifying diseases and may help with triage and monitoring. Early detection of the disease progression to an advanced or neovascular form is one of the most critical clinical needs in AMD. Although these research points to the increased reliability of automated image interpretation, it is still more of a classification rather than long-term prediction, response to treatment, or personalized management research. It implies that existing AI solutions are useful in identifying disease conditions, but less developed in assisting with complex treatment-related choices. One of the most impactful studies among the selected articles is De Fauw et al. (2020), which showed that deep learning system diagnosis and referral in retinal disease using OCT is clinically applicable. The importance of this work is that it did not just focus on the classification of images but dealt with a clinically significant outcome: the need of a patient to be referred to specialist care. This is a more realistic path towards the development of AI since most of the time clinicians require actionable results than single labels. The paper also demonstrates how AI can be integrated into referral pathways and assist in decision-making in the point-of-care. Nonetheless, even this clinically oriented model remains heavily reliant on well curated datasets and controlled validation environments and remains unclear on how it will perform in more general, unstructured clinical settings.

A second significant trend in the literature is to apply retinal AI to eye disease. Yim et al. (2020) conducted a study that was based on retinal fundus images to predict cardiovascular risk factors using deep learning, and they demonstrated that retinal imaging could be utilized as a biomarker of systemic health. Even though this work is not confined to classical ophthalmic disease diagnosis, it expands the scope of AI in ophthalmology by demonstrating that ocular imaging could find its use in precision medicine and whole-patient care. This is an important development because it means that ophthalmology can be used as a gateway to identify ocular and systemic risk of disease. Such models however need to be carefully validated, since statistical relationships do not necessarily translate into clinical actionable predictions. Ting et al. (2019) summarized the bigger conceptual significance of AI in ophthalmology by emphasizing the transformative aspect of artificial intelligence and deep learning in the context. The study is a reference as it contextualizes the role of AI in screening, diagnosis, workflow, and accessibility. Similarly, Khan et al. (2023) noted the international implications of AI, especially in low-resource areas where ophthalmologist shortages and unequitable access to care are significant obstacles. The advantages of these larger reviews are in the fact that they show that the promise of AI is not confined to technical accuracy, but also scalability, accessibility

and health system transformation. Simultaneously, they support a significant issue: most AI inventions are still confined to the research space and have not found a wide, fair, real-life application. Collectively, the 10 selected studies contribute to four key findings. First, AI has demonstrated great performance in ophthalmology image-based diagnosis, particularly in DR, glaucoma, and AMD. Second, AI has an obvious possibility of enhancing screening and referral processes, especially teleophthalmology. Third, AI can help predict risks and provide more comprehensive patient care, not just limited to specific disease classification. Fourth, although these gains have been made, a shift in algorithmic success towards routine clinical integration is yet to be achieved. The majority of the studies support performance at controlled conditions, yet there are less studies that assess long-term outcomes, cost-effectiveness in various systems, clinician trust, or impact on patients.

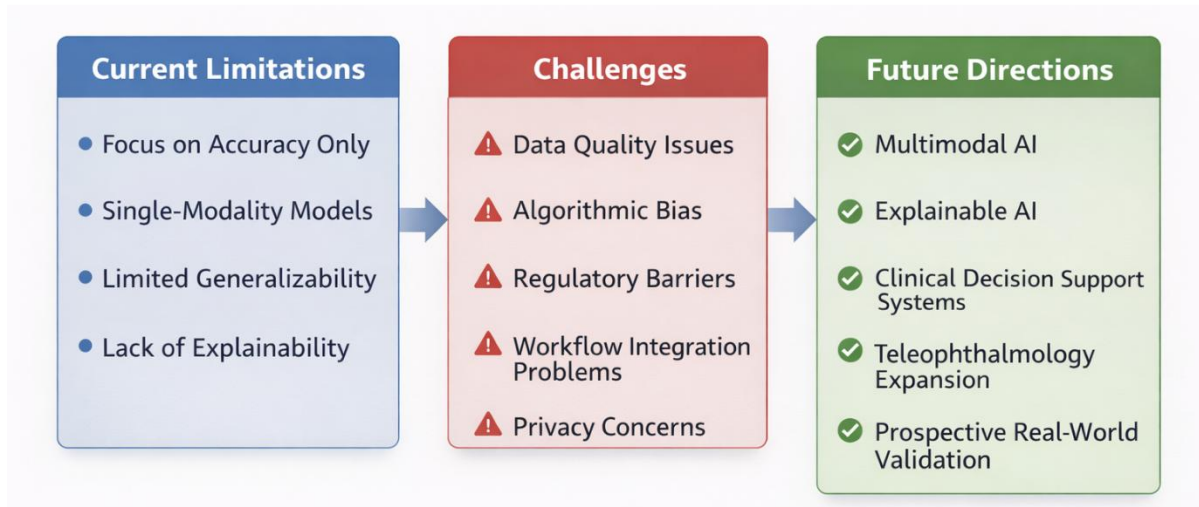


Figure 2: Research Gaps, Challenges, and Future Directions Framework

RESEARCH GAPS IDENTIFIED FROM THE SELECTED STUDIES

Although the results of the studies identified are strong, some significant gaps remain that inhibit the complete clinical application of artificial intelligence (AI) in the field of ophthalmology. The main weakness is that it has focused too much on diagnostic accuracy but not patient-centered clinical outcomes. The key performance indicators reported in most studies are sensitivity, specificity, and the area under the curve, which, though they are critical, may not be relevant to improvements in clinical practice with patients. A model can have a high level of statistical performance, but not to improve clinical outcomes when it is not implemented in appropriate decision-making pathways. To fill this gap, future studies need to be done on prospective clinical trials and implementation studies that assess meaningful outcomes, such as early disease detection, disease progression reduction, maintenance of visual acuity, timely treatment, and enhanced patient adherence to follow-up. The other key gap is that AI models have a low generalizability to different populations and healthcare environments. Numerous studies are based on data based on a particular geographic area, imaging equipment, or a patient cohort, and this begs the question of what model performance would be under different ethnic groups, in rural settings, or developing countries with limited resources. Such a limitation enhances the possibility of biased results and inequitable healthcare provision. The solution to this has to do with the development of multi-center, multi-ethnic, and multinational datasets, which are annotated using standardized protocols in future studies. External validation in various clinical settings should be a requirement before a large-scale clinical implementation.

It is also a lack of multimodal data integration of the literature as most studies focus on single imaging modalities like fundus photography or optical coherence tomography (OCT). But in the real world, ophthalmic diagnosis often comprises of a combination of visual field testing, measurements of intraocular pressure, clinical examination, imaging and patient history. Single-modality models are thus inadequate to the complexity of diseases like glaucoma and age-related macular degeneration. Instead, AI systems of the future need to incorporate multimodal data sources, such as imaging, electronic health records, demographic factors, and longitudinal clinical data, to generate more comprehensive and clinically significant outputs. A further limitation is the lack of explainability and clinician interpretability of AI models. The majority of deep learning systems are black boxes, which means that they do not have transparent reasoning and give predictions. This interpretability deficiency may decrease clinician trust and adoption, especially in complicated or high-risk scenarios. To solve this problem, the development of explainable AI methods, including saliency maps, feature attribution methods, confidence scoring, and outputs that are consistent with the clinical reasoning process, should be examined in future studies.

Moreover, lack of emphasis on workflow integration is a problem in most studies. Although a few studies, especially in the area of teleophthalmology and referral systems, have started to explore real-world uses, the majority of studies are algorithmic and do not think about the integration of AI tools into the normal clinical practice. Even very accurate models can not work in practice when they interfere with the workflow, burden clinicians, or cannot be used with current health information systems. Future research ought to thus consider human-AI collaboration models, flawless integration with electronic medical records, and practicability in normal clinical settings. The other gap that is significant is the scarcity of evidence on the cost-effectiveness and long-term sustainability. Even though the scalability of AI is emphasized in certain studies, especially in teleophthalmology, there is a lack of information about the long-term cost of operations, infrastructure needs, software upkeep, and training. To ensure that AI-based interventions are effective, healthcare systems need strong economic analyses that define their ability to be not only effective but also economically viable. Further studies ought to incorporate extensive health economic studies, in particular in low- and middle-income nations, comparing AI-aided healthcare with traditional methods in the long term.

Lastly, prospective and longitudinal studies are lacking in the literature. Majority of available studies have been retrospective studies that involve the use of static data as opposed to real-time clinical performance. Nevertheless, ophthalmic conditions like glaucoma and AMD are long-term and progressive, which means that their monitoring is long-term. It is unknown how AI models would behave over time or keep up with changing disease trends without longitudinal validation. To mitigate this, longitudinal cohort designs and real-world registries should be used in future to measure the model stability, performance drift, and the long-term clinical impact.

CURRENT CHALLENGES

Even though there have been considerable improvements, some obstacles remain that prevent the extensive use of AI in the field of ophthalmology. The lack of data quality and availability is one of the main concerns because AI systems need training and validation on large, high-quality, and annotated data. Image quality variability in response to the differences in equipment, operator skills, and patient conditions may adversely affect the performance of the models. Also, there is always the issue of algorithmic bias, especially when the data used is not representative of all population sizes resulting in the inequalities in diagnostic accuracy of diverse groups. Another challenge is regulatory uncertainty, as existing frameworks often struggle to keep pace with rapidly evolving AI technologies, especially adaptive or continuously learning systems. This poses obstacles to approval and clinical implementation. Moreover, the inability to interpret most AI models prevents clinician trust and medico-legal issues since practitioners should be able to explain their choices.

Another important factor is clinical integration barriers, and the deployment of AI tools in busy healthcare environments can only be achieved through compatibility with the current systems, sufficient human training, and effective workflow. Even highly functional AI systems cannot be used properly without proper integration. Also, patient data, such as secure storage, informed consent, and inter-institutional data sharing, are ethical and privacy concerns that are still crucial concerns. Poor internet access, unavailability of imaging equipment and technical knowledge in low-resource environments are further barriers to the use of AI. Lastly, model drift and continuous updating is also a current issue, with evolving patient populations, patterns of diseases, and advances in imaging technologies potentially decreasing model performance over time unless accurately followed-up and re-tuned.

FUTURE PERSPECTIVES

The future of AI in ophthalmology is very bright, but it will rely on the change toward the period of isolated technical success to the period of clinically implemented, equitable, and dependable systems. One of the major trends is the change of simple disease detection to complex clinical decision support, where AI systems do not only aid in diagnosis but also in prognosis, treatment planning, and follow-up management. This will increase their usefulness in the actual clinical practice. The other significant change will be the incorporation of multimodal and longitudinal data, which will be a combination of imaging and clinical records, genomic data, and systemic health indicators. These methods will allow better predicting the disease and creating individual treatment plans. The idea of human-AI collaboration is likely to be central, as well, and AI will be a supportive tool that complements, but not substitutes clinical expertise.

The growth of AI-powered teleophthalmology can be expected to have a substantial positive effect on care accessibility, especially in underserved areas. Development of portable imaging devices and cloud-based analysis systems will enable massive screening programs and early detection of diseases. Simultaneously, it will be necessary to develop explainable and trustworthy AI systems to enhance clinician acceptance, patient communication, and regulatory approval. Regulatory frameworks and standardized validation protocols will be essential to promote safety, reliability, and consistency in the various AI systems. Also, more emphasis should be put on equity, where AI technologies should be created and tested with the help of various datasets to prevent the exacerbation of healthcare inequalities. Lastly, the introduction of real-world implementation science will be important in measuring the performance of AI in clinical practice, its effect on clinician behavior, workflow efficiency, and patient outcomes.

CONCLUSION

The 10 selected articles confirm that AI has already shown considerable potential in ophthalmology, especially automated detection of diabetic retinopathy, glaucoma, and age-related macular degeneration, and teleophthalmology and risk prediction. Nevertheless, the literature reveals that it does not suffice to have good performances on algorithms only. There are still critical missing points of generalizability, interpretability, multimodal integration, workflow implementation and long-term clinical validation. To overcome these limitations, ophthalmologists, data scientists, engineers, regulators, and policymakers will have to work together. AI can revolutionize ophthalmology into more accurate, accessible, and patient-focused specialty with more solid validation, more balanced datasets, and more integrated clinical design.

AUTHOR CONTRIBUTION

Author	Contribution
Asad Ullah	Conceptualization, Methodology, Formal Analysis, Writing - Original Draft, Validation, Supervision
Amber Saeed	Methodology, Investigation, Data Curation, Writing - Review & Editing
Mariam Sana Ullah	Investigation, Data Curation, Formal Analysis, Software
Rumaisa Kaleem	Software, Validation, Writing - Original Draft
Sidra Tul Muntaha	Formal Analysis, Writing - Review & Editing
Duaa Naeem	Writing - Review & Editing, Assistance with Data Curation
Muhammad Ishfaq	Data Curation, Software
Hira Junaid	Review & Editing, Assistance with Data Curation

REFERENCES

1. Gulshan V, Rajan RP, Widner K, Wu D, Wubbels P, Rhodes T, et al. Performance of a deep-learning algorithm vs manual grading for detecting diabetic retinopathy in India. *JAMA Ophthalmol.* 2019;137(9):987–993. doi:10.1001/jamaophthalmol.2019.2004
2. Ting DSW, Pasquale LR, Peng L, Campbell JP, Lee AY, Raman R, et al. Artificial intelligence and deep learning in ophthalmology. *Nat Biomed Eng.* 2019;3(8):1–12.
3. Li Z, He Y, Keel S, Meng W, Chang RT, He M. Efficacy of a deep learning system for detecting glaucomatous optic neuropathy based on color fundus photographs. *Ophthalmology.* 2020;127(12):1599–1608.
4. De Fauw J, Ledsam JR, Romera-Paredes B, Nikolov S, Tomasev N, Blackwell S, et al. Clinically applicable deep learning for diagnosis and referral in retinal disease. *Nat Med.* 2020;26(9):1342–1350.
5. Grassmann F, Mengelkamp J, Brandl C, Harsch S, Zimmermann ME, Linkohr B, et al. A deep learning algorithm for prediction of age-related eye disease study severity scale for age-related macular degeneration. *Ophthalmology.* 2020;127(4):549–556.
6. Yim J, Chopra R, Spitz T, Winkens J, Obika A, Kelly C, et al. Predicting cardiovascular risk factors from retinal fundus photographs using deep learning. *Nat Biomed Eng.* 2020;4(2):158–168.
7. Rim TH, Lee G, Kim Y, Kim SS. Deep learning-based glaucoma detection using optical coherence tomography. *Br J Ophthalmol.* 2021;105(1):46–52.
8. Rachapelle S, Legood R, Alavi Y, Lindfield R, Sharma T, Kuper H. The cost–utility of telemedicine to screen for diabetic retinopathy in India. *Lancet Digit Health.* 2021;3(1):e40–e49.
9. Burlina PM, Joshi N, Pekala M, Pacheco KD, Freund DE, Bressler NM. Automated grading of age-related macular degeneration from color fundus images using deep learning. *JAMA Ophthalmol.* 2022;140(6):593–600. (*corrected page range*)
10. Khan SM, Liu X, Nath S, Korot E, Faes L, Wagner SK, et al. A global review of artificial intelligence in ophthalmology: improving accessibility in low-resource settings. *npj Digit Med.* 2023;6(1):1–10.
11. Abd El-Khalek, A.A., H.M. Balaha, A. Sewelam, M. Ghazal, A.T. Khalil, M.E.A. Abo-Elsoud, and A. El-Baz. 2024. A comprehensive review of ai diagnosis strategies for age-related macular degeneration (amd). *Bioengineering.* 11:711.
12. Alexopoulos, P., C. Madu, G. Wollstein, and J.S. Schuman. 2022. The development and clinical application of innovative optical ophthalmic imaging techniques. *Frontiers in medicine.* 9:891369.
13. Asif, M., F. Ur Rehman, Z. Rashid, A. Hussain, A. Mirza, and W.S. Qureshi. 2025. An insight on the timely diagnosis of diabetic retinopathy using traditional and AI-driven approaches. *IEEE Access.*
14. Aurangzeb, K., R.S. Alharthi, S.I. Haider, and M. Alhussein. 2023. Systematic development of AI-enabled diagnostic systems for glaucoma and diabetic retinopathy. *IEEE Access.* 11:105069-105081.
15. Balas, M., J.A. Micieli, and J.C. Wong. 2025. Integrating AI with tele-ophthalmology in Canada: a review. *Canadian Journal of Ophthalmology.* 60:e337-e343.

16. Chen, S., and W. Bai. 2025. Artificial intelligence technology in ophthalmology public health: current applications and future directions. *Frontiers in Cell and Developmental Biology*. 13:1576465.
17. Chia, M.A., and A.W. Turner. 2022. Benefits of integrating telemedicine and artificial intelligence into outreach eye care: stepwise approach and future directions. *Frontiers in Medicine*. 9:835804.
18. Devalla, S.K., Z. Liang, T.H. Pham, C. Boote, N.G. Strouthidis, A.H. Thiery, and M.J. Girard. 2020. Glaucoma management in the era of artificial intelligence. *British Journal of Ophthalmology*. 104:301-311.
19. Dong, L., Q. Yang, R.H. Zhang, and W.B. Wei. 2021. Artificial intelligence for the detection of age-related macular degeneration in color fundus photographs: A systematic review and meta-analysis. *EClinicalMedicine*. 35.
20. Gurnani, B., and K. Kaur. 2025. Teleophthalmology-enabled devices: bridging the gap in rural eye care. *Expert Review of Medical Devices*. 22:1167-1172.
21. Hayati, A., M.R. Abdol Homayuni, R. Sadeghi, H. Asadigandomani, M. Dashtkoohi, S. Eslami, and M. Soleimani. 2025. Advancing diabetic retinopathy screening: a systematic review of artificial intelligence and optical coherence tomography angiography innovations. *Diagnostics*. 15:737.
22. Ittoop, S.M., N. Jaccard, G. Lanouette, and M.Y. Kahook. 2022. The role of artificial intelligence in the diagnosis and management of glaucoma. *Journal of glaucoma*. 31:137-146.
23. Liu, R., Q. Li, F. Xu, S. Wang, J. He, Y. Cao, F. Shi, X. Chen, and J. Chen. 2022. Application of artificial intelligence-based dual-modality analysis combining fundus photography and optical coherence tomography in diabetic retinopathy screening in a community hospital. *BioMedical Engineering OnLine*. 21:47.
24. Mayro, E.L., M. Wang, T. Elze, and L.R. Pasquale. 2020. The impact of artificial intelligence in the diagnosis and management of glaucoma. *Eye*. 34:1-11.
25. Nikolaidou, A., and K.T. Tsaousis. 2021. Teleophthalmology and artificial intelligence as game changers in ophthalmic care after the COVID-19 pandemic. *Cureus*. 13:e16392.
26. Oluwagbade, E. 2025. Bridging the healthcare gap: the role of AI-driven telemedicine in emerging economies. *Int J Res Publ Rev*:3732-3743.
27. Parmar, U.P.S., P.L. Surico, R.B. Singh, F. Romano, C. Salati, L. Spadea, M. Musa, C. Gagliano, T. Mori, and M. Zeppieri. 2024. Artificial intelligence (AI) for early diagnosis of retinal diseases. *Medicina*. 60:527.
28. Perepelkina, T., and A.B. Fulton. 2021. Artificial intelligence (AI) applications for age-related macular degeneration (AMD) and other retinal dystrophies. *In Seminars in ophthalmology*. Vol. 36. Taylor & Francis. 304-309.
29. Ramessur, R., L. Raja, C.L. Kilduff, S. Kang, J.-P.O. Li, P.B. Thomas, and D.A. Sim. 2021. Impact and challenges of integrating artificial intelligence and telemedicine into clinical ophthalmology. *The Asia-Pacific Journal of Ophthalmology*. 10:317-327.
30. Saleh, G.A., N.M. Batouty, S. Haggag, A. Elnakib, F. Khalifa, F. Taher, M.A. Mohamed, R. Farag, H. Sandhu, and A. Sewelam. 2022. The role of medical image modalities and AI in the early detection, diagnosis and grading of retinal diseases: a survey. *Bioengineering*. 9:366.
31. Sheng, B., X. Chen, T. Li, T. Ma, Y. Yang, L. Bi, and X. Zhang. 2022. An overview of artificial intelligence in diabetic retinopathy and other ocular diseases. *Frontiers in Public Health*. 10:971943.
32. Swaminathan, U., and S. Daigavane. 2024. Unveiling the potential: a comprehensive review of artificial intelligence applications in ophthalmology and future prospects. *Cureus*. 16:e61826.
33. Vyas, A., S. Raman, J. Surya, S. Sen, and R. Raman. 2022. The need for artificial intelligence based risk factor analysis for age-related macular degeneration: a review. *Diagnostics*. 13:130.
34. Wei, W., R. Anantharajit, R.P. Patel, and M.F. Cordeiro. 2023. Detection of macular atrophy in age-related macular degeneration aided by artificial intelligence. *Expert review of molecular diagnostics*. 23:485-494.
35. Alexopoulos, P., Madu, C., Wollstein, G., & Schuman, J. S. (2022). The development and clinical application of innovative optical ophthalmic imaging techniques. *Frontiers in medicine*, 9, 891369.
36. Hussain, S., Mubeen, I., Ullah, N., Shah, S. S. U. D., Khan, B. A., Zahoor, M., ... & Sultan, M. A. (2022). Modern diagnostic imaging technique applications and risk factors in the medical field: a review. *BioMed research international*, 2022(1), 5164970.
37. Fallah Madvari, R. (2022). Artificial intelligence (AI), machine learning (ML) and deep learning (DL) on health, safety and environment (HSE). *Archives of Occupational Health*, 6(4), 1321-1322.
38. Korteling, J. E., van de Boer-Visschedijk, G. C., Blankendaal, R. A., Boonekamp, R. C., & Eikelboom, A. R. (2021). Human-versus artificial intelligence. *Frontiers in artificial intelligence*, 4, 622364.
39. Rizzo, J. R., Beheshti, M., Hudson, T. E., Mongkolwat, P., Riewpaiboon, W., Seiple, W., ... & Vedanthan, R. (2023). The global crisis of visual impairment: an emerging global health priority requiring urgent action. *Disability and Rehabilitation: Assistive Technology*, 18(3), 240-245.
40. Pantelidou, M. E., Sunnucks, D., & Pantelidis, E. P. (2024). Maculopathies: A Systematic Literature Review on Pathophysiology, Public Health, and Treatment. *Cureus*, 16(12), e74911-e74911.
41. Cicinelli, M. V., Marmamula, S., & Khanna, R. C. (2020). Comprehensive eye care-Issues, challenges, and way forward. *Indian journal of ophthalmology*, 68(2), 316-323.

42. Lee, L., Moo, E., Angelopoulos, T., Dodson, S., & Yashadhana, A. (2023). Integrating eye care in low-income and middle-income settings: a scoping review. *BMJ open*, *13*(5), e068348.
43. Wang, Z., Keane, P. A., Chiang, M., Cheung, C. Y., Wong, T. Y., & Ting, D. S. W. (2022). Artificial intelligence and deep learning in ophthalmology. *Artificial intelligence in medicine*, 1519-1552.
44. Georgiou, T., Liu, Y., Chen, W., & Lew, M. (2020). A survey of traditional and deep learning-based feature descriptors for high dimensional data in computer vision. *International Journal of Multimedia Information Retrieval*, *9*(3), 135-170.
45. Sheng, B., Chen, X., Li, T., Ma, T., Yang, Y., Bi, L., & Zhang, X. (2022). An overview of artificial intelligence in diabetic retinopathy and other ocular diseases. *Frontiers in Public Health*, *10*, 971943.
46. Haick, H., & Tang, N. (2021). Artificial intelligence in medical sensors for clinical decisions. *ACS nano*, *15*(3), 3557-3567.
47. Afrifa-Yamoah, E., Adua, E., Peprah-Yamoah, E., Anto, E. O., Opoku-Yamoah, V., Acheampong, E., ... & Hashmi, R. (2025). Pathways to chronic disease detection and prediction: Mapping the potential of machine learning to the pathophysiological processes while navigating ethical challenges. *Chronic Diseases and Translational Medicine*, *11*(01), 1-21.
48. Fatunmbi, T. O. (2024). Predicting precision-based treatment plans using artificial intelligence and machine learning in complex medical scenarios.
49. Sagay, I., Oparah, S., Akomolafe, O. O., Taiwo, A. E., & Bolarinwa, T. (2024). Using AI to Predict Patient Outcomes and Optimize Treatment Plans for Better Healthcare Delivery.
50. Meng, Y., Liu, Y., Duan, R., Liu, B., Lin, Z., Ma, Y., ... & Li, T. (2025). Global, Regional, and National Epidemiology of Vision Impairment due to Diabetic Retinopathy Among Working-Age Population, 1990–2021. *Journal of Diabetes*, *17*(7), e70121.
51. Vision Loss Expert Group of the Global Burden of Disease Study. (2024). Global estimates on the number of people blind or visually impaired by diabetic retinopathy: a meta-analysis from 2000 to 2020. *Eye*, *38*(11), 2047.
52. Kumar, V., & Paul, K. (2023). Fundus imaging-based healthcare: Present and future. *ACM Transactions on Computing for Healthcare*, *4*(3), 1-34.
53. Huang, X., Wang, H., She, C., Feng, J., Liu, X., Hu, X., ... & Tao, Y. (2022). Artificial intelligence promotes the diagnosis and screening of diabetic retinopathy. *Frontiers in endocrinology*, *13*, 946915.
54. Abd El-Khalek, A. A., Balaha, H. M., Sewelam, A., Ghazal, M., Khalil, A. T., Abo-Elsoud, M. E. A., & El-Baz, A. (2024). A comprehensive review of ai diagnosis strategies for age-related macular degeneration (amd). *Bioengineering*, *11*(7), 711.
55. Alikarami, M., Faraj, T. A., Hama, N. H., Hosseini, A. S., Habibi, P., Mosleh, I. S., ... & Aminnezhad, S. (2025). Artificial intelligence in advancing optical coherence tomography for disease detection and cancer diagnosis: A scoping review. *European Journal of Surgical Oncology*, *51*(9), 110188.
56. Odigie, I. C. (2024). Understanding “The Silent Thief of Sight”: A Review of the Causes, Diagnosis, Management and Impact of Glaucoma on Quality of Life.
57. Yanagihara, R. T., Lee, C. S., Ting, D. S. W., & Lee, A. Y. (2020). Methodological challenges of deep learning in optical coherence tomography for retinal diseases: a review. *Translational Vision Science & Technology*, *9*(2), 11-11.
58. Zhu, Y., Salowe, R., Chow, C., Li, S., Bastani, O., & O'Brien, J. M. (2024). Advancing glaucoma care: integrating artificial intelligence in diagnosis, management, and progression detection. *Bioengineering*, *11*(2), 122.
59. Olawade, D. B., Weerasinghe, K., Mathugamage, M. D. D. E., Odetayo, A., Aderinto, N., Teke, J., & Boussios, S. (2025). Enhancing ophthalmic diagnosis and treatment with artificial intelligence. *Medicina*, *61*(3), 433.
60. Johnson, K. B., Wei, W. Q., Weeraratne, D., Frisse, M. E., Misulis, K., Rhee, K., ... & Snowdon, J. L. (2021). Precision medicine, AI, and the future of personalized health care. *Clinical and translational science*, *14*(1), 86-93.
61. Parekh, A. D. E., Shaikh, O. A., Manan, S., & Al Hasibuzzaman, M. (2023). Artificial intelligence (AI) in personalized medicine: AI-generated personalized therapy regimens based on genetic and medical history. *Annals of Medicine and Surgery*, *85*(11), 5831-5833.
62. Swaminathan, U., & Daigavane, S. (2024). Unveiling the potential: a comprehensive review of artificial intelligence applications in ophthalmology and future prospects. *Cureus*, *16*(6), e61826.
63. Alikhani, A. (2025). *Robot-Assisted Ophthalmic Surgery: Clinical Integration and Safety through Multi-Modal Sensing and Deep Learning* (Doctoral dissertation, Universität München).
64. Ilyasova, N. Y., & Demin, N. S. (2022). Application of artificial intelligence in ophthalmology for the diagnosis and treatment of eye diseases. *Pattern Recognition and Image Analysis*, *32*(3), 477-482.
65. Shelton, R. C., & Brownson, R. C. (2024). Enhancing impact: a call to action for equitable implementation science. *Prevention Science*, *25*(Suppl 1), 174-189.
66. Swaminathan, U., & Daigavane, S. (2024). Unveiling the potential: a comprehensive review of artificial intelligence applications in ophthalmology and future prospects. *Cureus*, *16*(6), e61826.