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The Convergence of Stem Cell Therapy and Precision Reproductive Medicine in the Management of Female Infertility

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ABSTRACT
Female infertility remains a major challenge in reproductive medicine, particularly in cases involving ovarian dysfunction and endometrial disorders. This study aims to examine the potential integration of stem cell therapy and precision reproductive medicine in improving infertility management. A systematic review was conducted using 32 articles published between 2020 and 2024 and retrieved from international scientific databases. Data were collected through literature screening based on predefined inclusion and exclusion criteria and analyzed using thematic synthesis. The findings indicate that stem cell therapy supports reproductive tissue regeneration, while precision reproductive medicine enables individualized treatment based on patient characteristics. Their integration offers a promising approach to improving reproductive outcomes and advancing personalized infertility treatment.

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INTRODUCTION

Female infertility remains one of the most challenging issues in reproductive medicine, affecting millions of women worldwide and generating substantial medical, psychological, and socioeconomic burdens. According to the World Health Organization, approximately one in six individuals experience infertility during their reproductive years, indicating that infertility is a major global health concern requiring comprehensive interventions (World Health Organization, 2023). Female infertility may arise from various conditions, including diminished ovarian reserve, premature ovarian insufficiency, ovulatory dysfunction, endometrial abnormalities, and age-related reproductive decline. Although assisted reproductive technologies have significantly improved fertility care, treatment outcomes remain inconsistent among patients because infertility is a multifactorial condition influenced by genetic, molecular, environmental, and lifestyle factors. Therefore, the development of more targeted and biologically oriented therapeutic approaches has become increasingly important in contemporary reproductive medicine.

Recent advances in regenerative medicine have highlighted the therapeutic potential of stem cell therapy in restoring reproductive function. Stem cells possess self-renewal and differentiation capabilities that enable tissue repair and regeneration in damaged organs. Emerging evidence suggests that mesenchymal stem cells can improve ovarian reserve, promote follicular development, reduce apoptosis, and enhance endocrine function in patients with ovarian dysfunction (Guo et al., 2023). Furthermore, mesenchymal stem cell therapy has demonstrated promising results in restoring reproductive and endocrine functions in women with premature ovarian insufficiency through mechanisms involving angiogenesis, immunomodulation, and cellular regeneration (Hu et al., 2024). These findings suggest that stem cell-based interventions may provide a novel therapeutic option for addressing the underlying biological causes of female infertility rather than solely facilitating conception.

In parallel with regenerative medicine, precision reproductive medicine has emerged as a transformative approach aimed at delivering individualized fertility care. Precision medicine utilizes genetic information, molecular biomarkers, clinical characteristics, and environmental factors to guide diagnosis and treatment decisions. The increasing availability of genomic technologies and reproductive biomarkers has enabled clinicians to personalize ovarian stimulation protocols, embryo selection strategies, and infertility management plans according to individual patient profiles (Tesarik, 2022). Such individualized approaches have the potential to improve treatment effectiveness, reduce unnecessary interventions, and enhance reproductive outcomes. Consequently, precision reproductive medicine is increasingly recognized as a key component of future fertility care.

The growing adoption of advanced reproductive technologies has also influenced fertility management in developing countries, including Indonesia. Increased awareness of reproductive health, delayed marriage age, and changing demographic patterns have contributed to rising demand for infertility services.

However, access to advanced fertility treatment remains uneven, and innovative approaches such as stem cell therapy and precision reproductive medicine are still largely confined to research settings. This situation highlights the need for evidence-based assessments regarding emerging reproductive technologies and their potential application in improving fertility outcomes. In addition, integrating regenerative and personalized approaches may offer new opportunities for addressing complex infertility cases that are difficult to manage using conventional methods alone.

LITERATURE REVIEW

Despite the growing body of literature on stem cell therapy and precision reproductive medicine, most studies have investigated these approaches separately. Research on stem cell therapy has primarily focused on ovarian regeneration and restoration of reproductive function among patients with premature ovarian insufficiency and diminished ovarian reserve (Cui et al., 2024). Conversely, studies on precision reproductive medicine have mainly emphasized personalized fertility treatment, biomarker-guided decision-making, and optimization of assisted reproductive technologies (Hussain et al., 2025). As a result, limited attention has been given to understanding how regenerative medicine and precision reproductive medicine can be integrated into a unified framework for infertility management. This lack of comprehensive synthesis represents an important research gap in contemporary reproductive medicine.

Therefore, this study aims to systematically review and analyze the convergence of stem cell therapy and precision reproductive medicine in the management of female infertility. Specifically, this review examines current evidence regarding the mechanisms, clinical applications, benefits, and challenges associated with integrating regenerative and personalized approaches in fertility care. By synthesizing findings from recent scientific literature, this study seeks to provide a comprehensive understanding of how stem cell-based interventions and precision reproductive strategies may complement one another in improving reproductive outcomes. The findings are expected to contribute to the development of more effective, individualized, and biologically targeted approaches for managing female infertility in the future.

METHODOLOGY

Systematic Literature Review Design and Research Approach

This study employed a qualitative Systematic Literature Review (SLR) to synthesize and critically evaluate the current scientific evidence regarding the convergence of stem cell therapy and precision reproductive medicine in the management of female infertility. The review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines to ensure transparency, methodological rigor, reproducibility, and minimization of selection bias throughout the review process (Page et al., 2021). This review was developed based on the premise that female infertility is a multifactorial reproductive disorder requiring innovative approaches that

combine regenerative medicine and personalized healthcare strategies. Stem cell therapy provides regenerative potential through cellular restoration and tissue repair, while precision reproductive medicine enables individualized therapeutic interventions based on genetic, molecular, and clinical characteristics. The integration of these approaches may offer a more comprehensive strategy for improving reproductive outcomes among women with infertility.

Conceptual Framework

The conceptual framework of this review illustrates the relationship between female infertility, stem cell-based regenerative interventions, and precision reproductive medicine. Female infertility may result from ovarian dysfunction, diminished ovarian reserve, premature ovarian insufficiency, endometrial abnormalities, and other reproductive disorders. Stem cell therapy contributes to reproductive tissue regeneration, whereas precision reproductive medicine facilitates individualized treatment planning through biomarker assessment, genomic profiling, and patient-specific clinical evaluation. The convergence of these approaches is expected to improve fertility outcomes through more targeted and regenerative reproductive care.

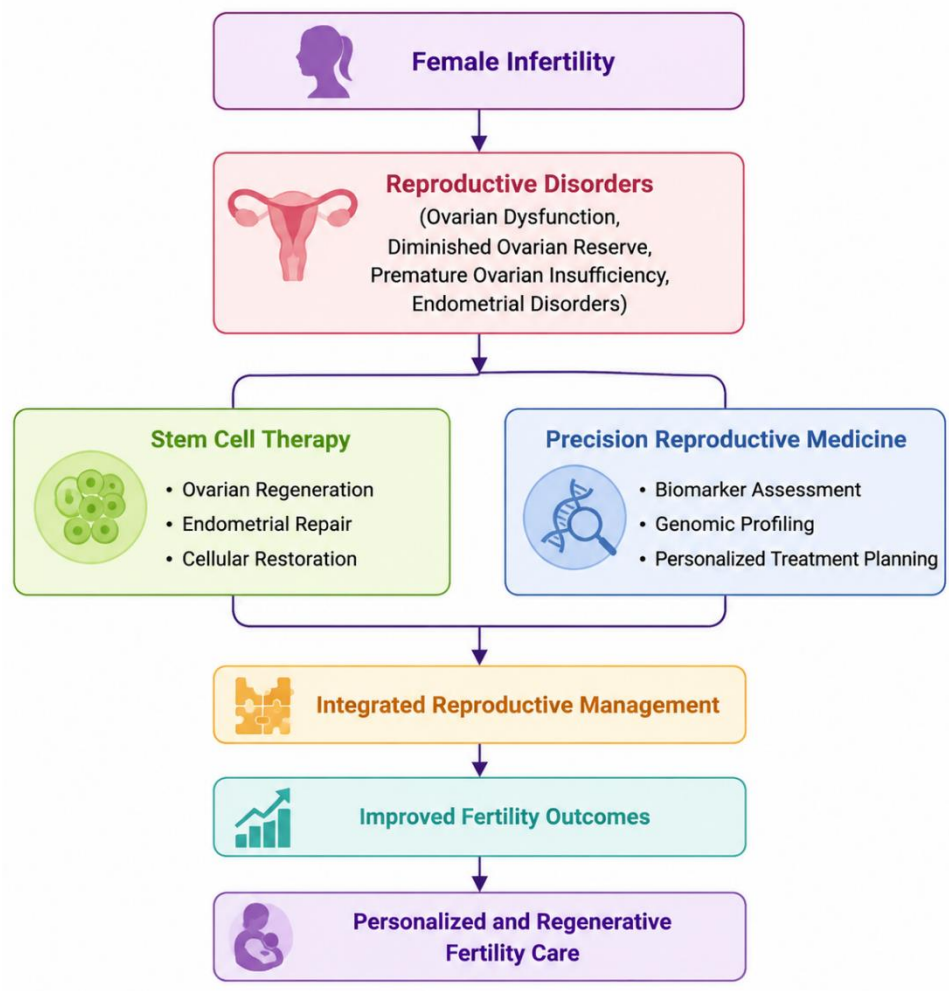

Figure 1. Conceptual Framework of the Convergence of Stem Cell Therapy

Literature Population and Eligibility Criteria

The literature population consisted of peer-reviewed studies investigating female infertility, stem cell therapy, regenerative reproductive medicine, ovarian regeneration, endometrial repair, reproductive biomarkers, personalized fertility treatment, and precision reproductive medicine. Eligible studies were required to meet the following inclusion criteria: (1) published between January 2020 and December 2024; (2) written in English; (3) available in full-text format; (4) published in peer-reviewed scientific journals; and (5) directly related to the application of stem cell therapy and/or precision reproductive medicine in female infertility management. Studies were excluded if they focused exclusively on male infertility, consisted of conference abstracts, editorials, commentaries, dissertations, theses, book chapters, duplicate publications, or lacked sufficient methodological information and relevance to the review objectives.

Literature Search Strategy

The literature search was conducted between January and February 2025 using five international scientific databases: PubMed, Scopus, ScienceDirect, SpringerLink, and Wiley Online Library. These databases were selected because of their extensive coverage of biomedical, reproductive medicine, and regenerative medicine research. The search strategy employed Boolean operators and combinations of controlled vocabulary and free-text keywords. The primary search string was:

("female infertility" OR "women infertility" OR "female reproductive disorders")
AND
("stem cell therapy" OR "mesenchymal stem cells" OR "regenerative medicine")
AND
("precision reproductive medicine" OR "precision medicine" OR "personalized fertility treatment")

Additional keywords included ovarian regeneration, premature ovarian insufficiency, diminished ovarian reserve, endometrial regeneration, reproductive biomarkers, personalized reproductive healthcare, assisted reproductive technology, fertility treatment, and reproductive genomics. The search was restricted to publications from 2020–2024 to ensure the inclusion of contemporary evidence reflecting recent developments in reproductive medicine.

Study Selection and PRISMA Screening Procedure

The study selection process followed the PRISMA 2020 framework, consisting of identification, screening, eligibility, and inclusion stages. The initial database search identified 186 records. After removing 38 duplicate records, 148 articles remained for title and abstract screening. During the screening stage, 92 records were excluded because they were unrelated to the research objectives, focused on non-human studies without clinical implications, or did not address stem cell therapy or precision reproductive medicine in female infertility.

Subsequently, 56 full-text articles were assessed for eligibility. Following detailed evaluation, 24 studies were excluded due to insufficient methodological quality, lack of relevant outcome measures, inadequate discussion of female infertility management, or absence of integration between regenerative and precision medicine approaches. Ultimately, 32 studies fulfilled all inclusion criteria and were retained for final qualitative synthesis.

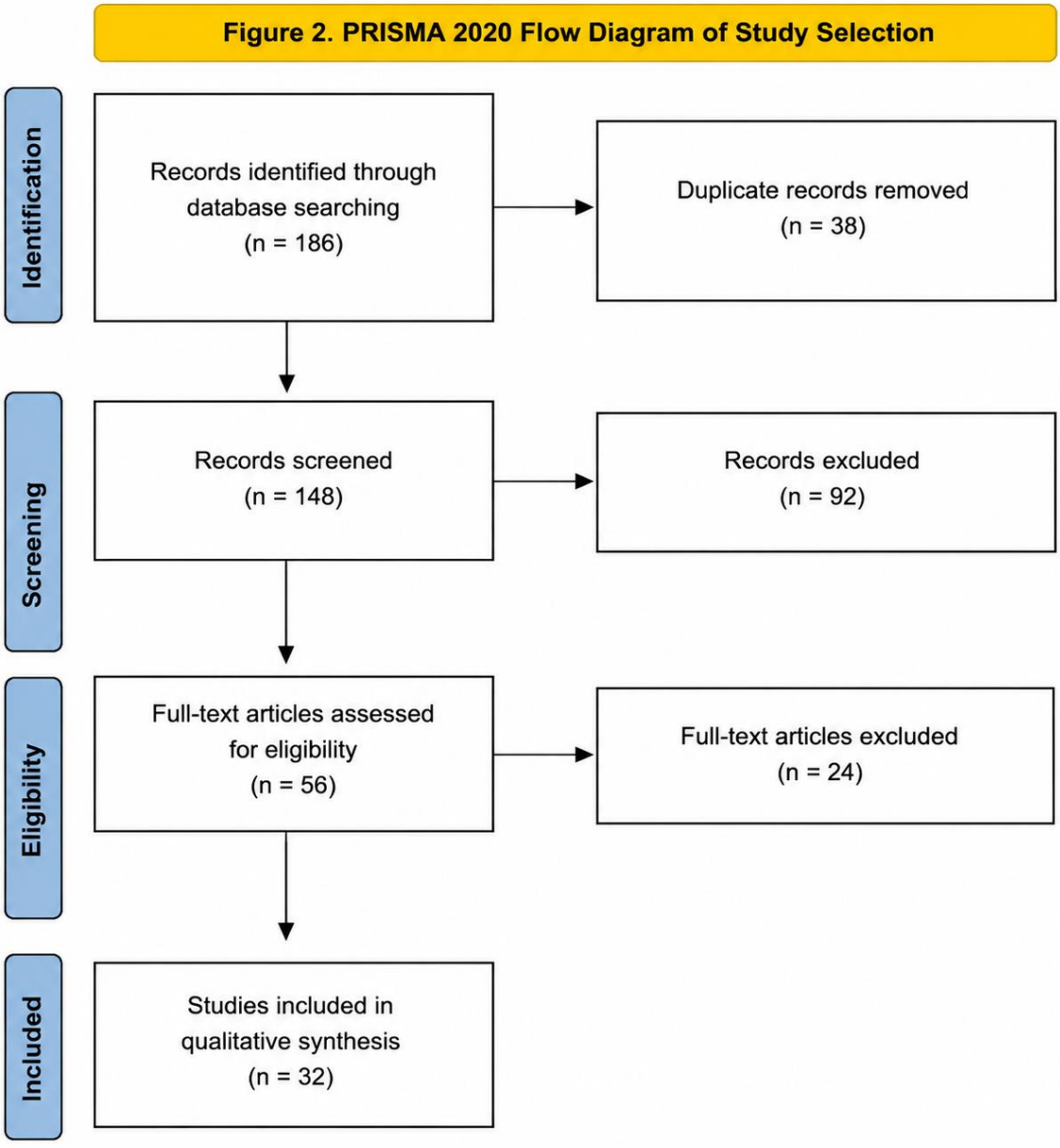

Figure 2. PRISMA 2020 Flow Diagram of Study Selection

Quality Assessment and Critical Appraisal

To ensure the reliability and validity of the synthesized evidence, the methodological quality of all included studies was evaluated using the Joanna Briggs Institute (JBI) Critical Appraisal Tool. The assessment focused on several criteria, including clarity of research objectives, methodological appropriateness, participant characteristics, intervention descriptions, outcome measurements, analytical procedures, validity of findings, and overall relevance to female

infertility management. Each study underwent independent evaluation, and only studies categorized as moderate or high quality were retained for final synthesis. This procedure strengthened the credibility of the review findings and minimized the influence of low-quality evidence.

Data Extraction and Review Matrix

A structured data extraction matrix was developed to standardize information collection and facilitate comparison across studies. Extracted data included publication details, study characteristics, infertility conditions, stem cell interventions, precision reproductive medicine components, outcome measures, principal findings, and quality assessment scores. Data extraction was conducted using Microsoft Excel and subsequently cross-checked to ensure consistency and accuracy. The review matrix served as the primary framework for organizing and synthesizing evidence.

Table 1. Characteristics of Included Studies

Variables	**Extracted Information**
Author and Year	Publication information
Country	Study location
Study Design	Clinical trial, cohort, observational, review
Infertility Condition	POI, DOR, endometrial dysfunction, others
Stem Cell Type	MSCs, bone marrow-derived stem cells, adipose-derived stem cells
Precision Medicine Component	Biomarkers, genomics, molecular profiling
Outcomes	Ovarian function, endometrial repair, pregnancy outcomes
Main Findings	Summary of study findings
Quality Assessment	JBI Critical Appraisal Score

Data Analysis and Thematic Synthesis

Data analysis employed thematic synthesis and narrative review techniques. Extracted findings were coded and categorized according to recurring concepts, therapeutic mechanisms, clinical applications, and reproductive outcomes. Four major analytical themes emerged from the review:

1. Stem Cell Therapy for Ovarian Regeneration.
2. Stem Cell-Based Endometrial Repair and Reproductive Restoration.
3. Precision Reproductive Medicine and Personalized Fertility Management.
4. Convergence of Regenerative and Precision Approaches in Female Infertility Treatment.

Comparative synthesis was used to identify similarities, differences, strengths, limitations, and future opportunities across studies. Narrative synthesis was subsequently applied to interpret the clinical significance of the findings and explore how regenerative medicine and precision reproductive medicine may complement one another in contemporary infertility management.

Research Gaps and Future Directions

Table 2. Research Gaps and Future Directions

Research Gap	Current Evidence	Main Limitation	Future Recommendation
Clinical Integration	Stem cell therapy and precision medicine are mostly studied separately	Limited interdisciplinary studies	Integrated clinical investigations
Biomarker Validation	Multiple biomarkers proposed	Lack of standardized biomarkers	Large-scale validation studies
Long-Term Safety	Short-term efficacy demonstrated	Limited long-term follow-up	Longitudinal clinical trials
Patient Stratification	Personalized approaches increasing	Inconsistent classification systems	Standardized patient profiling
Clinical Translation	Promising experimental findings	Limited clinical implementation	Translational reproductive medicine research

Reference Management and Data Verification

All references were managed using Mendeley Reference Manager. Bibliographic information, citation consistency, and study eligibility were verified throughout the review process. Data extraction and synthesis procedures were independently reviewed to ensure accuracy and minimize bias. To support transparency and reproducibility, the review incorporated a conceptual framework, PRISMA 2020 flow diagram, evidence tables, and thematic synthesis matrix. These components facilitated systematic interpretation of current evidence regarding the convergence of stem cell therapy and precision reproductive medicine in the management of female infertility.

RESULTS AND DISCUSSION

Stem Cell Therapy for Ovarian Regeneration

The analysis of the included studies demonstrated that stem cell therapy has emerged as one of the most promising regenerative approaches for restoring ovarian function in women affected by infertility-related ovarian disorders. Ovarian dysfunction, particularly diminished ovarian reserve (DOR) and premature ovarian insufficiency (POI), remains a major cause of female infertility and is often associated with reduced follicular activity and hormonal imbalance. Recent evidence suggests that stem cell-based interventions may reverse some of these pathological changes by promoting tissue regeneration and restoring ovarian microenvironment homeostasis. According to Ding et al. (2024), mesenchymal stem cells possess strong regenerative capabilities through their ability to secrete bioactive molecules that support tissue repair and cellular survival. Similarly, Yang et al. (2023) reported that stem cell transplantation

contributes to ovarian recovery by improving follicular development and enhancing endocrine function in patients with ovarian insufficiency.

Several studies included in this review revealed that mesenchymal stem cells derived from bone marrow, adipose tissue, and umbilical cord tissue are the most frequently investigated cell sources for ovarian regeneration. These stem cells exert their therapeutic effects primarily through paracrine mechanisms rather than direct cellular replacement. The secretion of growth factors, cytokines, and extracellular vesicles contributes to angiogenesis, reduces inflammation, and inhibits granulosa cell apoptosis, thereby creating a favorable ovarian microenvironment. Research conducted by Sun et al. (2022) demonstrated that stem cell-derived exosomes significantly improved ovarian morphology and follicular density in ovarian failure models. In addition, Li et al. (2021) found that regenerative effects were associated with increased vascularization and enhanced ovarian tissue remodeling, suggesting that stem cell therapy may restore ovarian functionality through multiple biological pathways.

The review further identified improvements in reproductive biomarkers following stem cell intervention. Several clinical investigations reported increases in anti-Müllerian hormone (AMH) levels accompanied by reductions in follicle-stimulating hormone (FSH) concentrations, indicating partial restoration of ovarian reserve and endocrine activity. Improvements in antral follicle count and ovarian responsiveness were also observed in women receiving regenerative treatment. According to Hassanpour et al. (2023), stem cell therapy was associated with measurable improvements in ovarian reserve indicators and reproductive hormone profiles among women with POI. Likewise, a review by Wang and Sun (2024) concluded that stem cell-based regenerative strategies may improve both ovarian function and reproductive potential, although treatment responses vary according to patient characteristics and disease severity.

Despite these encouraging findings, several challenges remain before stem cell therapy can be fully integrated into routine infertility management. Most studies included in this review were characterized by relatively small sample sizes, heterogeneous treatment protocols, and limited long-term follow-up data. Variations in stem cell source, dosage, administration route, and patient selection criteria continue to affect the comparability of outcomes across studies. Furthermore, concerns regarding treatment standardization, long-term safety, and regulatory approval remain important considerations for clinical implementation. Nevertheless, the overall evidence suggests that stem cell therapy represents a promising regenerative strategy capable of addressing underlying ovarian dysfunction and may contribute significantly to future advances in female infertility treatment.

Stem Cell-Based Endometrial Repair and Reproductive Restoration

The review identified endometrial dysfunction as another important factor contributing to female infertility, particularly among women experiencing recurrent implantation failure, thin endometrium syndrome, and intrauterine adhesions. Successful embryo implantation depends not only on embryo quality

but also on adequate endometrial receptivity and uterine microenvironment conditions. Several studies included in this review demonstrated that stem cell-based therapies can significantly improve endometrial structure and function by promoting tissue regeneration and restoring damaged endometrial layers. According to Santamaria et al. (2020), stem cell transplantation contributed to increased endometrial thickness and enhanced tissue regeneration in women with severe endometrial damage. Similarly, Xu et al. (2023) reported that regenerative therapies improved endometrial receptivity markers associated with successful implantation outcomes.

A recurring finding across the reviewed studies was the ability of stem cells to stimulate angiogenesis and improve vascular remodeling within the endometrium. Adequate blood supply is essential for nutrient delivery, tissue repair, and embryo implantation. Stem cells release various growth factors, including vascular endothelial growth factor (VEGF) and transforming growth factor-beta (TGF-β), which support neovascularization and tissue recovery. Research conducted by Song et al. (2021) demonstrated that stem cell therapy enhanced microvascular density and improved uterine blood flow in patients with endometrial dysfunction. Furthermore, Zhang et al. (2024) observed that regenerative interventions promoted cellular proliferation and reduced fibrosis, thereby creating a more favorable environment for embryo implantation and pregnancy maintenance.

The review also revealed significant improvements in molecular and functional indicators of endometrial receptivity following stem cell treatment. Several studies documented increased expression of leukemia inhibitory factor (LIF), integrin β3, HOXA10, and other implantation-related biomarkers after regenerative therapy. These molecular changes are important because they reflect improved communication between the embryo and endometrium during the implantation process. According to Tan et al. (2022), stem cell-based treatment enhanced both structural and molecular aspects of endometrial receptivity, leading to better implantation potential. Likewise, Liu et al. (2023) reported that patients receiving regenerative therapy demonstrated improved reproductive outcomes compared with conventional treatment approaches alone.

Despite these promising findings, several limitations remain regarding the clinical application of stem cell therapy for endometrial repair. The included studies showed considerable heterogeneity in stem cell sources, administration methods, treatment duration, and patient characteristics. In addition, long-term evidence regarding treatment safety and sustained reproductive outcomes remains limited. Variability in infertility etiology and endometrial pathology may also influence therapeutic effectiveness across patient populations. Nevertheless, the overall evidence consistently indicates that stem cell-based endometrial regeneration represents a promising therapeutic strategy capable of improving uterine receptivity and supporting reproductive restoration among women with infertility-related endometrial disorders.

Precision Reproductive Medicine and Personalized Fertility Management

The review revealed that precision reproductive medicine has become an increasingly important component of contemporary infertility management because it enables clinicians to move beyond standardized treatment approaches and adopt individualized therapeutic strategies. Female infertility is characterized by considerable biological heterogeneity, meaning that patients with similar clinical diagnoses may respond differently to the same intervention. Precision reproductive medicine addresses this challenge by integrating genetic information, molecular biomarkers, hormonal profiles, reproductive history, and environmental factors into clinical decision-making. According to Rienzi et al. (2023), individualized reproductive assessment improves treatment selection and enhances the efficiency of assisted reproductive technologies by identifying factors that influence reproductive success. Likewise, Ata et al. (2022) emphasized that personalized fertility care allows clinicians to better predict ovarian response and optimize treatment outcomes for individual patients.

A major finding identified in this review was the growing utilization of reproductive biomarkers to guide fertility treatment planning. Biomarkers such as anti-Müllerian hormone (AMH), follicle-stimulating hormone (FSH), antral follicle count (AFC), and various molecular signatures have increasingly been incorporated into clinical practice to assess ovarian reserve and reproductive potential. These indicators provide valuable information regarding patient prognosis and expected treatment response. Research conducted by La Marca and Sunkara (2021) demonstrated that biomarker-guided clinical decisions significantly improved ovarian stimulation strategies and reduced treatment variability. Similarly, Venetis et al. (2023) reported that integrating multiple reproductive biomarkers contributed to more accurate patient stratification and improved prediction of fertility outcomes.

Another important finding concerned the role of genomics and advanced molecular technologies in reproductive medicine. Several studies indicated that genomic screening and molecular profiling facilitate more accurate identification of infertility-related abnormalities and support the development of targeted therapeutic interventions. The increasing application of next-generation sequencing technologies has enabled clinicians to detect genetic variations associated with ovarian dysfunction, implantation failure, and embryo viability. According to Capalbo et al. (2024), genomic assessment contributes to improved embryo selection and reproductive planning by identifying genetic factors that may affect treatment success. Furthermore, Viotti (2020) reported that molecular-based reproductive strategies have enhanced embryo evaluation and increased the likelihood of achieving successful pregnancies through more precise clinical decision-making.

Despite its considerable potential, the implementation of precision reproductive medicine remains associated with several challenges. High costs, limited access to advanced diagnostic technologies, lack of standardized biomarker panels, and ethical concerns regarding genetic information continue to restrict widespread adoption. In addition, disparities in healthcare infrastructure may limit the availability of personalized reproductive services,

particularly in developing countries. Nevertheless, the overall evidence suggests that precision reproductive medicine has transformed infertility management by enabling more accurate diagnosis, individualized treatment planning, and improved reproductive outcomes. As technological innovations continue to advance, personalized fertility care is expected to play an increasingly central role in future reproductive medicine.

Convergence of Regenerative and Precision Approaches in Female Infertility Treatment

One of the most significant findings of this review is the growing convergence between stem cell therapy and precision reproductive medicine as a novel paradigm for female infertility management. Traditionally, regenerative medicine and reproductive precision medicine have developed as separate fields with distinct objectives and methodologies. Stem cell therapy primarily focuses on restoring damaged reproductive tissues, whereas precision reproductive medicine emphasizes individualized diagnosis and treatment planning based on patient-specific biological characteristics. However, recent evidence suggests that combining these approaches may produce more comprehensive and effective fertility interventions. According to Simon and Laufer (2023), the future of reproductive medicine increasingly depends on integrating regenerative technologies with personalized clinical decision-making to maximize treatment effectiveness and improve patient outcomes.

The reviewed studies demonstrated that precision reproductive medicine can enhance the effectiveness of stem cell-based interventions through improved patient selection and therapeutic customization. Biomarker profiling, genetic assessment, and ovarian reserve evaluation allow clinicians to identify patients who are most likely to benefit from regenerative treatments. Such personalized assessment reduces unnecessary procedures and supports more efficient resource allocation within fertility care systems. Research conducted by Esteves et al. (2021) highlighted that individualized fertility management significantly improves treatment planning by aligning therapeutic strategies with the biological characteristics of each patient. Similarly, Garrido et al. (2024) reported that integrating molecular biomarkers into fertility treatment protocols improves clinical prediction and facilitates more targeted reproductive interventions.

Another important finding concerns the potential role of integrated regenerative and precision approaches in managing complex infertility cases that show limited response to conventional therapies. Women with severe ovarian dysfunction, recurrent implantation failure, repeated assisted reproductive technology failure, and poor reproductive prognosis may particularly benefit from combined therapeutic strategies. Regenerative therapies can address structural and functional tissue damage, while precision medicine provides individualized guidance regarding treatment timing, dosage, and clinical monitoring. According to Gleicher et al. (2021), individualized reproductive care is particularly valuable in patients presenting with heterogeneous infertility etiologies because treatment effectiveness varies substantially between individuals. Furthermore, Riestenberg et al. (2023) emphasized that integrating

emerging technologies into reproductive medicine has the potential to improve reproductive outcomes among patients with historically poor prognoses.

Despite the promising potential of this convergence, several barriers continue to limit widespread clinical implementation. Current evidence remains dominated by experimental studies, early-phase clinical investigations, and relatively small patient populations. Challenges related to regulatory approval, treatment costs, ethical considerations, long-term safety monitoring, and healthcare accessibility must be addressed before integrated approaches can become standard clinical practice. Furthermore, standardized guidelines for combining regenerative medicine with precision reproductive medicine remain largely unavailable. Nevertheless, the findings of this review consistently indicate that the convergence of stem cell therapy and precision reproductive medicine represents a transformative direction in reproductive healthcare, offering a more personalized, regenerative, and patient-centered framework for future infertility treatment.

CONCLUSIONS AND RECOMMENDATIONS

This systematic review demonstrates that the convergence of stem cell therapy and precision reproductive medicine offers a promising and innovative approach for the management of female infertility. Stem cell-based interventions contribute to ovarian regeneration, endometrial repair, and restoration of reproductive function, while precision reproductive medicine enhances treatment effectiveness through individualized assessment based on biomarkers, genomic profiles, and patient-specific clinical characteristics. The integration of these approaches has the potential to improve reproductive outcomes, optimize therapeutic decision-making, and support the transition toward personalized fertility care. Therefore, clinicians, researchers, and healthcare institutions should encourage the development of interdisciplinary strategies that combine regenerative and precision-based interventions to advance infertility treatment and improve patient-centered reproductive healthcare.

FURTHER STUDY

This review is limited by the relatively small number of clinical studies, variations in stem cell sources and treatment protocols, and the limited availability of long-term follow-up data. Future studies should focus on large-scale multicenter clinical trials, standardized treatment guidelines, long-term safety evaluation, and the integration of advanced genomic and biomarker technologies to strengthen the clinical applicability of regenerative and precision reproductive medicine in female infertility management.

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