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2734 17 Avenue SW,  
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+15878858911  
editorial-office@sciformat.ca

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# INNOVATIVE TECHNOLOGIES IN THE DIAGNOSIS AND TREATMENT OF INFERTILITY: A COMPREHENSIVE REVIEW

**Zuzanna Dobrakowska** (Corresponding Author, Email: z.dobrakowska@gmail.com)

Private practice, Wrocław, Poland

ORCID ID: 0009-0009-2413-6627

**Marzena Swojnóg**

Private practice, Łódź, Poland

ORCID ID: 0009-0002-4363-7389

**Radosław Swędrak**

Private practice, Zgierz, Poland

ORCID ID: 0009-0007-0991-1088

**Jakub Klepacz**

Private practice, Łódź, Poland

ORCID ID: 0009-0009-2448-6790

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## ABSTRACT

Infertility is increasingly recognized as a condition affecting diverse populations and one that requires advanced medical and technological approaches to support effective diagnosis and treatment. In recent years, significant progress in medical sciences and digital technologies has refined the ways infertility is assessed and managed. Contemporary diagnostic methods now include high-resolution imaging, hormonal and genetic testing, microbiome evaluation, and immunological analysis. These advancements enable clinicians to identify reproductive disorders with greater precision.

Artificial intelligence (AI) and robotic systems further support clinical decision-making by improving embryo selection, predicting treatment outcomes, and standardizing laboratory procedures. Advances in assisted reproductive technologies (ART) have expanded therapeutic options for patients who previously had limited chances of achieving pregnancy.

Although technology plays a crucial role in modern infertility care, patient experiences and psychological well-being remain equally important, as treatment can be both emotionally and physically demanding. This review summarizes current knowledge on innovative technologies used in the diagnosis and treatment of infertility and highlights how the continued development of these methods enhances clinical outcomes and patient care.

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## KEYWORDS

Infertility, Assisted Reproductive Technologies, IVF, ICSI, Artificial Intelligence, Digital Twins, Genetic Testing, Microbiome, Reproductive Medicine, Laboratory Automation

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## 1. Introduction

Infertility has become a visible public health challenge, affecting millions of individuals and couples worldwide. According to the World Health Organization (WHO), it is defined as a disorder of the reproductive system characterized by the inability to achieve pregnancy despite regular unprotected intercourse for approximately 12 months (World Health Organization, 2025). For women aged 35 and older, or in cases where clinical indications suggest reduced fertility, this period may be shorter (American Society for Reproductive Medicine, 2023). Infertility is classified as primary, affecting those who have never achieved pregnancy, or secondary, when difficulties conceiving occur after a previous pregnancy. Studies show that as many as one in six people of reproductive age experience infertility at some point in their lives. Although infertility is often viewed primarily as a medical condition, its consequences extend far beyond biological factors, influencing emotional well-being, family planning, and social identity. As a result, it has become an important topic not only in medicine but also in psychology, public health, and the social sciences (Bueno-Sánchez et al., 2024; Hussain et al., 2025).

A number of demographic and societal changes contribute to the growing demand for infertility care. One of the most significant trends is the steady increase in the average age at which individuals choose to have children. Delayed parenthood often related to educational, professional and economic factors directly affects reproductive outcomes, especially in women whose ovarian reserve naturally declines with age (Carson & Kallen, 2021). At the same time, evidence continues to accumulate regarding a global decline in semen quality. Studies indicate reduced sperm concentration, impaired motility, and abnormal morphology across many regions of the world (Brannigan et al., 2024; Peluso et al., 2025).

Another important factor is the economic burden associated with infertility treatment. Many advanced procedures, such as IVF, ICSI, or genetic testing, remain costly and are not routinely reimbursed by national healthcare systems. For many patients, financial considerations influence treatment choice, timing of therapy, and even the decision to undergo diagnostic evaluation (World Health Organization Guideline Development Group, 2025, World Health Organization, 2025).

Over the past decade, remarkable advances in biomedical science and digital innovation have transformed the way infertility is diagnosed and treated. Traditional evaluations have evolved into comprehensive diagnostic strategies. These methods allow earlier and more accurate identification of reproductive disorders. Concurrently, developments in molecular biology and genomics have shed new light on mechanisms such as subtle hormonal irregularities, sperm DNA fragmentation, impaired endometrial receptivity, and epigenetic alterations.

Despite these technological advances, infertility remains a deeply personal experience, often accompanied by emotional strain, uncertainty, and social stress. Many individuals describe their treatment journey as overwhelming, underscoring the need for patient-centered care that addresses both the biological and psychosocial dimensions of infertility (Malina, 2024; Schwerdtfeger & Shreffler, 2009).

## 2. Methods

This article is a narrative review and was developed based on an analysis of the latest scientific research on the diagnosis and treatment of infertility, as well as the application of innovative technologies in reproductive medicine. To ensure the accuracy and currency of the review, a systematic literature search was conducted in databases including PubMed, Scopus, ScienceDirect, and SpringerLink, as well as in open-access scientific repositories and recent reports from public health organizations such as the WHO.

The review encompassed publications from 2009 to 2025, with particular focus on clinical studies, review articles, medical society guidelines (ASRM, EAU), and reports addressing emerging technologies such as artificial intelligence, laboratory automation, microbiome analysis, and molecular techniques.

The literature search employed a set of keywords corresponding to the main thematic areas discussed in the article, including: *infertility, assisted reproductive technologies, IVF, ICSI, AI in reproduction, robotics in ART, microbiome, genetic testing, digital twins, endometrial receptivity, sperm DNA fragmentation*.

### Inclusion criteria:

- peer-reviewed publications,
- articles addressing infertility diagnostics, epidemiology, etiology, or treatment,
- studies describing innovative clinical, laboratory, or digital technologies,
- availability of full-text versions.

**Exclusion criteria:**

- animal studies,
- papers focused solely on technical aspects without clinical relevance,
- older publications whose conclusions have been superseded by contemporary recommendations.

In total, approximately 24 publications were analyzed and synthesized narratively. The methodological aim was to present the current state of knowledge, identify the most significant technological trends, and outline future directions in reproductive medicine.

**3. Epidemiology**

Infertility represents a significant global health issue, carrying substantial medical, demographic, and social implications. Its widespread occurrence across all countries, regardless of income level, indicates that infertility is a universal challenge rather than a condition confined to specific regions of the world (World Health Organization, 2025).

Traditional epidemiological estimates suggest that approximately 40% of infertility cases can be attributed to female factors, 40% to male factors, and about 20–30% to mixed or unexplained causes. However, recent studies highlight the increasing importance of male infertility (Brannigan et al., 2024). Reports documenting declines in semen concentration and motility, alongside heightened exposure to endocrine-disrupting chemicals, thermal stress, and lifestyle-related factors, suggest that male reproductive health may be more at risk than previously assumed (Peluso et al., 2025).

A range of broader demographic and societal trends also influences global infertility rates. Delayed parenthood remains a major demographic factor. In many countries, individuals face growing pressure to achieve financial stability before starting a family, which often leads to postponement of reproductive decisions. Unfortunately, age-related declines in fertility in both women and men mean that such decisions have a direct impact on infertility statistics (Carson & Kallen, 2021).

Lifestyle factors and urbanization introduce additional risks. Individuals living in large cities are more frequently exposed to air pollution, shift work, heat stress, and limited access to green spaces. Lifestyle behaviors, including smoking, alcohol consumption, sedentary habits, and unhealthy diets can all disrupt hormonal balance and reproductive capacity. Other global trends, such as rising rates of obesity, chronic diseases, sexually transmitted infections, also play a significant role (de Santiago & Polanski, 2022; Ghorbani et al., 2023).

Marked geographical differences in reported infertility rates often reflect disparities in access to healthcare, availability of diagnostic services, and cultural attitudes toward seeking fertility evaluation. In high-resource countries, assisted reproductive technologies (ART) have improved the detection and classification of infertility, whereas in low-resource settings the condition often remains underdiagnosed or untreated. This imbalance underscores the need to develop accessible, cost-effective, and innovative diagnostic tools (Gitau et al., 2025; World Health Organization, 2025).

**4. Etiology**

Infertility is a multifactorial condition resulting from the interaction of biological, environmental, behavioral, and systemic determinants. Contemporary research shows that reproductive dysfunctions often involve subtle molecular, immunological, or metabolic disturbances that previously remained undetectable using conventional diagnostic methods (de Santiago & Polanski, 2022; Peluso et al., 2025). Advances in genomics, high-resolution imaging, and artificial intelligence (AI) have significantly improved the identification of underlying causes. The main etiological categories include female factors, male factors, mixed infertility, and cases that remain unexplained despite comprehensive evaluation.

**4.1. Female-factor infertility**

Female infertility most commonly arises from ovulatory disorders, diminished ovarian reserve, and abnormalities affecting the structure or function of the reproductive tract.

Ovulatory dysfunction is frequently associated with polycystic ovary syndrome (PCOS), thyroid disorders, and hyperprolactinemia. All of these conditions disrupt hormonal pathways essential for dominant follicle maturation and ovulation. Age-related fertility decline remains the dominant factor contributing to reduced reproductive capacity, leading to poorer oocyte quality, diminished ovarian reserve, and a greater risk of chromosomal abnormalities (Carson & Kallen, 2021). Structural abnormalities also play a significant role. Fallopian tube obstruction often caused by prior pelvic infections or adhesions may prevent fertilization.

Endometriosis contributes through chronic inflammation, distorted pelvic anatomy, and altered endometrial receptivity. Additional uterine abnormalities, including fibroids, polyps, and congenital malformations, may impair implantation or increase the likelihood of early pregnancy loss (Radwan et al., 2017).

#### 4.2. Male-factor infertility

Male infertility primarily results from impaired spermatogenesis, abnormal semen parameters, or disruptions in hormonal regulation.

Spermatogenic dysfunction may stem from genetic abnormalities such as Y-chromosome microdeletions or Klinefelter syndrome, as well as structural issues such as varicocele. Environmental and occupational exposures including pesticides, endocrine-disrupting chemicals, heavy metals, and heat stress are increasingly recognized as important contributors to reduced sperm concentration, motility, and DNA integrity (Brannigan et al., 2024; Peluso et al., 2025). Recent analyses also identify rising obesity rates and declining physical activity in men as significant epidemiological factors associated with worsening semen quality (Rabijewski, 2019).

#### 4.3. Mixed and unexplained infertility

Mixed infertility, where both partners exhibit identifiable biological factors contributing to reduced fertility, is common and reflects the combined influence of environmental, behavioral, and metabolic determinants in couples. Despite extensive advancements in diagnostics, unexplained infertility remains a substantial clinical challenge. Growing evidence indicates that many previously unexplained cases may result from subtle abnormalities undetectable by traditional methods, such as impaired endometrial receptivity, immunological dysfunctions, sperm DNA fragmentation, epigenetic alterations, and microbiome disturbances (de Santiago & Polanski, 2022; Mapari et al., 2024; Ghorbani et al., 2023). These findings highlight the increasing role of molecular diagnostics and AI-supported analyses in uncovering hidden etiological mechanisms.

#### 4.4. Epigenetic mechanisms in infertility

Recent studies emphasize the role of epigenetic changes in reproductive health. Unlike genetic mutations, epigenetic modifications do not alter the underlying DNA sequence. Instead, they influence how genes are switched on or off, affecting processes such as gamete development, embryo formation, and implantation. These subtle molecular changes may contribute to infertility even when classical diagnostic tests including hormonal profiles and genetic analyses appear normal. Environmental and lifestyle factors can shape epigenetic patterns in both oocytes and sperm. For example, alterations in DNA methylation and histone modifications have been observed in sperm from individuals exposed to air pollution or persistent organic pollutants (Peluso et al., 2025). Similarly, age-related epigenetic drift in oocytes may reduce embryo quality and increase the risk of chromosomal abnormalities, particularly in women conceiving later in life (Carson & Kallen, 2021). Epigenetic abnormalities also influence early embryo development. Research suggests that improper imprinting, disturbed methylation patterns, or dysregulated gene expression may lead to implantation failure or early pregnancy loss (de Santiago & Polanski, 2022). Although epigenetic diagnostics are not yet a routine component of fertility assessment, they represent a promising direction for future research.

### 5. Diagnostics

Diagnostics in infertility has undergone significant transformation over the past decade. Rather than relying solely on a few basic tests, contemporary clinicians integrate imaging, laboratory analyses, molecular tools, and digital technologies to obtain a more comprehensive understanding of each patient's reproductive health (de Santiago & Polanski, 2022; Carson & Kallen, 2021).

#### 5.1. Imaging and laboratory testing supported by technology

Classical diagnostic tools such as hormonal blood tests, semen analysis, and ultrasonography remain essential. High-resolution ultrasound systems can capture subtle details related to ovarian follicles, endometrial thickness, and uterine structure that older devices could not visualize. Three-dimensional imaging and Doppler techniques add further detail by enabling assessment of blood flow, follicle quality, and potential abnormalities that may hinder conception.

In male diagnostics, the shift from manual semen assessment to digital and computer-assisted systems has been particularly impactful. Traditional semen analysis relied heavily on the experience of laboratory personnel. Today, automated Computer-Assisted Sperm Analysis (CASA) systems provide more objective evaluation of sperm concentration, motility, and morphology, analyzing hundreds of sperm cells within

seconds. This not only improves accuracy but also reduces variability between clinics (Mapari et al., 2024; Brannigan et al., 2024).

**Emerging technological extensions:**

- In specialized centers, ultrasound systems augmented with augmented reality (AR) are beginning to appear. These platforms overlay anatomical guidance onto real-time imaging, helping clinicians detect structural abnormalities with greater confidence.
- Some clinics also use cloud-enabled imaging devices that automatically upload scans for AI-assisted analysis and allow remote second opinions (Findikli et al., 2025; Orovou et al., 2025).

**5.2. Molecular, genetic, and microbiome-based diagnostics**

Infertility diagnostics have expanded into molecular and genetic domains. Hormonal and genetic profiling can reveal early signs of diminished ovarian reserve, endocrine dysfunction, or hereditary conditions that may affect reproductive function. These tests support clinicians in predicting potential complications and tailoring treatment more effectively.

Preimplantation genetic testing (PGT), used alongside assisted reproductive technologies, enables assessment of embryos for chromosomal abnormalities prior to transfer into the uterus. For patients experiencing recurrent miscarriages or repeated IVF failure, PGT may serve as a key tool for identifying embryos with the greatest developmental potential (Orovou et al., 2025; Wu et al., 2025).

Another promising area is the analysis of the reproductive microbiome. Recent studies indicate that the balance of microorganisms in the vagina, uterus, or semen can influence fertility, embryo implantation, and even miscarriage risk (Ghorbani et al., 2023; de Santiago & Polanski, 2022). Such approaches are particularly valuable for couples who have undergone multiple treatments without a clear diagnosis.

**Emerging technological extensions:**

- Modern laboratories increasingly employ metabolomic and proteomic assays to noninvasively assess endometrial receptivity.
- Emerging RNA-based diagnostics analyze gene expression signatures in uterine fluid, offering an alternative to more invasive biopsies.
- "lab-on-a-chip" platforms that miniaturize diagnostic workflows and enable rapid analysis of hormones, semen parameters, or endometrial markers within minutes, without requiring large laboratory facilities (Peluso et al., 2025).

**5.3. Artificial intelligence in reproductive diagnostics**

Artificial intelligence represents a major advancement in infertility diagnostics. One of the best-known applications of AI in reproductive medicine is embryo selection. Time-lapse incubators capture continuous images of developing embryos. AI models analyze subtle developmental patterns and help identify embryos with the highest likelihood of successful implantation and pregnancy. Many clinics report that AI-assisted evaluation improves consistency and reduces the subjectivity inherent in manual assessment (Findikli et al., 2025; Skweres-Kuchta et al., 2025; Wu et al., 2025).

AI also enhances imaging diagnostics. Models can detect ovarian or uterine abnormalities that may be overlooked by human observers, especially at early stages. Predictive algorithms can analyze patient history, hormone levels, and semen parameters to estimate the likelihood of IVF success and suggest personalized treatment strategies (Orovou et al., 2025; Medenica et al., 2022). In male diagnostics, AI-supported semen analysis systems help identify complex motility patterns, DNA fragmentation risk, and morphological defects. These tools provide detailed insights that were not possible with manual assessment.

**Emerging technological extensions:**

- **Clinical decision support systems (DSS):** integrate imaging, genetic data, hormonal trends, the microbiome, and patient history into a unified platform that provides personalized diagnostic suggestions. (Findikli et al., 2025)
- **Digital twins:** early models of virtual menstrual cycles simulate hormonal responses and ovarian dynamics, enabling clinicians to test diagnostic interpretations without performing invasive procedures (Medenica et al., 2022).

#### 5.4. Automation, robotics, and digital monitoring systems

Robotics and automation are becoming increasingly widespread in embryology laboratories. Robotic arms can perform delicate tasks such as micromanipulation of oocytes and embryos, precise pipetting, cryopreservation, and sample preparation. These systems reduce the risk of human error, an essential improvement in procedures requiring high accuracy and precise timing.

Another important innovation is the time-lapse incubator. These devices allow embryos to develop under stable conditions with continuous monitoring via integrated imaging systems. This minimizes the need to remove embryos from the incubator for observation, improving their development while providing clinicians with uninterrupted insight into growth dynamics (Findikli et al., 2025; Wu et al., 2025).

Digital health tools also play a growing role in diagnostics. Mobile applications for menstrual-cycle tracking, wearable devices that measure body temperature or hormonal fluctuations, and remote monitoring platforms allow patients to actively participate in the diagnostic process. These tools provide clinicians with real-time data, making cycle monitoring more accurate and accessible (Ghorbani et al., 2023; Hussain et al., 2025).

##### Emerging technological extensions:

- Wearable biosensors detect not only temperature but also LH surges, progesterone metabolites, and heart-rate variability associated with ovulation.
- Smart home fertility monitors synchronize with clinic databases, enabling real-time cycle tracking without the need for in-person visits.
- Integrated laboratory networks automatically log device parameters, environmental conditions, and sample metadata, improving traceability and quality control

#### 6. Treatment

Treatment of infertility has undergone profound changes over the past several decades, evolving from a relatively limited set of options to a wide range of therapeutic strategies. Contemporary treatment focuses not only on overcoming biological barriers but also on improving patient comfort, reducing treatment-related burden, and personalizing care.

##### 6.1. Lifestyle interventions, pharmacological treatment, and hormonal therapy

Before advanced procedures are considered, many patients benefit from lifestyle modifications and targeted medical therapies. Improvements in diet, physical activity, and sleep patterns can support hormonal balance. Reducing smoking and alcohol consumption also influences reproductive outcomes. For some patients, these measures alone may improve fertility. When underlying medical issues are identified, treatment may include hormonal therapy, ovulation induction, or medications regulating thyroid hormones or prolactin levels. Women with ovulatory disorders, such as polycystic ovary syndrome (PCOS), often respond well to follicle-stimulating medications. In men, hormonal therapy or antioxidant supplementation can improve semen quality depending on the cause of infertility (Rabijewski, 2019). Although these interventions may appear simple, they remain one of the foundational pillars of fertility care.

##### 6.1.1. Pharmacological treatment of female infertility

Pharmacotherapy remains a key component of managing female infertility, particularly in cases of ovulatory dysfunction. The most common approach is ovulation induction, aimed at stimulating the development of a dominant follicle and the release of a mature oocyte.

- **Clomiphene citrate** is a classic first-line medication. It acts by blocking estrogen receptors in the hypothalamus, increasing FSH and LH secretion, which promotes follicular growth and ovulation. Although effective, its anti-estrogenic effects may influence endometrial thickness.
- **Letrozole**, an aromatase inhibitor, is now recommended as a more effective alternative, especially for women with PCOS. Unlike clomiphene, it does not negatively affect the endometrium (Radwan et al., 2017; Saleem Azam et al., 2025).

When oral therapy is ineffective, **gonadotropins** are used. These directly stimulate the ovaries but require careful monitoring due to the risk of ovarian hyperstimulation and multiple pregnancy. In patients with insulin resistance, particularly in PCOS, **metformin** is used as an adjunct therapy. It improves tissue sensitivity to insulin and can indirectly support ovulation.

Pharmacological management must be individualized based on hormonal evaluation, metabolic profile, and previous treatment response.

### **6.1.2. Pharmacological treatment of male infertility**

In the treatment of male infertility, pharmacotherapy plays a more limited role but remains important in selected hormonal or metabolic disorders.

In men with hypogonadotropic hypogonadism, **gonadotropins** (hCG and FSH) are administered to stimulate Leydig and Sertoli cells, improving spermatogenesis. In cases of hyperprolactinemia, which can suppress testosterone production, dopamine agonists (e.g., cabergoline) restore proper hypothalamic–pituitary–testicular regulation. In patients with micronutrient deficiencies or increased oxidative stress, antioxidant supplementation such as vitamin E, coenzyme Q10, or L-carnitine may be beneficial, although clinical evidence remains variable (Rabijewski, 2019; Brannigan et al., 2024).

### **6.2. Surgical treatment and minimally invasive procedures**

Some patients require surgical interventions to correct anatomical problems. Minimally invasive techniques such as laparoscopy and hysteroscopy are widely used to treat endometriosis, fibroids, adhesions, and fallopian tube obstruction. These procedures enable surgeons to restore normal anatomy while reducing recovery time and postoperative discomfort.

In male infertility, microsurgical techniques are particularly important. Procedures such as varicocele repair can improve semen parameters, while micro-TESE allows sperm retrieval in patients with azoospermia. These techniques rely on advanced optics and precise instruments, and their effectiveness has increased with modern equipment (Brannigan et al., 2024; Jankowska & Słowikowska-Hilczer, 2019).

### **6.3. Assisted Reproductive Technologies (ART)**

Assisted reproductive technologies are a cornerstone of infertility treatment. Advances in ART over recent decades have significantly expanded therapeutic possibilities and allowed many patients to achieve pregnancy despite complex or previously unsolvable causes of infertility. Contemporary methods range from minimally invasive procedures, such as intrauterine insemination, to complex laboratory techniques including in vitro fertilization. Technological progress particularly in automation and artificial intelligence has further enhanced their precision and effectiveness.

#### **6.3.1. Intrauterine Insemination (IUI)**

Intrauterine insemination (IUI) is one of the oldest and most widely used ART techniques, serving as a bridge between pharmacological treatment and more advanced procedures. It involves introducing prepared sperm directly into the uterine cavity during the peri-ovulatory period, increasing the concentration of motile sperm at the fertilization site and bypassing barriers associated with cervical mucus.

IUI is used in mild male-factor infertility, idiopathic infertility, ovulatory disorders after successful stimulation, and in cases requiring donor sperm. According to ASRM and ESHRE guidelines, it is considered a first-line procedure in younger patients and in cases where clinical parameters do not immediately warrant IVF (American Society for Reproductive Medicine, 2023). The effectiveness of IUI depends on numerous factors, including sperm quality, female age, and the number of follicles in a given cycle. Due to its low invasiveness, relatively low cost, and favorable safety profile, IUI remains an important part of the therapeutic pathway and often precedes the decision to initiate IVF.

#### **6.3.2. In Vitro Fertilization (IVF)**

In vitro fertilization (IVF) is the primary and most recognizable ART method. The procedure begins with controlled ovarian stimulation to obtain multiple mature oocytes. After retrieval, the oocytes are fertilized in laboratory conditions and the resulting embryos are cultured for several days in incubators that provide stable environmental parameters. Modern innovations have significantly transformed IVF practice. Time-lapse incubators enable continuous embryo observation without opening the incubation chamber, improving culture conditions and allowing analysis of morphokinetics (Findikli et al., 2025; Skweres-Kuchta et al., 2025).

IVF is particularly recommended in tubal-factor infertility, advanced endometriosis, diminished ovarian reserve, repeated IUI failure, and cases requiring preimplantation genetic testing.

#### **6.3.3. Intracytoplasmic Sperm Injection (ICSI)**

Intracytoplasmic Sperm Injection (ICSI) is a technique that revolutionized the treatment of male infertility. It involves the direct injection of a single sperm into the cytoplasm of an oocyte. Supported by advanced microscopes, precise micromanipulators, and robotic assistance, this method enables fertilization even in cases of extremely poor semen parameters (Brannigan et al., 2024; Mapari et al., 2024).

ICSI is also used when semen parameters are normal but previous attempts at conventional fertilization were unsuccessful, as well as in procedures involving surgical sperm retrieval such as micro-TESE. With the introduction of AI-assisted technologies, additional assessments of sperm morphology and DNA integrity are possible, facilitating optimal sperm selection.

#### **6.3.4. Preimplantation Genetic Testing (PGT)**

Preimplantation genetic testing (PGT) has become an integral part of ART, allowing embryos to be assessed for chromosomal abnormalities (PGT-A), monogenic disorders (PGT-M), or structural rearrangements (PGT-SR) prior to transfer. PGT may increase the likelihood of a successful pregnancy, particularly in patients with recurrent miscarriage, implantation failure, or advanced reproductive age.

Modern sequencing technologies and laboratory automation provide high analytical accuracy while minimizing the risk of embryo damage. In selected cases, PGT may shorten treatment duration and reduce the number of IVF cycles required to achieve a healthy pregnancy. These tools not only improve ART outcomes but also enhance reproducibility and safety by reducing reliance on human factors and inter-laboratory variability.

#### **6.4. Psychosocial support in infertility treatment**

Because infertility treatment is often emotionally demanding, psychosocial care plays an essential role. Patients frequently experience stress, uncertainty, and emotional fatigue during prolonged treatment cycles. Psychological counseling, support groups, and integrated mental health services help individuals cope with these challenges and improve overall well-being (Malina, 2024; Schwerdtfeger & Shreffler, 2009). Recent studies also suggest that psychological support may improve treatment adherence and contribute to better clinical outcomes (Hussain et al., 2025).

### **7. Innovations and Future Perspectives in Reproductive Medicine**

Advanced technologies are transforming the field of reproductive medicine, expanding both our understanding of infertility and the range of tools available for its diagnosis and treatment. While current methods such as AI-assisted embryo selection, time-lapse imaging, and advanced genetic testing have already reshaped clinical practice, the coming decade will likely bring even more substantial changes. Many of these innovations aim to make fertility care more precise, less invasive, and more personalized, thereby addressing patient needs as well as challenges identified in epidemiological and etiological research (Findikli et al., 2025; Skweres-Kuchta et al., 2025; Medenica et al., 2022).

#### **7.1. Digital Twins and Data-Driven Modeling**

One of the most promising developments is the concept of digital twins, virtual models that simulate a patient's reproductive cycle, hormonal patterns, or ovarian response. By integrating data from ultrasound imaging, hormonal testing, genetic analyses, and AI algorithms, digital twins may allow clinicians to predict how a given patient will respond to different stimulation protocols or treatment options (Orovou et al., 2025; Skweres-Kuchta et al., 2025). This could reduce trial-and-error cycles in IVF, shorten the duration of therapy, and potentially lower costs.

#### **7.2. Precision Reproductive Medicine**

Studies show that subtle differences in endometrial gene expression, sperm DNA integrity, immune responses, and the reproductive microbiome can influence treatment outcomes. As sequencing technologies become faster and more accessible, such biomarkers may become part of routine assessment, helping clinicians tailor both diagnostics and therapy to each patient's biological profile.

Personalized ovarian stimulation, supported by AI-based predictive tools, may also reduce the risk of overstimulation, improve oocyte quality, and enhance the overall effectiveness of ART (Findikli et al., 2025; Skweres-Kuchta et al., 2025). There is growing interest in non-invasive methods within reproductive biology, particularly for assessing embryos and endometrial receptivity.

##### **Several technologies are currently in development:**

- **Proteomic and metabolomic profiling** of embryo culture media, which may one day complement or replace embryo biopsy in preimplantation testing.
- **RNA-based receptivity tests**, which analyze gene expression patterns in uterine fluid instead of requiring invasive tissue biopsies.
- **Advanced morphokinetic analysis**, in which AI tracks micro-fluctuations in embryo development rates to more accurately predict implantation potential (Findikli et al., 2025; Wu et al., 2025).

### **7.3. Automation, Robotics, and the Fully Digital IVF Laboratory**

Automation in IVF laboratories is expected to expand its capabilities. Many clinics already use robots for micromanipulation and cryopreservation, but future systems may integrate the entire IVF workflow, from oocyte retrieval to embryo monitoring within a single, coordinated digital environment. Such technologies may reduce variability between embryologists and improve repeatability, which is particularly valuable in complex procedures such as ICSI or genetic testing.

### **7.4. Wearable Biosensors and Remote Fertility Monitoring**

Another rapidly developing field is remote monitoring supported by wearable biosensors capable of detecting subtle hormonal changes, shifts in basal body temperature, and heart-rate variability associated with ovulation. These devices can automatically synchronize with clinic software, enabling physicians to monitor menstrual cycles, treatment response, and follicular dynamics without frequent in-person visits.

For patients, this offers greater comfort, flexibility, and autonomy. For clinicians, it provides a more detailed and continuous dataset than traditional cycle monitoring.

### **7.5. Organoids, Microfluidics, and Bioengineering Models**

Innovative research systems such as endometrial organoids, ovarian follicle models, and microfluidic sperm-sorting platforms are beginning to influence both scientific studies and clinical practice.

Organoids, three-dimensional cultures derived from patient cells can replicate selected properties of reproductive tissues and may eventually allow testing of personalized therapies or evaluation of implantation dynamics. Microfluidic devices gently sort sperm using fluid-flow patterns that mimic natural environments, potentially improving fertilization efficiency while reducing mechanical stress on gametes (Mapari et al., 2024).

### **7.6. Ethical Aspects of Artificial Intelligence in ART**

The ethical consequences of AI in diagnosing and treating infertility are becoming an increasingly important area of reflection, as these technologies influence clinical decision-making. Predictive models that evaluate embryo quality, estimate IVF success, or recommend optimal treatment strategies may improve outcomes, but they also raise challenges related to transparency and accountability. Excessive reliance on automated assessments may weaken the clinician's role and limit individualized patient care.

Privacy and data security represent another major concern. Modern digital systems and time-lapse incubators generate vast amounts of data on gametes, embryos, treatment cycles, and hormonal parameters. Their storage, cloud processing, and AI-based analysis increase the risk of privacy breaches, especially in the context of the growing commercialization of reproductive services (Wu et al., 2025; Skweres-Kuchta et al., 2025).

A further issue involves responsibility for decisions made with AI support. If an algorithm incorrectly evaluates an embryo's implantation potential or recommends a suboptimal treatment protocol, it can be difficult to determine whether responsibility lies with the software developer, the clinic, or the physician. Researchers emphasize the need for clear legal and ethical frameworks. These safeguards are essential to ensure that technology supports rather than replaces clinical processes and to maintain patient trust in innovative treatment approaches.

### **7.7. Social Inequalities in Access to ART and Technological Innovations**

Access to assisted reproductive technologies (ART) and modern diagnostic tools remains uneven worldwide, significantly influencing patient experience and treatment outcomes. These disparities are especially visible between high-resource and low-resource countries, as well as among groups with differing socioeconomic status. In many regions, procedures such as IVF, ICSI, genetic testing (PGT), or advanced microbiome analyses are predominantly self-funded, excluding individuals with lower incomes. Where infertility treatment is not reimbursed or reimbursement is limited patients often forgo diagnostics or rely on less effective methods.

Another form of inequality concerns access to next-generation technologies such as time-lapse incubators, AI-based semen analysis systems, or molecular diagnostics. The most advanced equipment and procedures are typically available only in large specialized centers, while smaller clinics rely on more traditional methods.

Social factors including cultural norms, family expectations, and stigma also shape treatment accessibility. Women and couples in conservative regions or societies with strong traditional family norms may face social or even legal barriers to ART. Even in developed countries, single individuals, same-sex couples, and migrants may encounter formal or financial restrictions, placing them at a disadvantage.

## 8. Discussion

Diagnostics and treatment of infertility continue to evolve alongside scientific and technological progress, which is reshaping the landscape of reproductive medicine. Despite these remarkable advancements, many challenges remain. Infertility is not only a medical condition but also a deeply personal experience that affects individuals on physical, emotional, and social levels (Hussain et al., 2025; Malina, 2024). Understanding these complex dimensions is essential to applying modern technologies in ways that genuinely improve patient outcomes.

Although innovative diagnostic tools such as AI-assisted imaging, molecular profiling, microbiome analysis, and automated laboratory systems have significantly enhanced the detection of reproductive disorders, they do not resolve all clinical uncertainties. Many patients continue to face unexplained infertility, where available diagnostic methods cannot clearly identify an underlying cause. This gap highlights the limitations of current approaches and the need for continued research into subtle mechanisms such as epigenetic regulation, immunological dysfunction, and early molecular alterations in gametes and embryos (de Santiago & Polanski, 2022; Peluso et al., 2025). Moreover, access to advanced diagnostics often varies by region, creating disparities in care that disproportionately affect individuals of lower socioeconomic status.

The therapeutic landscape also presents numerous challenges. While assisted reproductive technologies offer hope to many, they remain complex, time-consuming, and emotionally demanding. Procedures such as IVF and ICSI involve physical discomfort, repeated hormonal stimulation, and financial burden, which may intensify the psychological stress already associated with infertility. Even with technological progress, treatment outcomes are not guaranteed, and uncertainty regarding success can heighten anxiety, stress, and feelings of lost control (Schwerdtfeger & Shreffler, 2009; Hussain et al., 2025).

Psychological well-being plays a crucial role in reproductive health. Many individuals and couples experience emotional distress, relationship strain, fear of failure, and social isolation throughout treatment. The stigma surrounding infertility, still present in some communities, further exacerbates these feelings. Research shows that high stress levels can influence treatment adherence, patient decision-making, and overall satisfaction with care. For this reason, integrating psychological support into infertility services is essential.

Despite these difficulties, emerging technologies offer new opportunities for more personalized and patient-friendly care. AI-based decision support systems, remote monitoring devices, and digital twins may reduce uncertainty and streamline treatment pathways. Non-invasive diagnostic techniques can minimize physical discomfort, while laboratory automation may shorten procedures and improve reproducibility. However, these innovations also raise ethical questions concerning transparency, fairness, and equitable access. Ensuring that advanced technologies are available to all patients not only those with substantial financial resources will be a key challenge for the future.

## 9. Conclusions

Infertility remains a complex global health challenge shaped by biological, environmental, social, and technological factors. As reproductive difficulties become increasingly common, the need for accurate diagnostics and accessible, effective treatment grows more evident. Traditional diagnostic and therapeutic methods have expanded dramatically in recent years due to advancements in imaging, molecular biology, laboratory automation, and artificial intelligence. These innovations have enabled a far more detailed understanding of reproductive processes and have made personalized care unthinkable just a decade ago possible.

Modern diagnostics integrate high-resolution imaging, genetic and hormonal profiling, microbiome analysis, and AI-supported assessments. Together, these tools allow clinicians to identify the causes of infertility earlier and with greater precision, which is essential for selecting the most appropriate therapeutic strategies. Similarly, progress in assisted reproductive technologies including IVF, ICSI, preimplantation genetic testing, and robotic laboratory systems has broadened treatment options for many patients, particularly those with complex or previously untreatable causes of infertility.

At the same time, emerging fields such as digital twins, non-invasive embryo assessment, wearable biosensors, and bioengineered reproductive models signal a shift toward even more personalized and minimally invasive methods. These innovations offer the potential to shorten treatment duration, reduce emotional and financial burden, and increase overall therapeutic effectiveness. However, they also raise important ethical and accessibility questions, especially regarding equitable access to advanced technologies.

Ultimately, the integration of innovative technologies into reproductive medicine represents a significant opportunity to improve clinical outcomes and enhance patient well-being. Continued collaboration among medicine, technology, and the social sciences will be crucial for shaping future diagnostic pathways, refining therapeutic practices, and ensuring that fertility care remains both effective and patient-centered.

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