ORIGINAL RESEARCH PAPER
Volume - 15 | Issue - 08 | August - 2026 | PRINT ISSN No. 2277 - 8179 | DOI : 10.36106/ijsr
INTERNATIONAL JOURNAL OF SCIENTIFIC RESEARCH

NANOTECHNOLOGY IN ENDOMETRIAL AND UTERINE DISEASES: A NEW ERA OF DIAGNOSIS AND PERSONALIZED THERAPY

Obstetrics & Gynaecology

Dr Hena F Kalam Specialist in Obstetrics & Gynecology

Dr Bhawna Sharma* Senior fellow*Corresponding Author

ABSTRACT

Nanotechnology has emerged as a rapidly evolving interdisciplinary field with the potential to address several unmet clinical needs in gynecology. Endometrial and uterine diseases represent a major source of morbidity among women and encompass a wide clinical spectrum ranging from benign conditions such as endometriosis, adenomyosis, abnormal uterine bleeding, and uterine fibroids to malignant entities including endometrial carcinoma and uterine sarcomas. Despite advancements in diagnostic imaging and therapeutic interventions, clinicians continue to face challenges related to delayed diagnosis, disease heterogeneity, systemic adverse effects of treatment, recurrence, and preservation of fertility. Recent insights into the molecular pathophysiology of uterine diseases have highlighted the need for precision-based diagnostic and therapeutic approaches. Nanotechnology offers innovative solutions by enabling highly sensitive diagnostic platforms, enhanced imaging modalities, targeted and sustained drug delivery systems, and personalized treatment strategies based on disease biology and patient-specific characteristics. Nanoparticle-based diagnostics, including nanosensors and liquid biopsy platforms, have the potential to facilitate early disease detection and longitudinal monitoring, while nanocarrier-mediated therapies allow selective delivery of hormonal agents, chemotherapeutics, anti-inflammatory drugs, and gene-based therapies with reduced systemic toxicity. Additionally, nanotechnology-based approaches may support fertility preservation and improve reproductive outcomes in selected patient populations. This review provides a comprehensive, clinician-focused overview of the role of nanotechnology in endometrial and uterine diseases, discussing pathophysiological rationale, diagnostic and therapeutic applications, translational challenges, safety considerations, and future clinical implications. The aim is to inform practicing clinicians about emerging nanotechnology-based strategies that may reshape gynecological care in the era of personalized medicine.

KEYWORDS

Nanotechnology, Endometriosis, Adenomyosis, Nanosensors, Liquid biopsy

INTRODUCTION

Endometrial and uterine diseases represent a substantial clinical burden in gynecological practice, affecting women across all age groups and significantly impacting reproductive health, quality of life, and long-term wellbeing. These disorders encompass a broad clinical spectrum, ranging from benign but often debilitating conditions such as endometriosis, adenomyosis, abnormal uterine bleeding, and uterine fibroids to malignant entities including endometrial carcinoma and uterine sarcomas. Despite advances in imaging, surgical techniques, and pharmacological therapies, clinicians continue to face challenges related to delayed diagnosis, nonspecific symptomatology, disease recurrence, treatment-related adverse effects, and preservation of fertility. In recent years, growing insights into the molecular and cellular mechanisms underlying uterine pathology have highlighted the need for more precise diagnostic tools and targeted therapeutic strategies. Against this background, nanotechnology has emerged as a promising interdisciplinary approach with the potential to transform the diagnosis and management of endometrial and uterine diseases through enhanced sensitivity, specificity, and personalization of care.

Clinical Burden of Endometrial and Uterine Diseases

Conditions such as endometriosis, adenomyosis, abnormal uterine bleeding, and uterine fibroids affect women predominantly during their reproductive years and are associated with chronic pelvic pain, menstrual disturbances, infertility, and significant impairment of quality of life. From a clinician's perspective, the cumulative burden of these disorders places substantial demands on healthcare systems and underscores the need for more effective and durable management strategies[1].

Limitations of Current Diagnostic and Therapeutic Approaches

Despite advances in imaging, surgical techniques, and pharmacotherapy, the diagnosis and management of uterine and endometrial diseases remain challenging. Conventional diagnostic tools such as transvaginal ultrasonography, hysteroscopy, magnetic resonance imaging, and histopathological evaluation often detect disease only after structural or histological changes have occurred. Early molecular alterations that precede clinical disease are frequently missed, leading to delayed diagnosis, particularly in conditions like endometriosis and early-stage endometrial pathology. Therapeutically, current options including hormonal therapy, surgery, chemotherapy, and radiotherapy are effective but often limited by systemic adverse effects, variable response rates, recurrence, and negative impact on fertility[2].

Evolving Understanding of Disease Biology and Precision Medicine

Recent advances in molecular biology have significantly improved understanding of the pathophysiology of endometrial and uterine diseases. Hormonal dysregulation, chronic inflammation, angiogenesis, immune dysfunction, and genetic and epigenetic alterations are now recognized as central drivers of disease initiation and progression. These insights have shifted the clinical paradigm toward precision medicine, where diagnosis and treatment are tailored according to individual disease biology rather than solely clinical presentation. However, the translation of molecular knowledge into routine clinical practice has been constrained by the lack of sensitive diagnostic tools and effective delivery systems capable of targeting diseased tissue without affecting healthy organs[3].

Emergence of Nanotechnology in Gynecological Care

Nanotechnology, defined as the design and application of materials at the nanoscale, has emerged as a promising platform to address many of the limitations of conventional gynecological care. Nanomaterials possess unique physicochemical properties that enable interaction with biological systems at the cellular and molecular levels. For clinicians, this translates into opportunities for enhanced disease detection, targeted drug delivery, improved imaging, and reduced systemic toxicity. The uterus represents a particularly suitable target for nanotechnology-based interventions due to its hormone-responsive nature and anatomical accessibility, allowing both systemic and localized therapeutic approaches[4].

Rationale for a Clinician-Focused Review

As research in nanotechnology continues to expand rapidly, there is a growing need for clinician-oriented synthesis of available evidence that emphasizes practical relevance rather than technical complexity. Many existing reviews focus heavily on material science or preclinical engineering aspects, which may limit their utility for practicing physicians[5]. This review aims to bridge that gap by providing a comprehensive, clinically relevant overview of nanotechnology applications in endometrial and uterine diseases.

PATHOPHYSIOLOGY OF ENDOMETRIAL AND UTERINE DISEASES AND ITS CLINICAL IMPLICATIONS

Hormonal Dysregulation and Progesterone Resistance

Hormonal imbalance is central to the pathogenesis of most endometrial and uterine diseases, with estrogen excess and progesterone resistance playing a dominant role. Estrogen promotes endometrial proliferation, angiogenesis, and inflammatory signaling,

while progesterone normally counteracts these effects by inducing differentiation and limiting excessive growth. In conditions such as endometriosis, adenomyosis, endometrial hyperplasia, and Type I endometrial carcinoma, impaired progesterone receptor expression or downstream signaling leads to reduced responsiveness to progesterone[5].

Chronic Inflammation and Oxidative Stress

Chronic inflammation is a defining feature of many uterine disorders and significantly contributes to symptom severity and disease progression. In endometriosis, ectopic endometrial tissue triggers sustained inflammatory responses characterized by elevated cytokines, prostaglandins, and reactive oxygen species. This inflammatory microenvironment promotes fibrosis, angiogenesis, and nerve sensitization, leading to chronic pelvic pain and dysmenorrhea. Adenomyosis similarly exhibits increased inflammatory mediators within the myometrium, contributing to uterine hypercontractility and heavy menstrual bleeding. From a clinician's perspective, the inflammatory basis of these diseases explains the limited efficacy of symptom-based treatment alone and highlights the need for therapies targeting underlying inflammatory pathways[6].

Angiogenesis and Neurovascular Remodeling

Aberrant angiogenesis is a shared pathological hallmark across benign and malignant uterine diseases. Estrogen-mediated upregulation of vascular endothelial growth factor and other proangiogenic factors facilitates the survival and expansion of ectopic endometrial implants in endometriosis and supports fibroid growth. In malignancies such as endometrial cancer, abnormal angiogenesis enables tumor growth, invasion, and metastatic potential. Neuroangiogenesis also contributes to pain generation in benign conditions. Clinically, angiogenic activity correlates with disease aggressiveness and therapeutic response, making it a critical target for both diagnostic imaging and therapeutic intervention.

Immune Dysfunction and Altered Tissue Surveillance

Normal immune surveillance plays a crucial role in eliminating aberrant endometrial cells. In endometriosis, impaired natural killer cell activity, altered macrophage polarization, and immune tolerance allow ectopic tissue survival and implantation. In malignant uterine disease, tumor-induced immune evasion mechanisms promote progression and resistance to therapy. Clinically, immune dysfunction contributes to chronicity, recurrence, and treatment resistance, underscoring the emerging relevance of immunomodulatory strategies in both benign and malignant uterine disorders[7].

Genetic and Molecular Heterogeneity

Genetic and epigenetic alterations are particularly significant in endometrial carcinoma but also influence benign disease behavior. Mutations affecting cell proliferation, apoptosis, and DNA repair pathways contribute to carcinogenesis, while epigenetic changes modulate hormone responsiveness and inflammatory signaling in benign conditions. Clinically, molecular heterogeneity explains variations in disease behavior, prognosis, and treatment response among patients with similar histopathological diagnoses. This variability reinforces the need for personalized and targeted therapeutic approaches.

Clinical Implications

The overlapping and interconnected biological mechanisms underlying uterine and endometrial diseases contribute to diagnostic ambiguity and therapeutic challenges in routine practice. Understanding disease pathophysiology enables clinicians to move beyond symptom-driven management toward mechanism-based, individualized care. This biological foundation provides the rationale for precision diagnostics and targeted therapies, including nanotechnology-based approaches, which aim to address disease at the molecular level while minimizing systemic adverse effects.

NANOTECHNOLOGY PLATFORMS AND THEIR RELEVANCE TO CLINICAL PRACTICE

Lipid-Based Nanoparticles and Clinical Translation

Lipid-based nanoparticles, including liposomes and solid lipid nanoparticles, are the most clinically mature nanotechnology platforms currently used in medicine. Their high biocompatibility, ability to encapsulate both hydrophilic and lipophilic drugs, and favorable safety profiles make them particularly relevant to gynecological practice. From a clinician's perspective, lipid-based nanocarriers improve drug pharmacokinetics by prolonging circulation time and reducing nonspecific tissue distribution. In gynecologic oncology, liposomal formulations of chemotherapeutic agents have demonstrated reduced hematologic and gastrointestinal toxicity, which is especially valuable for elderly patients and those with comorbidities. In benign uterine disorders, lipid-based systems provide a promising avenue for localized hormonal or anti-inflammatory drug delivery with fewer systemic adverse effects[8].

Table 1. Nanotechnology platforms used in endometrial and uterine diseases and their clinical relevance

Nanotechnology platform	Key characteristics	Potential clinical applications in uterine diseases	Clinical relevance for physicians
Lipid-based nanoparticles (liposomes, solid lipid nanoparticles)	High biocompatibility, ability to encapsulate hydrophilic and lipophilic drugs, prolonged circulation time	Targeted delivery of hormonal agents, chemotherapeutics, and anti-inflammatory drugs	Reduced systemic toxicity, improved tolerability in long-term therapy, suitability for elderly and comorbid patients
Polymeric nanoparticles	Controlled and sustained drug release, stimulus-responsive (pH, enzymes, inflammation)	Localized therapy in endometriosis, adenomyosis, and abnormal uterine bleeding	Improved adherence, prolonged symptom control, reduced dosing frequency
Metallic nanoparticles (gold, iron oxide)	Unique optical and magnetic properties	Enhanced imaging, disease localization, staging, and theranostic applications	Improved diagnostic confidence, support for surgical planning and image-guided therapy
Biomimetic nanoparticles	Cell membrane–coated, immune evasion, enhanced cellular uptake	Targeted delivery in inflammatory and malignant uterine disease	Improved targeting efficiency, reduced immunogenicity
Exosome-based nanocarriers	Natural extracellular vesicles, high biocompatibility	Gene therapy, immunomodulation, targeted drug delivery	Potential for personalized therapy with lower risk of immune reactions

Polymeric Nanoparticles and Controlled Drug Release

Polymeric nanoparticles offer greater flexibility in drug design and release kinetics. These systems can be engineered to provide sustained or stimuli-responsive drug release based on pH, enzymatic activity, or inflammatory signals, all of which are altered in uterine disease microenvironments. Clinically, this allows prolonged therapeutic effect with lower dosing frequency, improving adherence in chronic conditions such as endometriosis and adenomyosis. For physicians, polymeric platforms represent a step toward precision dosing tailored to disease activity rather than fixed systemic regimens[9].

Metallic Nanoparticles and Imaging Integration

Metallic nanoparticles, particularly gold and iron oxide nanoparticles, have gained attention for their diagnostic and theranostic applications. Iron oxide nanoparticles enhance magnetic resonance imaging contrast, improving lesion delineation and staging accuracy. Gold nanoparticles offer unique optical properties that may support image-guided therapy and photothermal treatment. Clinically, these platforms strengthen diagnostic confidence and may guide surgical planning and targeted interventions.

Biomimetic and Exosome-Based Nanocarriers

Biomimetic nanoparticles and exosome-based systems represent an emerging and clinically exciting platform. By mimicking natural cell membranes, these carriers improve immune evasion, cellular uptake, and tissue specificity. From a physician's standpoint, these systems

may allow highly selective drug or gene delivery with minimal immunogenicity, aligning closely with personalized medicine goals[10].

NANOTECHNOLOGY IN DIAGNOSIS AND DISEASE MONITORING

Nanoparticle-Enhanced Imaging Modalities

Nanotechnology-enhanced imaging improves the sensitivity and specificity of conventional radiological techniques. Iron oxide nanoparticles used as MRI contrast agents improve visualization of myometrial invasion, junctional zone abnormalities, and tumor margins. Clinically, improved imaging accuracy aids in preoperative staging, surgical planning, and risk stratification, particularly in endometrial cancer and adenomyosis[11].

Biomarker Detection and Nanosensor Platforms

Nanosensors enable detection of disease-specific biomarkers at extremely low concentrations. Nanotechnology-assisted assays can identify circulating tumor DNA, microRNAs, inflammatory cytokines, and hormone-related markers associated with endometrial pathology. For clinicians, these platforms offer minimally invasive diagnostic alternatives and support early disease detection when structural changes are not yet apparent[12].

Liquid Biopsy and Longitudinal Disease Monitoring

Nanotechnology-based liquid biopsy platforms allow real-time monitoring of disease burden and therapeutic response. In endometrial cancer, detection of circulating tumor DNA may identify minimal residual disease or early recurrence before clinical progression[13]. This capability enables earlier therapeutic intervention and individualized surveillance strategies.

Monitoring Chronic Benign Disease Activity

In chronic conditions such as endometriosis and adenomyosis, nanotechnology-enabled biomarker monitoring may help assess disease activity and response to therapy[14]. Clinically, this addresses a major unmet need, as current management often relies on symptom reporting rather than objective disease markers.

NANOTECHNOLOGY-BASED THERAPEUTIC STRATEGIES IN BENIGN UTERINE DISORDERS

Rationale for Nanotechnology in Benign Uterine Disease Management

Benign uterine disorders such as endometriosis, adenomyosis, uterine fibroids, and abnormal uterine bleeding account for a substantial proportion of gynecological morbidity and often require long-term treatment. From a clinician's perspective, the major limitations of conventional therapies include systemic hormonal adverse effects, incomplete symptom control, disease recurrence, and negative impact on fertility and quality of life. Nanotechnology-based therapeutic strategies provide a mechanistic advantage by enabling targeted, localized, and sustained drug delivery within the uterine environment, thereby addressing many of these challenges[15].

Targeted Drug Delivery in Endometriosis

Endometriosis management traditionally relies on hormonal suppression and analgesics, which are frequently associated with hypoestrogenic symptoms and limited long-term tolerability. Nanoparticle-mediated delivery of hormonal agents, nonsteroidal anti-inflammatory drugs, angiogenesis inhibitors, and immunomodulatory molecules has demonstrated improved lesion specificity in preclinical and early translational studies[16]. Clinically, this targeted approach allows higher local drug concentrations at ectopic lesions while reducing systemic exposure, thereby minimizing endocrine side effects and improving adherence.

Localized Therapeutic Approaches in Adenomyosis and Abnormal Uterine Bleeding

Adenomyosis and abnormal uterine bleeding often require prolonged hormonal therapy, which may be poorly tolerated or contraindicated in patients with metabolic or thromboembolic risk factors. Nanotechnology-based intrauterine or localized drug delivery systems enable sustained release of progestins or anti-inflammatory agents directly within the uterine cavity[17]. From a clinician's standpoint, this localized therapy improves bleeding control and pain relief while minimizing systemic hormonal exposure.

Nanotechnology-Driven Nonsurgical Management of Uterine Fibroids

Uterine fibroids remain a leading indication for hysterectomy despite the availability of medical and minimally invasive treatments. Nanocarrier-mediated delivery of antiproliferative agents, selective hormone modulators, and gene-targeted therapies directly to fibroid tissue is an area of active research. Clinically, these strategies aim to reduce fibroid volume and symptom burden without surgery, offering uterine-preserving alternatives for women desiring fertility or those at high surgical risk[18]. For clinicians, the potential to provide effective nonsurgical therapy represents a significant shift in fibroid management paradigms.

NANOTECHNOLOGY IN ENDOMETRIAL CANCER AND UTERINE MALIGNANCIES

Clinical Rationale for Nanotechnology in Uterine Oncology

Endometrial cancer and other uterine malignancies pose unique clinical challenges due to their molecular heterogeneity, variable response to treatment, and the need to balance oncologic control with quality of life. From a clinician's perspective, conventional management strategies—surgery, radiotherapy, chemotherapy, and hormonal therapy—are effective but often limited by systemic toxicity, treatment resistance, and recurrence, particularly in advanced or high-risk disease[19]. Nanotechnology-based approaches offer an opportunity to enhance therapeutic precision by improving tumor targeting, drug bioavailability

Nanoparticle-Based Chemotherapy Delivery

One of the most clinically relevant applications of nanotechnology in uterine malignancies is nanoparticle-encapsulated chemotherapy. Liposomal and polymer-based nanocarriers improve solubility and pharmacokinetics of cytotoxic agents and preferentially accumulate within tumor tissue via enhanced permeability and retention effects. For clinicians, this translates into reduced hematologic, gastrointestinal, and neurologic toxicity compared with conventional chemotherapy[20]. Such benefits are especially important in elderly patients, those with multiple comorbidities, and patients requiring prolonged systemic therapy. Improved tolerability may allow better treatment adherence and completion of planned regimens.

Targeted and Molecularly Guided Nanotherapies

With the increasing incorporation of molecular classification into endometrial cancer management, targeted nanotherapeutic platforms have gained attention. Nanoparticles functionalized with ligands targeting estrogen receptors, growth factor receptors, or other tumor-specific markers enable selective delivery of therapeutic agents to malignant cells while sparing normal tissue[21]. From a physician's standpoint, this strategy aligns closely with precision oncology, offering the potential for improved response rates, reduced off-target toxicity, and individualized treatment selection based on tumor biology.

Gene Therapy, Immunomodulation, and Resistance Management

Nanotechnology also provides a platform for delivering gene-based therapies and immunomodulatory agents. Nanocarriers capable of transporting small interfering RNA, tumor suppressor genes, or immune-activating molecules offer novel strategies to overcome chemotherapy resistance and modulate the tumor microenvironment. Clinically, these approaches may be particularly valuable in recurrent or advanced uterine malignancies where standard treatment options are limited[22].

Theranostic Applications and Clinical Monitoring

Theranostic nanoparticles combine diagnostic and therapeutic functions, allowing simultaneous treatment delivery and real-time monitoring of response. For clinicians, this capability supports early identification of non-responders and timely modification of treatment strategies. As clinical evidence continues to evolve, nanotechnology is poised to become an important adjunct in the personalized management of endometrial cancer and uterine malignancies.

Table 2. Clinical applications of nanotechnology in endometrial cancer and uterine malignancies

Application area	Nanotechnology-based approach	Potential clinical benefit	Physician-oriented implication
Chemotherapy delivery	Nanoparticle-encapsulated cytotoxic agents	Enhanced tumor accumulation, reduced systemic toxicity	Better tolerability, improved treatment completion rates

Targeted therapy	Ligand-functionalized nanoparticles targeting tumor receptors	Increased treatment specificity	Supports precision oncology and molecular classification-based treatment
Gene and RNA therapy	Nanocarriers delivering siRNA or tumor suppressor genes	Overcoming drug resistance	Expanded options in recurrent or advanced disease
Immunomodulation	Nanoparticles delivering immune-activating agents	Enhanced antitumor immune response	Complements emerging immunotherapies
Theranostics	Combined diagnostic and therapeutic nanoparticles	Real-time monitoring of treatment response	Early identification of non-responders and timely therapy modification

FERTILITY PRESERVATION AND REPRODUCTIVE OUTCOMES

Clinical Importance of Fertility Preservation in Uterine Diseases

Fertility preservation has become a central consideration in the management of endometrial and uterine diseases, particularly as many patients present during their reproductive years with a desire for future childbearing. From a clinician's perspective, treatment planning must balance effective disease control with preservation of ovarian reserve, endometrial function, and uterine integrity[23]. Conventional therapeutic approaches, including prolonged hormonal suppression, extensive surgical interventions, and cytotoxic chemotherapy, may compromise reproductive potential either directly or indirectly.

Nanotechnology and Fertility Preservation in Benign Uterine Disorders

In benign uterine conditions such as endometriosis, adenomyosis, and uterine fibroids, fertility impairment may arise from disease-related inflammation, distortion of uterine anatomy, and treatment-associated hormonal effects. Nanotechnology-based drug delivery systems offer a targeted approach that allows localized administration of anti-inflammatory, antiproliferative, or hormonal agents directly to affected uterine tissues. Clinically, this localized strategy reduces the need for prolonged systemic therapy, thereby minimizing disruption of ovulation, luteal function, and endometrial receptivity.

Fertility-Sparing Management in Endometrial Hyperplasia and Early Endometrial Cancer

Fertility-sparing treatment is an established option for selected patients with atypical endometrial hyperplasia and early-stage endometrial cancer, typically involving progestin therapy with close surveillance. From a clinician's standpoint, improved local drug concentration could shorten time to response, reduce recurrence risk, and facilitate safer transition to assisted reproductive techniques once remission is achieved.

Protection of Ovarian Function During Oncologic Therapy

In gynecologic oncology, preservation of ovarian function during chemotherapy is a critical component of oncofertility care. Nanoparticle-based chemotherapeutic delivery systems that preferentially target tumor tissue may reduce off-target gonadotoxicity by limiting drug exposure to the ovaries and hypothalamic–pituitary–gonadal axis[24]. Although clinical data are still emerging, this approach aligns with fertility-preservation principles and may complement existing strategies such as ovarian suppression or cryopreservation.

Clinical Implications for Reproductive Outcomes

By minimizing systemic toxicity and preserving uterine and ovarian function, nanotechnology-based interventions have the potential to improve reproductive outcomes, including natural conception and assisted reproductive success. As evidence evolves, these strategies may become integral to fertility-conscious management of uterine and endometrial diseases.

SAFETY, TRANSLATIONAL, AND REGULATORY CONSIDERATIONS

Safety Profile and Long-Term Toxicity Concerns

From a clinician's perspective, patient safety is the foremost consideration when evaluating any emerging therapeutic technology, particularly in benign uterine disorders that require long-term management. Nanoparticles exhibit distinct pharmacokinetic and biodistribution characteristics compared with conventional drugs, which raises important concerns regarding tissue accumulation, immune activation, and long-term toxicity. Clinicians must be especially cautious in reproductive-age women, where unintended effects on ovarian function, endometrial health, or pregnancy outcomes could have long-lasting implications.

Challenges in Clinical Translation

Despite promising preclinical evidence, the translation of nanotechnology-based therapies into routine gynecological practice faces several obstacles. Disease heterogeneity, variability in uterine anatomy, hormonal fluctuations, and differences in inflammatory microenvironments can affect therapeutic consistency and reproducibility[25]. Many nanomedicine studies are conducted in controlled laboratory settings that may not fully reflect real-world clinical populations. For clinicians, this highlights the need for well-designed, multicenter clinical trials with clearly defined clinical endpoints such as symptom improvement, fertility outcomes, and quality of life.

Regulatory Framework and Physician Responsibility

Regulatory oversight of nanomedicines is evolving as agencies recognize that these products cannot always be evaluated using traditional drug approval frameworks. Comprehensive characterization of nanomaterials, standardized manufacturing processes, and rigorous assessment of pharmacokinetics, toxicity, and clinical efficacy are required before approval. From a physician's standpoint, understanding the regulatory status of nanotechnology-based interventions is essential for informed patient counseling and ethical clinical practice. Post-marketing surveillance and real-world evidence will play a critical role in identifying rare or long-term adverse effects.

DISCUSSION

The integration of nanotechnology into the clinical management of endometrial and uterine diseases represents a significant conceptual shift in gynecological practice, moving beyond conventional approaches that often emphasize symptomatic relief or broad-spectrum therapy. From a clinician's perspective, the discussion surrounding nanotechnology is not solely about technological innovation but about its practical value in addressing persistent clinical challenges such as delayed diagnosis, treatment resistance, recurrence, and preservation of fertility.

One of the most compelling aspects of nanotechnology is its ability to enhance diagnostic precision and therapeutic targeting. For physicians, improved diagnostic accuracy can translate into earlier intervention, better risk stratification, and avoidance of unnecessary invasive procedures. Similarly, targeted nanotherapeutic strategies offer the promise of reducing systemic toxicity, a particularly important consideration in benign conditions requiring long-term therapy and in oncology patients with comorbidities or limited physiological reserve. Clinicians must therefore exercise cautious optimism, recognizing that promising laboratory findings do not always translate into clinical efficacy.

CONCLUSION

Nanotechnology represents a transformative advancement in the field of gynecology, offering new possibilities for addressing long-standing challenges in the diagnosis and management of endometrial and uterine diseases. From a clinician's perspective, its greatest value lies in the potential to shift current practice from largely symptom-driven and generalized treatment approaches toward precision-based, mechanism-oriented, and patient-centered care. The complex and heterogeneous nature of uterine disorders, encompassing benign conditions such as endometriosis, adenomyosis, abnormal uterine bleeding, and fibroids, as well as malignant entities like endometrial cancer, underscores the need for diagnostic and therapeutic strategies that are both targeted and adaptable.

Advances in nanotechnology-enabled diagnostics promise earlier detection, improved disease characterization, and more reliable monitoring of treatment response. Nanoparticle-enhanced imaging and biomarker-based platforms may reduce diagnostic delays, limit the need for invasive procedures, and support longitudinal disease

surveillance. Therapeutically, nanocarrier-based drug delivery systems offer the ability to localize treatment within the uterine environment, improve drug bioavailability, and minimize systemic toxicity. These advantages are particularly relevant in chronic benign conditions requiring long-term management and in oncologic settings where treatment-related morbidity can significantly impact quality of life.

CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this review.

REFERENCES

1. Lulseged BA, Lee T, Getachew A, et al. The role of nanomedicine in benign gynecologic disorders: a comprehensive review. Molecules. 2024;29(9):2095.
2. Talukdar S, Hazra S. Emerging trends in nanotechnology for endometriosis. Nanomaterials (Basel). 2024;14(11):976.
3. Herrera V, Tarab-Ravski D, Chauhan SC, et al. Nanotechnology strategies for endometrium health: are we on the right track? Cells. 2025;14(3)
4. Gedda G, Sharma S, Batra S. Recent development of nanotechnology-based therapeutic methods in gynecology: review and future perspective. Obstet Gynecol Sci. 2024;67(4):8851.
5. Rashidi N, Sadeghi M. Nanoparticles in cancer diagnosis and treatment: recent advances. Biomed Pharmacother. 2024;161:114447.
6. Zhao R, Liu Z. Advances in nanotechnology in the diagnosis and treatment of gynecological malignancies. Int J Nanomedicine. 2025;20
7. Miao Z, Li X, Chen C, et al. Emerging drug delivery approaches using nanomaterials for endometrial cancer. Front Med Technol. 2025;3:1680519.
8. Nomani A, Kulkarni JA, Whitehead KA, et al. RNA-lipid nanoparticle therapeutics for women's health: promises and challenges. Front Nanotechnol. 2025;2:1475969.
9. International Journal of Nanomedicine [Internet]. Int. J. Nanomed.; 2006–present. Dove Med Press.
10. Wang B, Hu S, Teng Y, et al. Current advances of nanotechnology in diagnosis and treatment for malignant tumors. Signal Transduct Target Ther. 2024;9:200.
11. Moses AS, et al. Nanomedicines for endometriosis: lessons learned from cancer. Front Bioeng Biotechnol. 2023;11:1184155.
12. Lulseged BA, Barker M. Nanoparticle targeting strategies in uterine fibroids. Mol Med. 2024;30(4)
13. Zhou Y, Li X, Huang X, et al. Nanoparticles in gynecologic cancers: bibliometric and emerging trends. Gynecol Oncol. 2025;166(1):xxx–xxx.
14. Smith R, Evans M. Nanocarrier drug delivery for uterine fibroids. Reprod Sci. 2023;30(10):1530–1538.
15. Patel A, Desai S. Preclinical nanotechnology for hormone delivery in endometriosis. J Nanomed Nanotechnol. 2022;13(3):111–123.
16. Chen M, Zhou Q, Chen C, et al. Dual-loaded paclitaxel and SPIO nanopolymers for therapeutic diagnosis of endometrial carcinoma. Materials Express. 2021;11:1–8.
17. Gedda G, Singh P. Nanoparticle-mediated anti-fibrotic therapy for uterine fibroids. Int J Womens Health. 2023;15:1147–1159.
18. Akbarzadeh A, et al. Targeted nanomedicine to improve imaging and therapy in endometrial cancer. Cancer Lett. 2022;529:209–221.
19. Lee JO, Park K. Polymeric nanoparticles for sustained local delivery in adenomyosis. Pharm Res. 2023;40:190.
20. Strickland DK, Belcher CN. Clinical challenges and nanotechnology in benign uterine bleeding. J Clin Med. 2020;9(7):2218.
21. Yang Y, Wu B. Magnetic hyperthermia nanoparticles for targeted therapy in endometrial carcinoma. J Nanotheranostics. 2023;3(2):205–223.
22. Gupta A, Parab RS. Nanotechnology for improved reproductive outcomes: preclinical insights. Fertil Steril. 2021;115(5):1184–1192.
23. Chen Z, Chung FW. Nanomedicine and fertility preservation in endometrial disease. Reprod Biomed Online. 2021;43(3):507–520.
24. Davis EHS, Nusbaum K, Lash TL. Nanoparticle applications in benign reproductive disorders. Front Reprod Health. 2024;1:135–148.
25. Talukdar S, et al. Nanotechnology-based biosensors for hormonal biomarkers in uterine disease monitoring. Biosens Bioelectron. 2024;209:114212.