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Review Article

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Artificial Intelligence in Infertility Management: A Narrative Review of Current Evidence

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Abstract

In recent years, artificial intelligence (AI) has become a powerful tool in various aspects of our daily lives. One of the most particular areas revolutionized by AI is medicine. Reproductive medicine is no exception to this integration. A narrative review was conducted to evaluate the current applications of AI-powered tools in the management of infertility. Searches were performed on October 25th, 2025, in PubMed, Scopus, Web of Science, Google Scholar, Embase, Cochrane Library, and IEEE Xplore using predefined keywords and Boolean operators. After duplicate removal, screening, and eligibility assessment, original English-language studies relevant to AI-assisted infertility management were included for analysis. Our search identified 18 studies published between 2013 and 2025. Embryo selection and implantation prediction in in vitro fertilization (IVF) and intracytoplasmic sperm injection (ICSI) were the most common applications (8 studies), with AI models demonstrating superior performance compared to embryologists in several studies. The STORK deep neural network also demonstrated high accuracy in blastocyst quality assessment, while machine learning models showed promise in predicting ovarian reserve and fertilization outcomes. Other applications included ovarian stimulation optimization (3 studies), male infertility assessment (2 studies), and broader reproductive outcomes including live birth and miscarriage prediction (5 studies). AI shows promising potential to support infertility management by improving embryo selection, ovarian stimulation, assessment of male infertility, and broader reproductive outcomes. To ensure safe clinical adoption, future work must prioritize multicenter prospective trials, transparency, and standardized frameworks.

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Introduction

In recent years, artificial intelligence (AI) has become a powerful tool in various aspects of our daily lives. One of the most particular areas revolutionized by AI is medicine (1-4), in which AI has the capability of addressing complex challenges both in diagnosis and therapy. Reproductive medicine, as an evolving branch of medicine concerned with the clinical management of infertility, is no exception to this integration (5). Infertility affects approximately 9 to 15% of couples across the world and is associated with profound physical, emotional, and financial complications (6). While traditional diagnostic and treatment approaches often depend on subjective assessments and rigid protocols that fail to reflect unique variations among patients, AI holds immense potential to transform this matter. By utilizing large-scale data and recognizing intricate patterns via algorithms, AI presents an opportunity to advance infertility care (7). Such progress

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has the potential to advance diagnostic precision, support individualized care, and yield more effective treatment outcomes (7).

Many subtypes of AI can aid in this integration, consisting of machine learning (ML), deep learning (DL), natural language processing (NLP), and computer vision. These technologies support areas such as image analysis, treatment prediction and planning, embryo selection in IVF, and the discovery of fertility biomarkers (5). Predicting semen parameters—such as sperm concentration and motility—based on environmental factors and lifestyle is another significant task that can be accomplished using AI-based decision support tools (8). Similarly, deep learning models have demonstrated high accuracy in selecting embryos for transfer, showing potential to support embryo prioritization in IVF (9).

Despite the aforementioned advancements, significant challenges remain. Ethical concerns, data privacy issues, validation requirements, and the essential need for a structured framework are among the notable instances. Additionally, since clinicians depend on transparent decision-making pathways, the nature of many AI models and their interpretability issues continue to delay their acceptance and integration into clinical practice (10). The current literature on this topic is fragmented and lacks a comprehensive review of AI's effectiveness, implementation challenges, and future directions in infertility care. This narrative review was conducted to evaluate the current applications of AI-powered tools and algorithms in the diagnosis and management of infertility, and highlight its potential benefits, limitations, and future directions. By synthesizing existing evidence, our main purpose is to establish a foundation for further development and clinical application of AI-driven solutions in reproductive medicine.

Methods

In this narrative review, studies that focus on the use of AI and AI-powered tools to aid the diagnosis and management of infertility were examined. The study's defined keywords were searched using online sources such as PubMed/MEDLINE, Web of Science (WoS), Scopus, Embase, Cochrane Library, Google Scholar, and IEEE Xplore. To identify all relevant publications, comprehensive search queries were created that combined the pertinent keywords using Boolean operators. The search was completed on October 25th, 2025. Two keywords and their synonyms were used, applying one search strategy as detailed below in table 1. The results were compiled in an EndNote library, with duplicates removed. Following this, screening, selection, and data extraction steps were conducted.

The following search query was applied in the PubMed/MEDLINE database: ((Infertility [Title/Abstract] OR "Assisted reproductive technology" [Title/Abstract] OR IVF [Title/Abstract] OR "Embryo selection" [Title/Abstract] OR "Sperm analysis" [Title/Abstract] OR "Ovarian reserve" [Title/Abstract] OR Subfertility [Title/Abstract] OR Sterility [Title/Abstract]) AND ("Artificial intelligence" [Title/Abstract] OR "Machine learning" [Title/Abstract] OR "Deep learning" [Title/ Abstract] OR "Neural network" [Title/Abstract] OR "Computer vision" [Title/Abstract] OR "Predictive modeling" [Title/Abstract] OR Algorithm [Title/Abstract] OR "Natural language processing" [Title/Abstract] OR "Computer reasoning" [Title/Abstract] OR "Convolutional neural network" [Title/Abstract])).

This phase was divided into two distinct parts. Initially, two researchers reviewed the titles and abstracts of the articles to determine their relevance to the study's concept. In the second part, the researchers carefully reviewed the full texts of the screened articles. Publications that fulfilled the eligibility criteria were then selected for data extraction.

Original studies, written in English, published

Table 1. Overview of keywords

Groups	Keywords	Synonyms
Group 1		
	AI	- Artificial intelligence - Machine learning - Deep learning - Neural network - Computer vision - Predictive modeling - Algorithm - Natural language processing - Computer reasoning - Convolutional neural network
Group 2		
	Infertility	- Infertility - Assisted reproductive technology - IVF - Embryo selection - Sperm analysis - Ovarian reserve - Subfertility - Sterility

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between 2013 and 2025, with relevance to the subject of review, were included. Review articles, case series, case reports, duplicate publications, conference abstracts, opinion pieces, editorial letters, preprints, abstracts lacking accessible full texts, articles not written in English, and articles not pertinent to the study's aim were excluded. After removing duplicates using referencing software, the screening process of titles and abstracts and then the full text of the articles was carried out using a semi-automated workflow by two independent authors.

Results

A total of 4376 records were recognized through a research strategy. After removing 505 duplicates, 3871 titles and abstracts were screened, of which 3561 were removed due to lack of relevance to the topic, and 310 articles remained for full-text review. In the next phase, 292 records were excluded after full-text review, and finally, 18 studies met the eligibility criteria and were included in the final review.

After finalizing the screening process, 18 studies met the eligibility criteria for our review and were scrutinized. These studies were explored, aiming to extract data such as the year they were conducted, the country of origin, their main objectives and study type, the AI subset that was utilized in the study, population, and finally, the key points and main conclusions. The findings are presented in table 2. The included studies were primarily conducted in China, followed by the USA and Australia, with the remainder originating from various countries across Asia, Europe, and the Americas (Figure 1).

Among the various AI technologies used, machine learning was the most prevalent, appearing in 10 studies. Deep learning was utilized in six studies, and a convolutional neural network was employed in two studies. Artificial neural networks and deep neural networks were used in one study each. Articles were classified into four categories based on clinical application. The majority focused on "Embryo Selection and Implantation Prediction (IVF/ICSI [intracytoplasmic sperm injection])" (8 studies), followed by "Ovarian Stimulation, Reserve, and Fertilization Outcomes" (3 studies). Other applications included "Male Infertility" (2 studies) and "Broader Reproductive Outcomes" (5 studies) (Figure 2). The 18 studies were conducted between 2013 and 2025, with 2025 being the most frequent year, accounting for 6 studies, followed by 2023 and 2024, accounting for 3 studies each. The majority of studies employed observational designs, often retrospective, though a few randomized controlled trials (RCTs) were also reported.

Discussion

Infertility remains a significant global health concern, affecting millions of couples of reproductive age worldwide, with reported cases and clinical detection steadily increasing due to improved awareness and enhanced diagnostic capabilities (27). ARTs serve as the cornerstone of infertility management; however, traditional approaches are often limited by subjective assess-

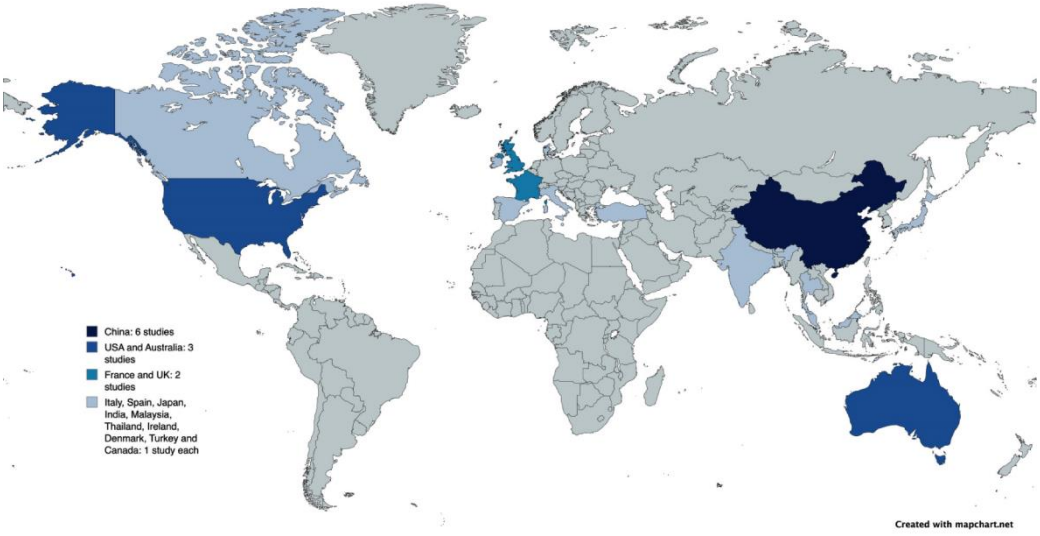


Figure 1. The distribution of studies conducted in each country

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Table 2. Description of the findings reported in eligible studies

Author, year (Ref)	Country	Aim	Study design	Sample size	Population	AI subtype	Application domain	Key findings
Bormann et al. (2020) (11)	USA	To develop and evaluate a deep convolutional neural network for automated embryo selection	Retrospective observational study	3469 records	Embryos from couples undergoing IVF/ ICSI treatments	Deep learning– Convolutional neural network	Embryo selection and implantation prediction (IVF/ICSI)	A CNN trained on static embryo images achieved 90% accuracy in selecting the best-quality embryo, and when trained for implantation potential, it significantly outperformed 15 expert embryologists
Girela et al. (2013) (8)	Spain	To apply AI methods to predict semen parameters based on environmental, lifestyle, and health factors, proposing a potential decision-support tool for assessing male fertility	Retrospective observational study	123 volunteers	Young and healthy men	Artificial neural network	Male infertility	The artificial neural network accurately predicted semen parameters, particularly sperm concentration and, to a lesser extent, motility, showing promise as a tool for early diagnosis of seminal disorders and for selecting potential semen donors
Khosravi et al. (2019) (12)	USA	To develop and evaluate a deep neural network (STORK) trained on time-lapse images of human embryos to provide an unbiased, automated assessment of blastocyst quality and improve embryo selection in IVF	Retrospective observational study	10,148 embryos	Human embryos from patients undergoing IVF	Deep neural network – Deep learning	Embryo selection and implantation prediction (IVF/ICSI)	The deep neural network (STORK) classified embryo quality with high accuracy, generalized across centers, and outperformed individual embryologists
Koike et al. (2025) (13)	Japan	To develop and validate machine learning models for predicting both the quantity and quality of ovarian reserve using easily obtainable clinical and serum data	Retrospective observational study	442 patients	Women undergoing ART	Machine learning	Ovarian stimulation, reserve, and fertilization outcomes	Machine learning models accurately predicted ovarian reserve, offering a practical tool for ART planning and preconception care
Salih et al. (2025) (14)	Australia, India, Malaysia, Thailand	To develop and evaluate an AI fusion model that integrates clinical patient data with embryo images to improve the prediction of clinical pregnancy and live birth outcomes in IVF/ICSI	Retrospective observational study	1,394 IVF/ICSI cycles	Patients undergoing IVF/ICSI	Multi-layer perceptron - Convolutional neural network	Embryo selection and implantation prediction (IVF/ICSI)	The fusion model integrating clinical and embryo image data outperformed image-only models
Tran et al. (2019) (9)	Australia, Ireland, UK, Denmark	To evaluate whether the deep learning model can predict implantation potential (fetal heart activity)	Retrospective observational study	8836 embryos	Human embryos from IVF patients	Deep learning	Embryo selection and implantation prediction (IVF/ICSI)	The IVY deep learning model predicted implantation (defined as fetal heart activity on ultrasound) with high accuracy, suggesting that it is a reliable tool for embryo selection and may reduce variability in IVF practice

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Contd. Table 2. Description of the findings reported in eligible studies

Author, year (Ref)	Country	Aim	Study design	Sample size	Population	AI subtype	Application domain	Key findings
Uyar et al. (2015) (15)	Turkey, Canada, UK	To develop and evaluate a machine learning–based decision support system that predicts implantation outcomes of individual embryos by combining morphological, patient, and cycle characteristics	Retrospective observational study	2,453 embryos	Women undergoing IVF	Machine learning	Embryo selection and implantation prediction (IVF/ICSI)	The Naïve Bayes–based machine learning model predicted embryo implantation with 80.4% accuracy, outperforming expert embryologists and showing promise as a decision support tool
Wang et al. (2025) (16)	China	To develop and validate machine learning models for predicting fertilization failure in conventional IVF (c-IVF) cycles	Retrospective observational study	691 cycles	Patients undergoing ART treatment	Machine learning	Ovarian stimulation, reserve, and fertilization outcomes	Machine learning models, especially logistic regression, effectively predicted fertilization failure in c-IVF cycles
Yuan et al. (2023) (17)	China	To develop a predictive model combining clinical parameters to assess blastocyst euploidy and live birth outcomes in PGT-A treatments	Retrospective observational study	403 patients	Women undergoing IVF/ICSI with PGT-A	Machine learning	Broader reproductive outcomes (couple classification, polycystic ovary syndrome (PCOS), live birth)	The combined model effectively predicted euploidy, outperforming KIDScore alone
Boucret et al. (2025) (18)	France	To build a deep learning model that predicts embryo implantation by comparing embryos from the same IVF cycle with different outcomes	Cohort study	1580 records	Embryos with known implantation data (KID), obtained from IVF stimulation cycles	Deep learning	Embryo selection and implantation prediction (IVF/ICSI)	The model predicted implantation outcomes with modest accuracy and may serve as a supportive tool to help embryologists refine embryo selection and minimize unnecessary transfers
Liu et al. (2023) (19)	China	To construct and evaluate a machine learning–based model to predict live birth outcomes in women undergoing their first IVF or ICSI treatment	Retrospective cohort study	1857 women	women undergoing their first IVF or ICSI	Machine learning	Broader reproductive outcomes (couple classification, PCOS, live birth)	The study supports ML as a personalized predictive tool to improve counseling, treatment planning, and patient expectations in ART
Tang et al. (2024) (20)	China	To develop an artificial intelligence–based miscarriage prediction (AI-MP) model that predicts pregnancy outcomes before conception using pre-pregnancy serum metabolome and clinical data	Prospective cohort study	481 women	Women of reproductive age with a normal or recurrent miscarriage history	Machine learning	Broader reproductive outcomes (couple classification, PCOS, live birth)	The model demonstrates strong potential for early miscarriage risk assessment and preventive counseling

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Contd. Table 2. Description of the findings reported in eligible studies

Author, year (Ref)	Country	Aim	Study design	Sample size	Population	AI subtype	Application domain	Key findings
Wang et al. (2023) (21)	China	To compare clinical and neonatal outcomes of single-blastocyst transfer (SBT) between AI-assisted embryo selection and manual embryologist evaluation	Prospective cohort trial	250 patients	Women undergoing fresh SBT	Deep learning	Embryo selection and implantation prediction (IVF/ICSI)	The study found that AI-assisted embryo selection significantly improved implantation rates compared to manual evaluation
Zhu et al. (2025) (22)	China	To identify predictive factors of live birth in PCOS patients undergoing fresh embryo transfer and develop machine learning models to improve individualized prognosis and treatment	Retrospective cohort study	1,062 IVF/ICSI cycles	Women with PCOS	Machine learning	Broader reproductive outcomes (couple classification, PCOS, live birth)	The study succeeded in the development of 7 machine learning based models, and XGBoost outperformed the other 6 models
Bachelot et al. (2021) (23)	France	To develop and test the performance of a machine learning powered model that classifies couples who are cases of unexplained infertility	Cross-sectional case-control study	196 couples	Infertile couples with primary idiopathic infertility versus fertile couples	Machine learning	Broader reproductive outcomes (couple classification, PCOS, live birth)	The results indicated that analyzing couples as a single unit provided better discrimination than evaluating men and women separately. The model may serve as a valuable decision-support aid in the field it was developed
Cilia et al. (2025) (24)	Italy	To evaluate the prediction of varicocele and its impact on semen quality via the application of a machine learning model	Case control study	169 patients	Patients with unilateral varicocele and controls	Machine learning	Male infertility	Machine learning improved the classification of varicocele and oligoasthenoteratozoospermia (OAT)
Illingworth et al. (2024) (25)	Australia and Europe	To evaluate the effectiveness of deep learning in selecting the optimal embryo for IVF	Randomized controlled trial	1066 patients	Women undergoing IVF treatment	Deep learning	Embryo selection and implantation prediction (IVF/ICSI)	The trial did not demonstrate non-inferiority of deep learning–based embryo selection compared with standard morphology and prioritization in terms of clinical pregnancy rates
Canon et al. (2024) (26)	USA	To assess IVF outcomes when clinicians used an AI platform to guide the starting FSH dose and timing of trigger injection	Prospective clinical trial study	291 patients	Patients undergoing IVF	Machine learning	Ovarian stimulation, reserve, and fertilization outcomes	The AI platform showed a safe, non-significant trend toward better outcomes, with slightly more mature oocytes and total oocytes, along with reduced FSH use. These results suggest AI can help refine FSH dosing and trigger timing to optimize oocyte yield in IVF

AI: Artificial intelligence, ML: Machine learning, PCOS: Polycystic ovary syndrome, IVF: *In vitro* fertilization, ICSI: Intracytoplasmic sperm injection, DL: Deep learning, CNN: Convolutional neural network, KID: Known implantation data, FSH: Follicle stimulating hormone, OAT: oligoasthenoteratozoospermia, ART: Assisted reproductive technology, SBT: Single blastocyst transfer

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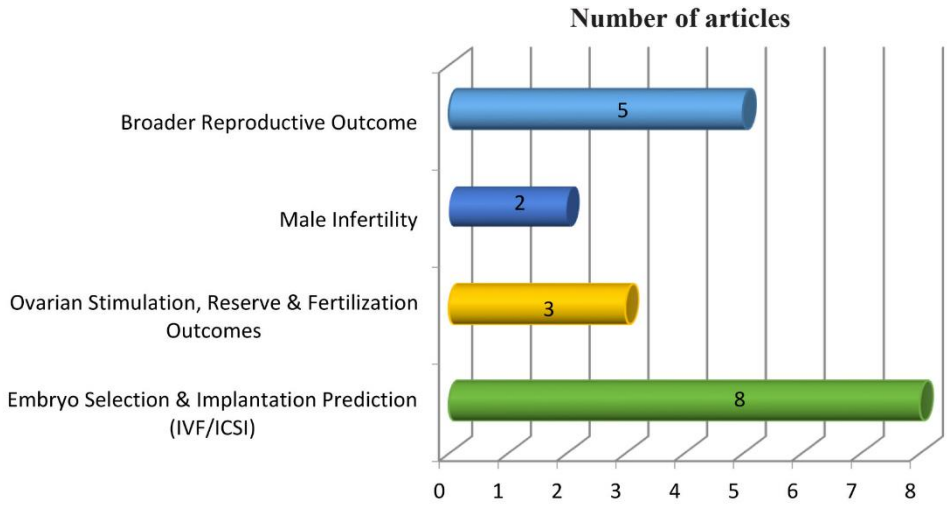


Figure 2. Application domains of AI in reproductive medicine

ments, inter-observer variability, and rigid protocols that fail to account for individual patient variations (28). The integration of AI into this field offers a paradigm shift by introducing objectivity, precision, and personalization into fertility care. Our review synthesizes evidence from 18 studies to map the current landscape of AI applications in infertility management and critically evaluate their potential, limitations, and future directions.

Embryo selection and implantation prediction (IVF/ICSI): Our findings demonstrate that AI has shown promising performance compared with conventional morphology-based grading in several retrospective studies. The high accuracy achieved by CNN-based models (up to 90%) and the STORK deep neural network in blastocyst quality assessment underscores AI's capacity to reduce subjective bias and inter-observer variability (11, 12). This is clinically significant because embryo selection is arguably the most critical determinant of IVF success, and even marginal improvements in accuracy can translate into meaningful increases in live birth rates and reductions in multiple gestation rates.

However, the recent randomized controlled trial by Illingworth et al. (2024) that failed to demonstrate non-inferiority of AI-based selection compared to standard morphology (25), raises important questions about the generalizability and clinical readiness of these tools. This discrepancy between retrospective and prospective findings is not unique to reproductive medicine; it mirrors challenges seen in other AI applications in healthcare, where models trained on curated, single-center datasets often underperform in real-world, multi-center settings (10). The modest predictive accuracy reported by Boucret et al. (2025) (18) further reinforces that model performance is highly context-dependent and influenced by dataset characteristics, imaging protocols, and laboratory conditions.

These findings collectively suggest that while AI holds immense promise for standardizing embryo assessment, its current evidence base is insufficient to recommend widespread clinical adoption without rigorous prospective validation. The absence of standardized benchmarks for embryo quality remains a critical gap, as it impedes direct comparison of AI models and complicates regulatory approval pathways (28).

Ovarian stimulation, reserve, and fertilization outcomes: The integration of machine learning models to predict ovarian reserve and fertilization outcomes represents a promising avenue for personalizing ART protocols. Our review indicates that AI can accurately predict ovarian reserve using routine clinical and biochemical parameters (13), effectively forecast fertilization failure (16), and guide FSH dosing and trigger timing (26). These capabilities are particularly valuable because ovarian stimulation protocols are currently guided by generalized algorithms that often result in suboptimal responses, either through under-stimulation (leading to poor oocyte yield) or over-stimulation (increasing OHSS risk).

The ability to predict ovarian reserve and fertili-

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zation outcomes at the outset of treatment could enable clinicians to stratify patients into risk categories, select optimal stimulation regimens, and avoid unnecessary cycles or cancellation. This aligns with the broader movement toward personalized medicine, where treatment decisions are informed by individual patient characteristics rather than population averages (29). However, as noted by AlSaad et al. (2024) (30), most AI models in this domain are derived from single-center datasets, limiting their generalizability across diverse patient populations and clinical settings.

Emerging AI technologies are moving beyond static predictions toward dynamic, full-cycle stimulation management. By integrating multi-parametric data, these models have the potential to predict individualized responses to agonist/antagonist regimens, refine gonadotropin dosing in real-time, and accurately forecast OHSS risk (30, 31). Compared with conventional clinical stratification tools such as the POSEIDON and Bologna criteria, AI-based systems demonstrate improved precision in differentiating poor and hyper-responders, suggesting that they may eventually replace or augment traditional risk assessment tools.

Male infertility and broader reproductive outcomes: Our review highlights AI's emerging role in male infertility assessment, particularly through automated prediction of semen parameters (8), varicocele classification (24), and potential applications in sperm morphology and DNA fragmentation analysis. These tools could address a significant unmet need, as semen analysis remains largely subjective and variable across laboratories. By introducing standardization and objectivity, AI-powered sperm assessment could improve diagnostic accuracy and facilitate early intervention.

The application of AI to broader reproductive outcomes, including live birth prediction in PCOS patients, couple-level infertility classification (22, 23), and miscarriage risk assessment and live birth outcomes (19, 20), represents an exciting frontier. These studies collectively suggest that AI can synthesize complex, multi-dimensional data (clinical, biochemical, and demographic) to generate individualized prognostic information that could enhance patient counseling, treatment planning, and shared decision-making. The ability to predict live birth outcomes with machine learning models, for example, could help manage patient expectations and guide decisions about whether to pursue additional IVF cycles.

Our findings are broadly consistent with recent systematic reviews and meta-analyses in this field. Wu et al. (2025) (28) similarly noted that AI demonstrates the potential to enhance accuracy and implantation prediction, yet large-scale prospective validation remains limited. Kakkar et al. (2025) (32) and Olawade et al. (2025) (33) emphasized the gap between retrospective AI model development and clinical implementation, highlighting the need for standardized benchmarks, multi-center trials, and regulatory frameworks. The inconsistency between retrospective and prospective findings observed in our review mirrors concerns raised across the broader AI in healthcare literature, where models that perform exceptionally in controlled settings often fail to replicate in real-world clinical environments (10, 34).

The fusion of AI with this field presents both opportunities and ethical challenges. The main issue that leads to skepticism among both patients and clinicians is the "black box" nature of these algorithms. These technologies lack interpretability, and in a setting where the patient is already vulnerable due to the infertility issue at hand, they create an atmosphere of anxiety and helplessness. Transparent decision-making and treatment planning are a necessity. On the other hand, clinicians can either over-rely on AI outputs or dismiss them altogether, consequently worsening the issue (34).

Secondly, small sample sizes and retrospective datasets limit the generalizability of these approaches and introduce various algorithmic biases. Lack of structured frameworks on this integration leaves questions on data privacy unresolved (34). Critically, these technologies risk reinforcing value judgments, such as "good" versus "bad" embryos and lead to social consequences of AI-driven embryo ranking (34). The ethical concerns in this area extend beyond the "black box" nature. Researchers must also scrutinize issues of interpretability, clinical accountability, and algorithmic bias. Factors such as limited data diversity and the absence of regulatory frameworks should be addressed before moving further. AI-powered technologies are a significant augmentation tool, but without proper oversight, biased value judgments still exist. In light of that, the development of a structured and standard framework to clarify clinical responsibility is a crucial requirement to ensure that AI supports, rather than compromises, ethical fertility care (7). To ensure AI becomes an augmentation tool rather than a harmful tool, fu-

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ture directions must focus on the previously mentioned challenges.

A limitation of the current study was the narrow scope of the studies scrutinized. A total of 18 studies may not fully represent the growing body of literature with this focus. English-language studies were only included which raises the probability of selection bias. Eligible studies were mainly single-centered and were mostly retrospective. This restricts the generalizability of evidence compared with large samples. Moreover, sample sizes of included studies were often modest, which exaggerates the aforementioned bias. Furthermore, most AI-powered tools and algorithms have a "black-box" nature, meaning there is no clarity on how a prediction is made by a model. Additionally, no formal risk-of-bias assessment or quality grading (*e.g.*, GRADE) was performed. Thus, the potential for publication bias should also be acknowledged. Finally, the necessity for a regulated framework to address ethical issues of AI integration remains.

The fusion of AI with the realm of infertility management holds great promise for revolutionizing this subspecialty. Future studies should focus more on multicenter trials with larger sample sizes and standardized frameworks to validate AI-powered models across diverse populations. To gain clinicians' trust, a more structured framework for ethics, data privacy, and transparency must be implemented. By addressing these issues, the way towards the utilization of AI-based models from experimental studies into clinical routine will be paved.

Conclusion

This review shows that AI—particularly machine learning and deep learning—has been applied across four domains of infertility management: embryo selection and implantation prediction, ovarian stimulation/reserve and fertilization outcomes, male infertility, and broader reproductive outcomes. Deep learning models such as CNN-based systems and the STORK network achieved high accuracy in blastocyst quality assessment and often outperformed embryologists in retrospective settings; machine learning models predicted ovarian reserve and fertilization failure, and showed promise for live birth and miscarriage prediction. Current evidence supports AI as a decision-support tool that augments—rather than replaces—clinician and embryologist judgment, with multi-center prospective trials and standardized, transparent frameworks needed before routine clinical adoption. To ensure the safe implementation of artificial intelligence in clinical settings, it is recommended that future studies focus on multicenter prospective trials, transparency, and standardized frameworks.

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AI tools were used only for language refinement and improving the manuscript's readability. The authors performed all data collection, interpretation, and referencing without reliance on AI-generated content.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript.

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