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Nanotechnology for reproductive healthcare: a comprehensive review

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Abstract

The advancement of nanotechnology has revolutionized reproductive healthcare worldwide. It has enabled the treatment of various conditions, such as infertility, endometriosis, ectopic pregnancies, erectile dysfunction, sexually transmitted infections (STIs), and reproductive tissue cancers. Nanotechnology offers improved imaging, personalized drug administration, and early diagnosis, leading to more accurate treatment outcomes. It can enhance fertility preservation, improve individualized therapy, and improve diagnostic methods. Additionally, nanotechnology-powered drug delivery systems increase effectiveness while reducing side effects. Clinical trials utilizing nanoparticles for cellular treatments, targeted drug delivery, early infection detection, reproductive system malignancies and precise medication delivery are currently underway. Nanotechnology has opened new possibilities in areas such as disease detection, drug administration, diagnostic imaging, and cancer treatment. This review aims to provide an overview of the different types, characteristics, and synthesis methods of nanocarriers designed for medication delivery in the context of reproductive disorders and diseases. It seeks to enhance the understanding of the current state of the art and explore potential future advancements in this field.

Keywords Nanotechnology, Reproductive health, Targeted drug delivery, Biosensor

Introduction

Reproductive medicine continues to confront substantial clinical challenges. Conditions such as infertility, endometriosis, polycystic ovary syndrome (PCOS), preeclampsia, and reproductive-tract infections affect millions worldwide and are often resistant to current diagnostic and therapeutic modalities [1–3]. Traditional approaches frequently suffer from low specificity, systemic toxicity, and inefficient delivery of therapeutics to reproductive tissues [4]. Furthermore, the intricate physiology of the reproductive tract, the immunological complexity of pregnancy, and the ethical constraints surrounding gamete and embryo manipulation underscore the need for novel, precision-based interventions ([5]. – [6])

Nanotechnology offers a transformative framework to address these unmet needs. Engineered nanomaterials—such as liposomes, polymeric nanoparticles, dendrimers, and metallic nanostructures—exhibit unique physicochemical characteristics that enhance drug stability, improve pharmacokinetics, and enable targeted delivery to specific reproductive organs [7, 8]. The clinical success of nanocarrier platforms in oncology and infectious diseases (e.g., liposomal doxorubicin, lipid-nanoparticle mRNA vaccines) provides a compelling precedent for their application in reproductive health [9].

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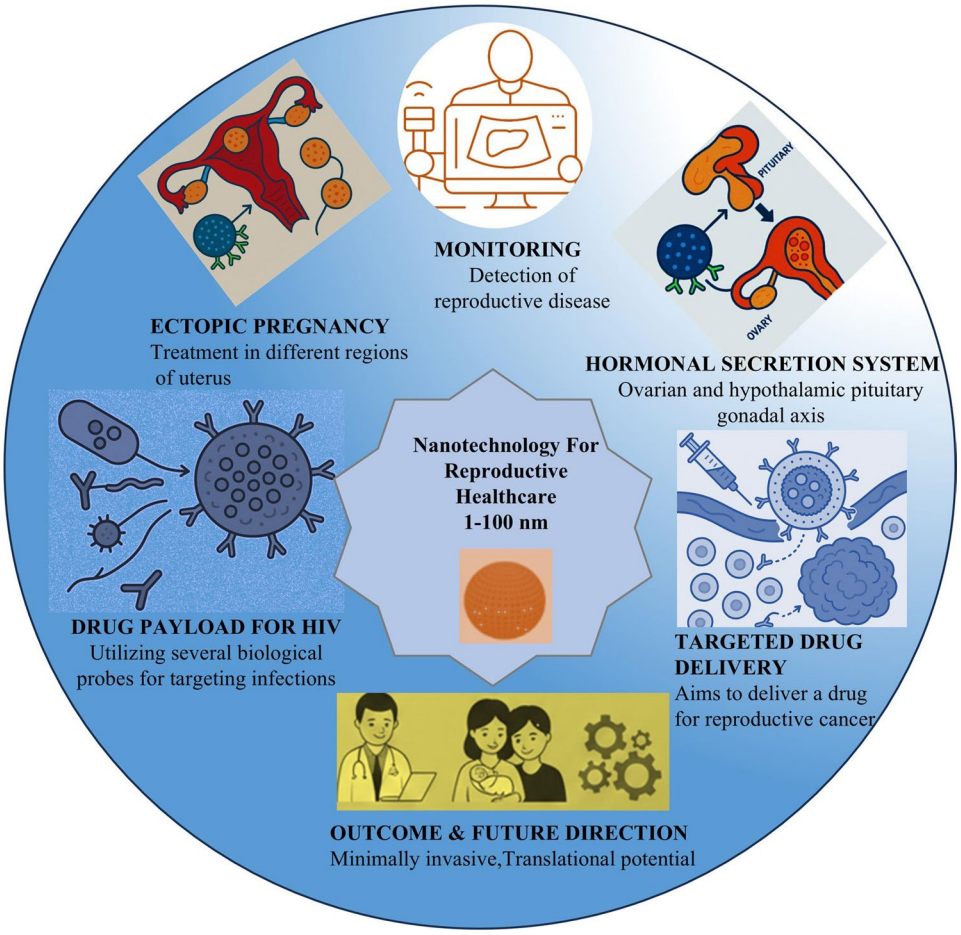
Graphical Abstract



Recent advances demonstrate the potential of nano-enabled strategies for a wide range of reproductive applications: targeted hormonal and gene delivery to ovarian tissue [10], nanocarrier-assisted therapy for endometriosis [11], nanosensors for non-invasive fertility and ovulation monitoring [12], and nanoparticle-based contraception [13]. In male reproductive medicine, nanotechnology is being explored for sperm selection, cryopreservation, and controlled delivery of antioxidants to counteract oxidative stress-related infertility [14]. Despite these promising developments, clinical translation remains limited due to gaps in reproductive toxicology data, challenges in long-term biocompatibility, and the lack of standardized regulatory frameworks [15–17].

Therefore, this review aims to provide a comprehensive overview of recent advances and the therapeutic potential of nanotechnology-based drug-delivery systems in the management of reproductive disorders. We discuss the major types of nanocarrier platforms currently explored—such as polymeric nanoparticles, liposomes, lipid-based systems, dendrimers, and inorganic nanomaterials—and how their tailored physicochemical properties enhance targeted and controlled delivery within reproductive tissues. Special emphasis is placed on the role of nanotechnology in modulating ovarian hormones, including nano-enabled approaches for restoring hormonal balance and improving outcomes in conditions such as PCOS, endometriosis, and ovarian insufficiency. Additionally, we summarize applications of nanomedicine in female reproductive health, covering its use in treating uterine and ovarian pathologies, improving fertility outcomes, and enhancing local therapeutic precision. Finally, we outline the future prospects of nanotechnology in reproductive medicine and assess recent developments in regulatory frameworks and safety evaluations, which are critical for translating nanoscale innovations into clinically viable, ethically sound reproductive-health solutions.

Types of delivery systems

Nanomedicine delivery systems have been developed to create drug and hormone delivery platforms via

nanotechnology design and manufacturing [18]. These systems are designed to transport medications to specific areas where they are administered. To encapsulate and protect medications, carrier materials such as nanomicelles, nanofibers, nanotubes, magnetic nanoparticles, etc., are used. This allows their release at appropriate locations and times [19]. Numerous fields, including oncological therapy, medication therapeutic interventions, genetic modification therapies, and immunization delivery, have heavily invested in studying and using nanomedicine delivery systems because of their unique benefits (Fig. 1).

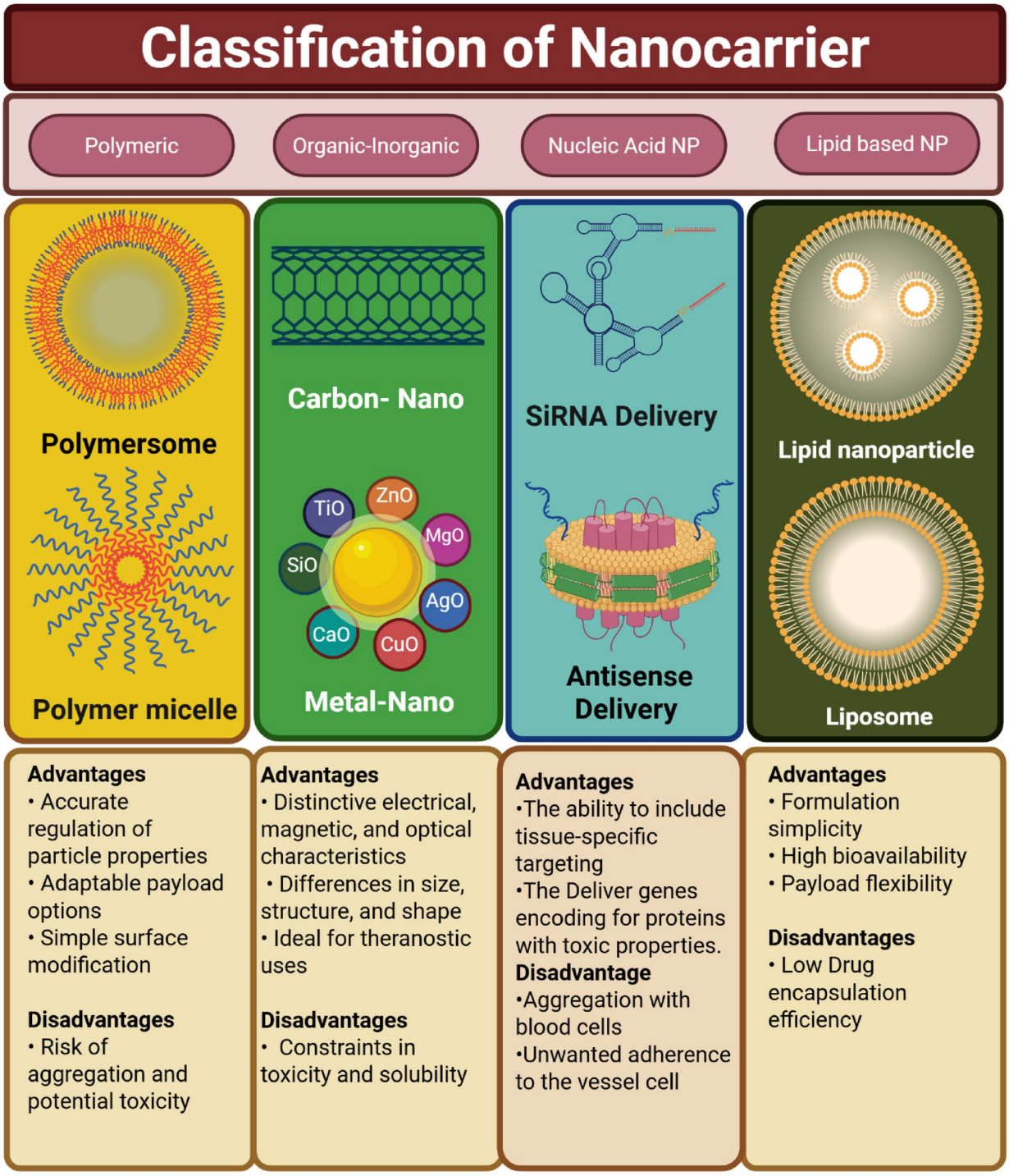


Fig. 1 Classifying nanomedicine delivery mechanisms

Nano-micelles are self-assembled amphiphilic nanostructures with hydrophobic cores and hydrophilic shells that encapsulate poorly water-soluble drugs, enhancing solubility, bioavailability, and mucosal permeation to improve therapeutic efficacy. They have been explored as targeted carriers for anti-inflammatory agents in endometriosis and related reproductive disorders, enabling localized and controlled drug release within the female reproductive tract [19]. A clinical trial reported that oral curcumin nanomicelles (120 mg/day for 10 weeks) significantly reduced follicular fluid TNF-α and IL-8 levels and improved fertilization and embryo quality in women with stage III/IV endometriosis [20]. In postoperative adhesion models, dexamethasone-loaded micelles in thermosensitive hydrogels markedly reduced adhesion scores compared with free drug or blank hydrogel [21]. Reviews on vaginal delivery emphasize that polymeric micelles improve residence time, bioavailability, and tissue targeting while minimizing systemic exposure [22]. In gynecologic oncology, cremophor-free paclitaxel micelles (Genexol-PM) have demonstrated feasibility and safety with carboplatin as first-line therapy for epithelial ovarian cancer [23]. Furthermore, lipid-modified chitosan micelles have shown selective lesion accumulation and therapeutic efficacy in endometriosis models [24].

Lipid nanoparticles (LNPs)—including ionizable LNPs, solid-lipid nanoparticles, and liposomes—have emerged as modular carriers for small molecules and nucleic acids in reproductive healthcare, enabling enhanced solubility, mucosal retention, and tissue-selective delivery across the vaginal and uterine tracts while limiting systemic exposure [25–27]. Preclinical and translational studies demonstrate LNP-enabled vaginal/uterine therapies (e.g., estradiol and other hormones) with improved local bioavailability and mucoadhesion [26–28], and growing interest in RNA-LNP approaches for gynecologic disorders and cancers [28, 29]. In maternal–fetal medicine, targeted LNPs have achieved in vivo mRNA delivery to the murine placenta via receptor-directed formulations (e.g., EGFR-targeted LNPs) and tuning of particle properties, while ex vivo human placental perfusion models are being used to quantify trans-placental passage and safety constraints [30, 31]. Magnetic nanoparticles (MNPs), typically composed of biocompatible iron, cobalt, or nickel oxides, have emerged as multifunctional tools in female reproductive healthcare for targeted therapy, imaging, and hyperthermia. Shalaby et al. developed a magnetic nanoparticle–based, programmable gene delivery system for uterine fibroid cells, enhancing adenoviral transfection efficiency and providing a potential non-invasive alternative to surgery [32]. In gynecologic oncology, Yi et al. reported that hybrid zinc–copper oxide magnetic nanocomposites encapsulated in micelles sensitized ovarian cancer cells to PARP inhibitors, suggesting utility in overcoming chemoresistance [33]. Other studies highlight iron-oxide MNPs as platforms for image-guided therapy and hyperthermia in endometriosis and ovarian cancer models, underscoring their growing therapeutic and diagnostic relevance in reproductive medicine [34, 35].

Nucleic acid nanomaterials, primarily DNA or RNA, are small particles ranging from 1 to 100 nm in size [36]. Chemical techniques can produce nanostructures, nanochips, and nucleic acid nanoparticles. Nucleic acid nanoparticles have emerged as versatile tools in gene therapy, drug delivery, diagnostics, and antimicrobial research, particularly in addressing female reproductive health issues [37]. According to Baxi et al., a lipid-derived nucleic acid nanocarrier can target reproductive system problems. Small interfering RNA-encapsulated lipidomic nanoparticles target reproductive gene silencing [38]. Garzon et al. examined the therapeutic applications of nanoparticles for treating endometriosis. A nanomedicine study by Yang et al. aimed to increase the local delivery of vaginal infection medications. Researchers have used nucleic acid nanoparticles to construct stable, permeability-enhancing nanocarriers for vaginal drug accumulation and therapeutic efficacy [39]. These materials can also be used to treat reproductive system conditions, including endometriosis and vaginal infections locally [40].

The incorporation of drugs such as acyclovir, emtricitabine, and remdesivir into nanocarriers enables targeted delivery and improved efficacy in treating reproductive disorders. Nanoscience has also led to the development of noninvasive biosensors that provide real-time insights into embryonic development and implantation viability. Table 1 summarizes advances in nanotechnology for managing conditions such as ovarian cancer, sexually transmitted infections (STIs), ectopic pregnancy, uterine fibroids, erectile dysfunction, endometriosis, and polycystic ovary disease (PCOD). Figure 2 presents an overview of nanoparticle-based strategies employed to manage reproductive disorders in male and female patients.

Table 1 Specific nanoparticles for reproductive disorders and their biomarkers

Reproductive disorders	Type of nanoparticle	Specific biomarkers or cell	References
Ovarian cancer	Gold Nanoparticles	HE4, CA125	[21–25]
Endometriosis	Polymer-based NPs	Stromal cells lining the fallopian tubes	[23–25]
Contraceptives and other STIs	Quantum dots	Bacterial and viral infections	[]
Chronic Polycystic Ovary Syndrome	Magnetic NPs	Receptors for insulin, androgen	[21–27]

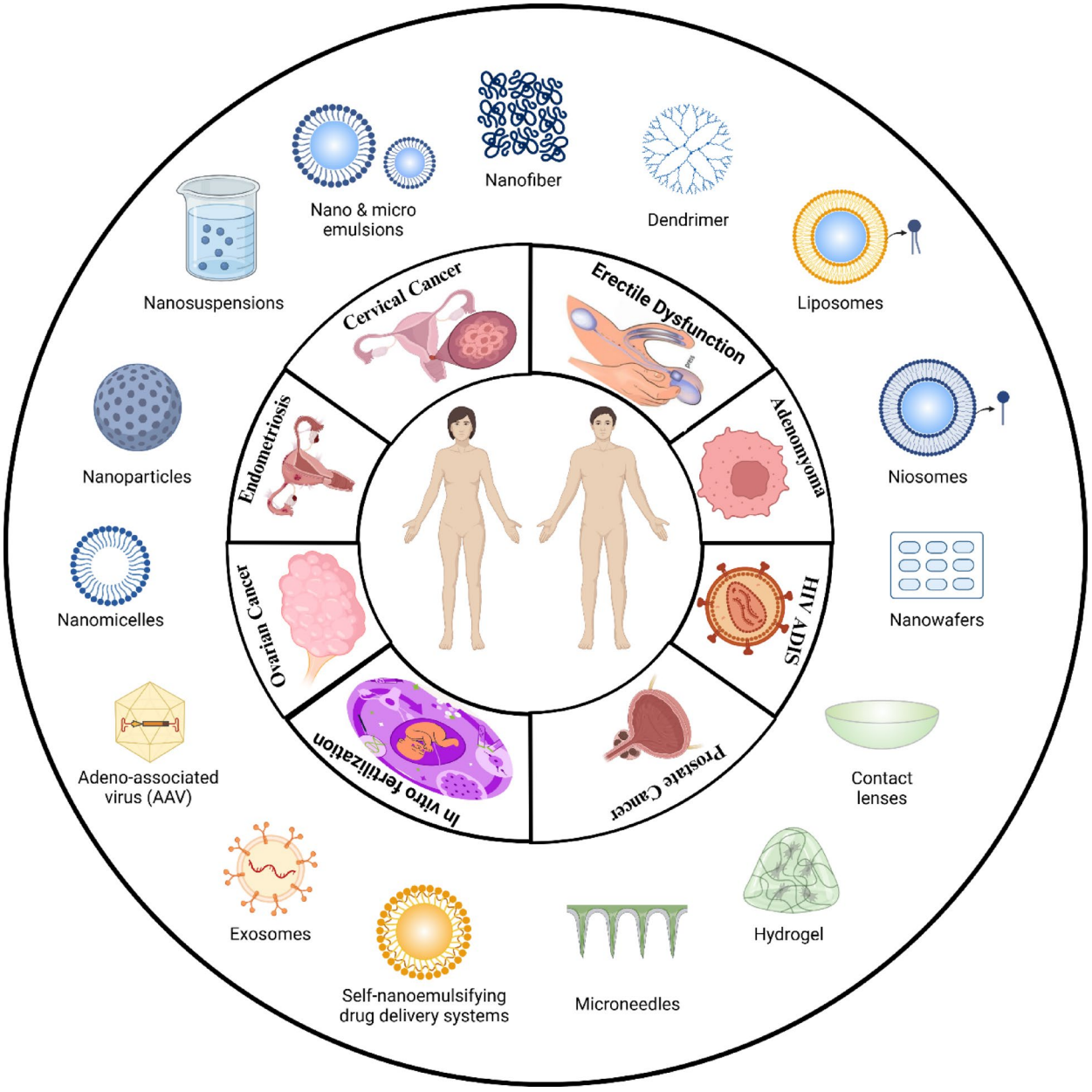


Fig. 2 Applying diverse nanoparticles to address multiple reproductive disorders in both women and men

Additionally, nanoparticles play a vital role in reproductive technologies, with their selection depending on specific applications. Gold NPs are used in assisted reproductive techniques like IVF to enhance sperm motility and embryo development, while silver nanoparticles act as antibacterial agents during intrauterine insemination (IUI) procedures [41]. Polymeric nanoparticles enable controlled drug release for conditions such as endometriosis and polycystic ovarian syndrome [42], whereas inorganic types like silica nanoparticles improve imaging of reproductive organs. Other systems—including polymer micelles, dendrosomes, nanospheres, and quantum dots—facilitate targeted drug delivery and enhance therapeutic efficacy while minimizing side effects [43]. Liposomes and lipid nanoparticles encapsulate hormones and growth factors to improve stability and bioavailability. Proper nanoparticle selection requires consideration of size, surface charge, biocompatibility, and targeting ability, along with toxicity and long-term safety evaluations. Table 2 summarizes the chemical and physical attributes of nanoparticles for optimized drug delivery, and Fig. 3 illustrates the encapsulation process of pharmaceuticals using polymers and ligands. Naturally derived nanoparticles have gained attention for their biocompatibility, low toxicity, and sustainability, offering controlled and prolonged drug release verified

Table 2 Unique characteristics of nanoparticles utilized in reproductive medicine and frequently employed Preparation techniques

NP type	Preparation methods	Particle size	Types of drugs	Application in reproductive diseases	Advantages	Disadvantages	Refs.
Albumin NPs	Coacervation, desolvation	50–200 nm	Hydrophobic drugs	Ovarian cancer therapy, contraception	Biocompatible, biodegradable	Limited stability, potential immunogenicity	[44, 45]
Ceramic NPs	Sol–gel synthesis, coprecipitation	10–200 nm	Various	Drug delivery, male contraception	Biocompatible, versatile	Limited drug loading, potential toxicity	4647]
Chitosan NPs	Ionic gelation, coacervation	10–500 nm	Hydrophilic drugs	Vaginal drug delivery, sexually transmitted infection treatment	Biocompatible, mucoadhesive	Limited drug loading, potential stability issues	[48, 49]
CNTs	Chemical vapor deposition (CVD), arc discharge	1–100 nm	Hydrophobic drugs	Drug delivery, male infertility treatment	High aspect ratio, unique structure	Potential toxicity, challenging production	[50, 51]
Dendrimers	Divergent or convergent synthesis	1–10 nm	Various	Gene delivery, sexually transmitted infection treatment	Controlled structure, multivalency	Potential toxicity, complex synthesis	[52, 53]
Gold NPs	Citrate reduction, seed-mediated growth	2–100 nm	Various, including anticancer drugs	Imaging, ovarian cancer therapy	Photothermal therapy, surface modification	Limited drug capacity, potential toxicity	[54–56]
Iron Oxide NPs	Coprecipitation, thermal decomposition	5–100 nm	Contrast agents for imaging	Imaging, uterine fibroids treatment	Biodegradable, versatile	Potential toxicity, stability concerns	[57, 58]
Lipid NPs	High-pressure homogenization, microemulsion	50–500 nm	Hydrophobic drugs	Drug delivery, contraception	Biocompatible, controlled-release	Limited drug loading, potential stability issues	[59, 60]
Liposomes	Thin film hydration, sonication	50–200 nm	Hydrophilic and hydrophobic drugs	Gene delivery, contraception	Targeted drug delivery, biocompatible	Batch-to-batch variability, limited stability	[61, 62]
Magnetic NPs	Coprecipitation, thermal decomposition	5–100 nm	Various (often used for hyperthermia)	Hyperthermia, assisted reproductive technologies	Magnetic targeting	Potential toxicity, stability concerns	[63, 64]
PLGA-PEG NPs	Emulsion solvent evaporation	10–200 nm	Hydrophobic drugs	Drug delivery, imaging	Extended circulation time	Potential toxicity, complex synthesis	[65–67]
Polymer Micelles	Self-assembly	10–100 nm	Hydrophobic drugs	Drug delivery, gene therapy	Improved stability, controlled release	Limited drug loading, potential toxicity	[68, 69]
Polymeric NPs	Emulsion polymerization, solvent evaporation	10–200 nm	Variety (depends on the polymer)	Contraception, endometriosis treatment	Controlled release, stability	Potential toxicity, complex synthesis	[70, 71]
QDs	Colloidal synthesis	2–10 nm	Various, often used for imaging	Imaging, diagnostics	Bright fluorescence, tunable emission	Cadmium toxicity, potential environmental impact	[43, 72, 73]
Silica NPs	Stöber synthesis, sol–gel method	10–200 nm	Hydrophobic drugs	Ovarian cancer treatment, drug delivery	High surface area, biocompatible	Limited drug loading, potential toxicity	[74, 75]
Solid Lipid NPs	High-pressure homogenization, microemulsion	50–1000 nm	Hydrophobic drugs	Hormone therapy, endometriosis treatment	Improved stability, controlled release	Limited drug loading, potential toxicity	[76, 77]

by pharmacokinetic studies. These eco-friendly materials reduce reliance on synthetic carriers, aligning with global efforts toward greener biomedical technologies. Table 3 outlines key nanoparticle synthesis techniques, while Table 4 lists natural polymers utilized in nanocarrier development for reproductive disorder treatment.

Potential of nanotechnology in the regulation of ovarian hormones

Ovarian hormones, such as estrogen and progesterone, play crucial roles in the female reproductive system. Nanotechnology offers promising applications for regulating the synthesis, release, and response time of these hormones (Fig. 4). Case studies highlight that nanoparticles can be engineered to influence the secretion, delivery, and activity of key ovarian hormones—estrogen and progesterone—through precise biochemical and cellular mechanisms. For instance, chitosan-based nanocarriers encapsulating gonadotropin-releasing hormone (GnRH) have demonstrated the ability to modulate luteinizing hormone (LH) and follicle-stimulating hormone (FSH) release, thereby indirectly regulating ovarian steroidogenesis and ovulation timing in vivo [122]. Similarly, lipid- and polymer-based progesterone nanocarriers have achieved enhanced bioavailability, controlled release, and improved endometrial response in clinical settings,

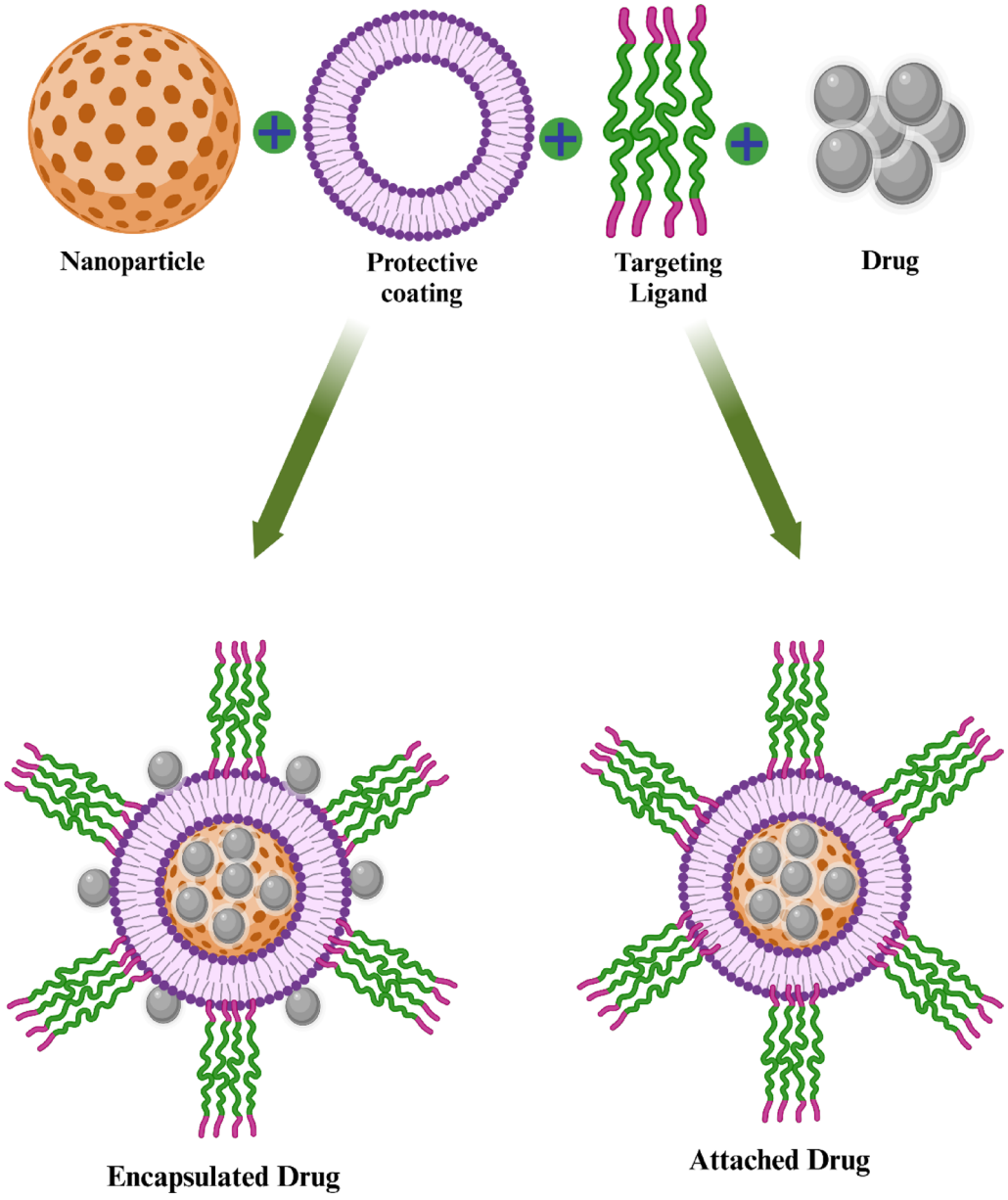


Fig. 3 Incorporating the necessary drug with crucial nanoparticles and polymers to create a targeted delivery mechanism for addressing reproductive system disorders

underscoring their translational relevance for luteal-phase support and infertility management [27]. On the other hand, studies on metallic and silica nanoparticles reveal that uncontrolled nanoparticle exposure can accumulate in granulosa and thecal cells, altering aromatase activity and steroidogenic enzyme expression, leading to dysregulated estrogen and progesterone synthesis [123]. These findings collectively demonstrate that nanotechnology can either therapeutically regulate or inadvertently disrupt ovarian hormonal balance, depending on its design and biodistribution. The core innovation lies in the ability of nanomaterials to precisely interact with the hypothalamic–pituitary–gonadal axis or directly with ovarian steroidogenic cells, offering both opportunities for targeted endocrine therapy and essential insights for reproductive toxicology. Translationally, the integration of biodegradable, hormone-responsive, and ligand-targeted nanocarriers holds promise for precision hormone replacement, fertility modulation, and ovarian function restoration, marking a significant step toward personalized reproductive nanomedicine.

Estrogen

Nanotechnology allows for the modulation of estrogen levels by altering ovarian feedback pathways. Nucleic acid-based nanoparticles can target and inhibit the

Table 3 Predominant nanoparticle fabrication techniques for enhanced reproductive drug Delivery, including all necessary specifications

Preparation method	Description	Examples of nanoparticles	Types of drugs for reproductive disorders	Examples of encapsulated drugs	Properties	Advantages	Disadvantages	Refs.
Coacervation	Phase separation leading to the formation of coacervate droplets containing the drug	Albumin nanoparticles	Anticancer drugs, hormone therapy	Paclitaxel, Doxorubicin, Insulin	Biodegradable, controlled release	Biocompatible, sustained drug release	Limited scalability, potential instability	[78, 79]
Coprecipitation	Simultaneous precipitation of drug and carrier materials from a solution	Iron oxide nanoparticles	Imaging agents, hyperthermia	Doxorubicin, Magnetic Resonance Imaging Agents	Magnetic properties, controlled release	Scalable, biocompatible	Limited control over particle size, potential impurities	[80–82]
Emulsion Solvent Evaporation	Organic phase dispersed in aqueous phase, solvent evaporation yields nanoparticles	PLGA-PEG nanoparticles, Liposomes	Hormones, contraceptives, fertility drugs	Estradiol, Levonorgestrel, Methotrexate	Controlled release, biocompatible	High drug loading, versatile	Potential toxicity of organic solvents	[83, 84]
High-Pressure Homogenization	Mechanical force to break down particles into nanoscale through high pressure	Solid lipid nanoparticles, Lipid nanocarriers	Anticancer drugs, gene therapy	Docetaxel, Paclitaxel, siRNA	Improved stability, controlled release	High drug loading, scalability	Equipment cost, potential impact on drug integrity	[85, 86]
Ionic Gelation	Formation of nanoparticles through ionic interactions between polymers and counterions	Chitosan nanoparticles	Anti-inflammatory drugs, antimicrobials	Ibuprofen, Insulin	Mucoadhesive, biocompatible	Simple and cost-effective, sustained release	Limited stability, potential burst release	[87–89]
Microemulsion	Maintaining thermal stability in oil-water-surfactant-cosurfactant colloidal systems	Nanoemulsions, Microemulsion-based nanoparticles	Antifungals, hormones, fertility drugs	Clotrimazole, Estradiol, Norethindrone	Enhanced drug solubility, stability	Improved bioavailability, ease of scale-up	Formulation complexity, potential toxicity of surfactants	[90–92]
Nanoprecipitation	Rapid mixing of organic and aqueous phases resulting in nanoparticle precipitation	Polymeric nanoparticles, Lipid nanoparticles	Anticancer drugs, contraceptives	Docetaxel, Rapamycin, Resveratrol	Small particle size, scalability	Simple process, reproducible	Limited control over particle size distribution	[93, 94]

Table 3 (continued)

Preparation method	Description	Examples of nanoparticles	Types of drugs for reproductive disorders	Examples of encapsulated drugs	Properties	Advantages	Disadvantages	Refs.
Self-Assembly	Spontaneous organization of molecules into nanoparticles driven by forces like hydrophobicity	Polymer micelles, Lipid nanoparticles	Gene delivery, hormone therapy	siRNA, Testosterone, Paclitaxel	Controlled release, stability	Simple process, versatile	Limited payload capacity, potential instability	[95, 96]
Sol–Gel Synthesis	Conversion of precursor solution or sol into a gel, followed by drying to form nanoparticles	Silica nanoparticles, Cera	Imaging agents, drug delivery	Paclitaxel, Doxorubicin, siRNA	Biocompatible, high surface area	Controlled size and shversatile	Long processing time, potential toxicity of precursors	[97, 98]
Solvent Displacement	Displacement of a solvent by an antisolvent, causing precipitation of nanoparticles	Polymeric nanoparticles, Lipid nanoparticles	Anticancer drugs, contraceptives	Paclitaxel, Levonorgestrel, siRNA	Controlled release, biocompatible	Simple and scalable, versatility	Residual solvents, potential stability issues	[99, 100]
Thin Film Hydration	Lipid films hydrated to form liposomes or solid lipid nanoparticles	Liposomes, Solid lipid nanoparticles	Antifungals, anti-inflammatories, gene therapy	Amphotericin B, Curcumin, siRNA	Versatile, biocompatible	Controlled release, stability	Batch-to-batch variability, potential oxidation	[101, 102]

regulatory components involved in estrogen synthesis to reduce estrogen production and release [124]. The use of nanoparticles, nanocapsules, and other carriers has been significant in delivering antiestrogen medications, improving stability, bioavailability, and targeted administration, thus aiding in dose reduction and minimizing side effects [103, 125]. Gene therapy medications, including siRNA, have been effectively delivered via nucleic acid nanomaterials, such as polymer nanoparticles and liposomes, to regulate estrogen production and modulate response mechanisms. This approach to gene therapy makes use of nanomaterial carriers to improve medication delivery and open up new possibilities for treatment.

Progesterone

Conventional progesterone therapy remains limited by pharmacokinetic and physiological constraints, including poor aqueous solubility, rapid hepatic metabolism, and low oral bioavailability, which collectively result in subtherapeutic and inconsistent systemic levels [126]. Vaginal administration provides an alternative route that bypasses first-pass metabolism, but it suffers from short mucosal residence time and fluctuating absorption [127]. Nanotechnology-enabled drug delivery systems have been developed to overcome these challenges by improving solubility, enhancing mucosal penetration, and enabling targeted tissue delivery. Among these, ligand-decorated nanoconstructs specifically designed to recognize the progesterone receptor (PR) represent a promising direction. A key example is the ProGlo series—progesterone–gadolinium (Gd) conjugates engineered for magnetic resonance imaging—which demonstrated selective accumulation and enhanced signal intensity in PR-rich uterine and tumor tissues, confirming receptor-mediated targeting in vivo [128]. Although originally designed as imaging probes, this approach establishes a mechanistic framework for the development of PR-ligand-functionalized nanocarriers for targeted drug delivery in reproductive medicine.

In parallel, non-ligand nanocarriers such as transethosomes, liposomes, and electrospun nanofibers have been applied to improve progesterone bioavailability and local retention. In a randomized clinical trial, progesterone-loaded transethosomes embedded in a mucoadhesive gel (particle size 133–350 nm, encapsulation efficiency 88–97%) demonstrated significant increases in serum progesterone levels, endometrial thickness, and pregnancy rate in anovulatory PCOS patients compared

Table 4 Expanding on particular natural polymers employed in the formulation of carriers incorporating nanoparticles for enhanced drug delivery

Natural polymer	Examples	Properties	Incorporation methods	Specific drug delivery example in reproductive disorder	Refs.
Alginate	Alginate microspheres, nanoparticles	Biocompatible, biodegradable, gel-forming	Ionotropic gelation, emulsification	Alginate nanoparticles for sustained release of progesterone	[103–105]
Chitosan	Chitosan hydrogel, nanoparticles	Biocompatible, mucoadhesive, antimicrobial	Ionic gelation, coacervation, and emulsification	Chitosan nanoparticles for delivering siRNA in ovarian cancer	[106, 107]
Dextran	Dextran nanoparticles	Biocompatible, water-soluble, low toxicity	Nanoprecipitation, emulsion	Dextran nanoparticles for delivery of anti-inflammatory drugs in pelvic inflammatory disease	[108, 109]
Gelatin	Gelatin nanoparticles	Biodegradable, biocompatible, low antigenicity	Coacervation, desolvation	Gelatin nanoparticles for controlled release of estradiol	[110, 111]
Guar Gum	Guar gum nanoparticles	Biodegradable, mucoadhesive, nontoxic	Coacervation, emulsification	Guar gum nanoparticles for delivery of metformin in polycystic ovary syndrome	[112, 113]
Hyaluronic Acid	Hyaluronic acid nanoparticles	Biocompatible, viscoelastic, lubricating	Cross-linking, self-assembly	Nanoparticles derived from hyaluronic acid for endometriosis targeted delivery	[114, 115]
Pectin	Pectin nanoparticles	Biodegradable, mucoadhesive, gelling agent	Ionic gelation, coacervation	Microparticles made of pectin that release misoprostol in a regulated manner during an abortion	[115, 116]
Poly(lactic-co-glycolic acid) (PLGA)	PLGA nanoparticles	Biodegradable, tunable degradation rate	Double emulsion, solvent evaporation	Agonist treatment with gonadotropin-releasing hormone agonist delivered by PLGA nanoparticles in endometriosis	[113, 117]
Polyethylene Glycol (PEG)	PEGylated nanoparticles	Hydrophilic, biocompatible, stealth effect	Conjugation, blending	PEGylated nanoparticles for targeted delivery of anticancer drugs in ovarian cancer	[118, 119]
Silk Fibroin	Silk fibroin nanoparticles	Biocompatible, biodegradable, versatile	Electrospinning, coacervation	Silk fibroin nanoparticles for doxorubicin delivery in cervical cancer	[120, 121]

with conventional formulations [129]. Similarly, electrospun cellulose acetate and polycaprolactone (PCL) nanofibers have shown sustained release and enhanced mucosal adhesion properties, offering localized and prolonged progesterone delivery. Recent work integrating PCL nanofiber coatings onto Arabin pessaries illustrates the potential for device-assisted, site-specific hormone delivery aimed at preventing preterm birth [130, 131]. Collectively, these studies demonstrate that nanotechnology-based progesterone delivery systems not only improve pharmacokinetic performance but also open new avenues for receptor-specific and localized hormonal therapy in reproductive health.

Follicle-stimulating hormone (FSH) and luteinizing hormone (LH)

Nanotechnology can influence luteinizing hormone (LH) and follicle-stimulating hormone (FSH) secretion primarily through controlled delivery of gonadotropin-releasing hormone (GnRH), which regulates pituitary output. Encapsulation of GnRH in biodegradable chitosan nanoparticles has been shown to modulate the timing and amplitude of the LH surge and ovulation by providing sustained or pulsatile release in animal models, demonstrating an indirect yet functional control of gonadotropin secretion [122]. In contrast, nanoparticle systems designed to "capture and release" FSH generally refer to nano-encapsulation strategies—for example, FSH-loaded liposomes and nanostructured lipid carriers that physically entrap the hormone and release it gradually, thereby enhancing its stability, bioavailability, and ovarian bioactivity without altering endogenous secretion [132]. Other platforms employ molecularly imprinted polymer (MIP) nanoparticles or aptamer-based biosensors to capture FSH in vitro for analytical detection and hormone monitoring rather than therapeutic modulation [133, 134]. Thus, while nanotechnology does not directly control pituitary secretion, it enables precise modulation of GnRH delivery kinetics and FSH bioavailability, offering novel endocrine and diagnostic tools for reproductive regulation. (Fig. 5).

Nanotechnology for the female reproductive system and associated illnesses

Various nanoparticles are used to administer drugs for female reproductive issues in different ways. Liposomes contain drugs that attach to cell membranes for targeted delivery. Quantum dots can carry drugs and provide imaging capabilities, whereas the biocompatibility of graphene oxide is enhanced through surface modifications and drug loading. Each material is chosen on the basis of the specific treatment needs and the conditions being targeted to ensure controlled release, accurate drug delivery, and improved therapeutic effectiveness in female

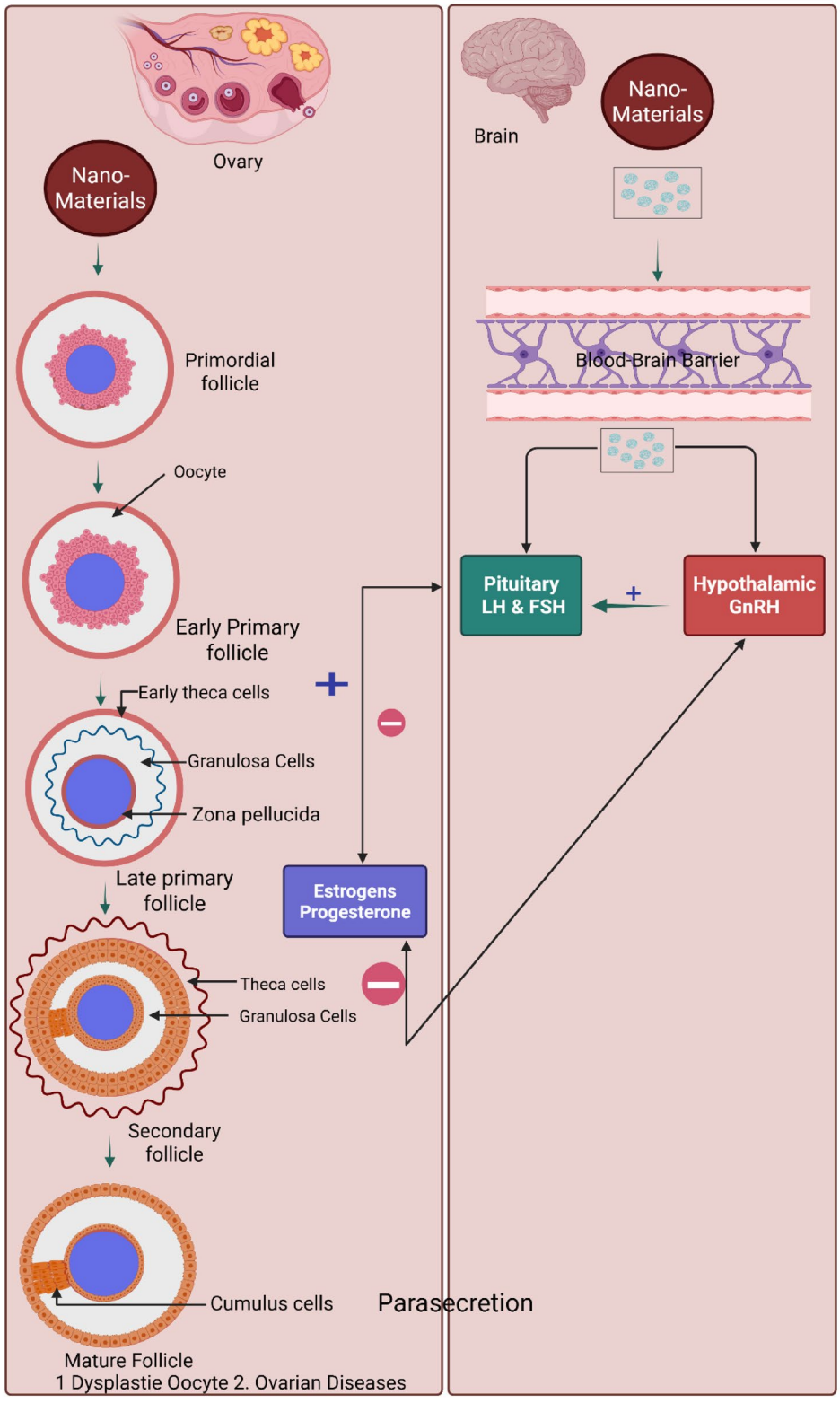


Fig. 4 (See legend on next page.)

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Fig. 4 The Utilization of nanotechnology within the hormonal secretion system of the ovarian and hypothalamic-pituitary-gonadal axis. Nanoparticles have the capacity to affect hormone secretion through two primary pathways: 1) by crossing the blood-brain barrier to target hypothalamic and pituitary secretory cells, thereby altering the release of GnRH, LH, and FSH hormones. As a result, this modification disrupts the complex feedback mechanisms of the hypothalamic-pituitary-gonadal axis, which affects the normal secretion of ovarian estrogen and progesterone) by circulating to the ovaries, where they accumulate in the membrane and granulosa cells, disrupting steroidogenesis. These irregular hormonal secretions, in turn, impair oocyte development and may lead to the development of various ovarian disorders

reproductive disorders. Hydrogels, dendrimers, carbon nanotubes, scaffolds, and gold nanoparticles are also utilized [135].

Biomolecules linked with nanoparticles for use in the early stages of cancer detection

Biomolecules are linked with nanoparticles for early cancer detection in the female reproductive system, which is susceptible to various malignancies, such as ovarian, cervical, endometrial and vaginal cancers [136]. Its early detection is crucial for improving treatment outcomes and survival rates, as many early-stage cancers do not present any symptoms. Therefore, it is essential to improve patient outcomes by exploring early diagnostic strategies.

Cervical cancer

Cervical cancer is a prevalent malignant neoplasm among females, with the cervical region being the most common site for it to occur. Worldwide, the prevalence of this malignancy has been increasing among younger people in recent years [137, 138]. Many fields, including medicine, cellular and molecular research, and imaging, rely on fluorescence imaging (FI) to better understand and visualize biological samples [139]. The precise targeting of lesions using nanoparticles coated with ligand-modified fluorescent dyes facilitates both initial diagnosis and subsequent treatment. Using near-infrared fluorescence imaging, Choi et al. monitored in vivo tumors and distant tumor cells; in addition, nanoparticles were developed to focus on cervical cancer cells that overexpress CD44 (Fig. 6) [140]. Additionally, Alomari et al. clarified drug internalization by improving TAM delivery to ER-negative cervical carcinoma cells treated with nanoparticles made of poly(methyl methacrylate) and tamoxifen (TAM) encapsulating Nile red [141]. The optical responses of the subcellular-targeting nanoprobes created by Budhathoki et al. were used to validate their effectiveness in nuclear targeting. Furthermore, diagnostic imaging has made use of FI nanoparticles that respond to the tumor microenvironment [142]. Cervical cancer detection and monitoring extensively utilize a hybrid imaging technique called photoacoustic imaging (PAI), which integrates optical and acoustic principles [143]. Using nanocomposites with high near-infrared absorption, Zhang et al. created a PAI platform that can detect drug accumulation in tumors and acquire strong signals [144]. Rad et al. developed a reliable framework utilizing BSA-Bi2S3-MnO2 nano disks to obtain high-quality near-infrared absorption images [145]. The increased spatial resolution of photoacoustic imaging, in contrast to conventional ultrasonography, allows for more precise morphological identification of tissue features, which in turn makes it easier to detect and localize early lesions [146]. Multimodal imaging capabilities, made possible by the complementary utilization of photoacoustic imaging in conjunction with additional techniques such as fluorescence and ultrasonic imaging, allow for the acquisition of detailed data from multiple angles. This multimodal imaging method improves the accuracy of cervical cancer diagnosis by allowing doctors to evaluate the morphological, functional, and molecular-level properties of tissues all at once. Thorough imaging of affected areas and functional information can be obtained with nanoparticle-enhanced magnetic resonance imaging (no irradiation) [147]. Magnetic resonance imaging (MRI) techniques based on nanomaterials offer significant advantages in the context of cervical cancer. These techniques not only enhance early diagnosis and localization but also provide clearer anatomical structures of tissues and the ability to delineate tumors. For example, Liu et al. achieved impressive imaging results in both in vitro and in vivo MRI using nanoparticles of biocompatible copper oxide and iron, which exhibit increased contrast compared with dyes [148]. In addition, Luong et al. developed cores of iron oxide that are superparamagnetic nanoparticles decorated with dendrimers of folate and poly(amidoamine). These cores encapsulate nanoparticles containing 3,4-difluorobenzylurea and curcumin, which have anticancer activity, increase drug accumulation, and provide better contrast in magnetic resonance imaging [149]. However, various techniques, such as photoacoustic imaging (PPAI) and magnetic resonance imaging (MRI) based on nanomaterials, have shown promising results in the early detection and treatment of cervical cancer.

Despite the significant potential of nanotechnology-based imaging and therapeutic systems, including fluorescence imaging (FI), photoacoustic imaging (PAI), and magnetic resonance imaging (MRI), in enhancing the early detection and treatment of cervical cancer, numerous challenges continue to prevent their clinical translation. The primary challenges involve the difficulty of achieving accurate and selective targeting of

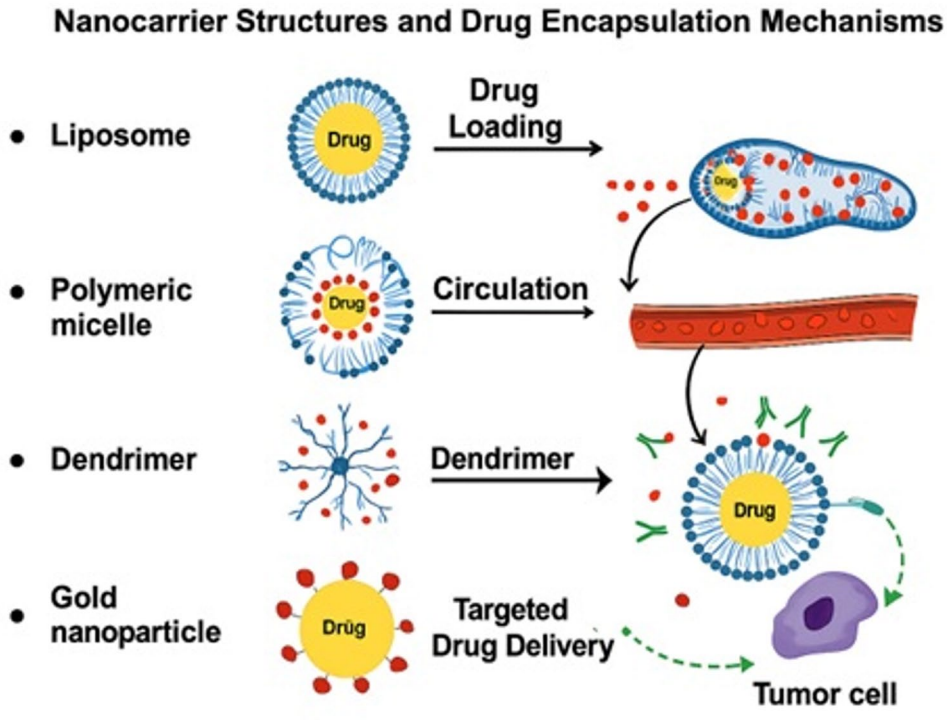

Fig. 5 Shows a schematic diagram explaining the process of drug loading and targeted delivery

nanoparticles to cervical tumor locations, hindered by biological barriers such as mucus and the varied nature of tumor microenvironments. Moreover, fluctuations in nanoparticle stability, biodistribution, and biocompatibility may diminish imaging precision and therapeutic effectiveness. Unresolved issues about nanotoxicity, possible immune responses, and long-term safety persist, while the complex synthesis, repeatability, and large-scale production of multifunctional nanoparticles present further challenges. Furthermore, despite robust laboratory findings, inadequate clinical validation and regulatory ambiguity persist in hindering the extensive implementation of nanotechnology in the detection and treatment of cervical cancer.

Ovarian carcinoma

Ovarian cancer is more prevalent in older women than in younger women because of the increased risk associated with advanced age. Some genetic mutations, specifically in the BRCA1 and BRCA2 genes, have been recognized as potential risk factors for ovarian cancer [134]. Numerous medications have been incorporated into particular polymeric materials to improve their characteristics and functionality in recent years. The application of these polymers in conjunction with pharmaceuticals has demonstrated significant promise in various domains, including controlled drug delivery systems and tissue engineering. Table 5 presents a compilation of various frequently utilized medications alongside their corresponding polymeric materials.

Extensive research on these drug–polymer combinations has revealed promising results regarding their biocompatibility and rate of drug release [145, 160]. It also reveals newly developed anticancer medications and commonly used nanoparticles that can be integrated for optimal delivery in ovarian cancer. The imaging technique employs nanoparticles, micelles, liposomes, and quantum dots to specifically target cancer cells in the ovarian area. It is possible that nanotechnologies might be created to administer therapeutic drugs to the exact location of the neoplasm, increasing their concentration and efficacy against cancer cells [161, 162]. The active targeting method involves the utilization of certain chemicals or antibodies capable of detecting and adhering to specific surface indicators found on cancer stem cells. By incorporating these antibodies or targeting compounds onto generic nanoparticles, medicinal medications can be delivered to cancer stem cells with targeted accuracy. The efficacy of these targeted nanoparticles can be enhanced by including a stimulus-responsive drug release system [163]. This method facilitates the regulated administration of pharmaceutical compounds in response to specified stimuli, such as changes in temperature, pH, or the presence of specific enzymes. There is a confirmed report that the medications are released solely at the appropriate time and location [164, 165]. After binding to CSC markers, these moieties may release drugs from internal

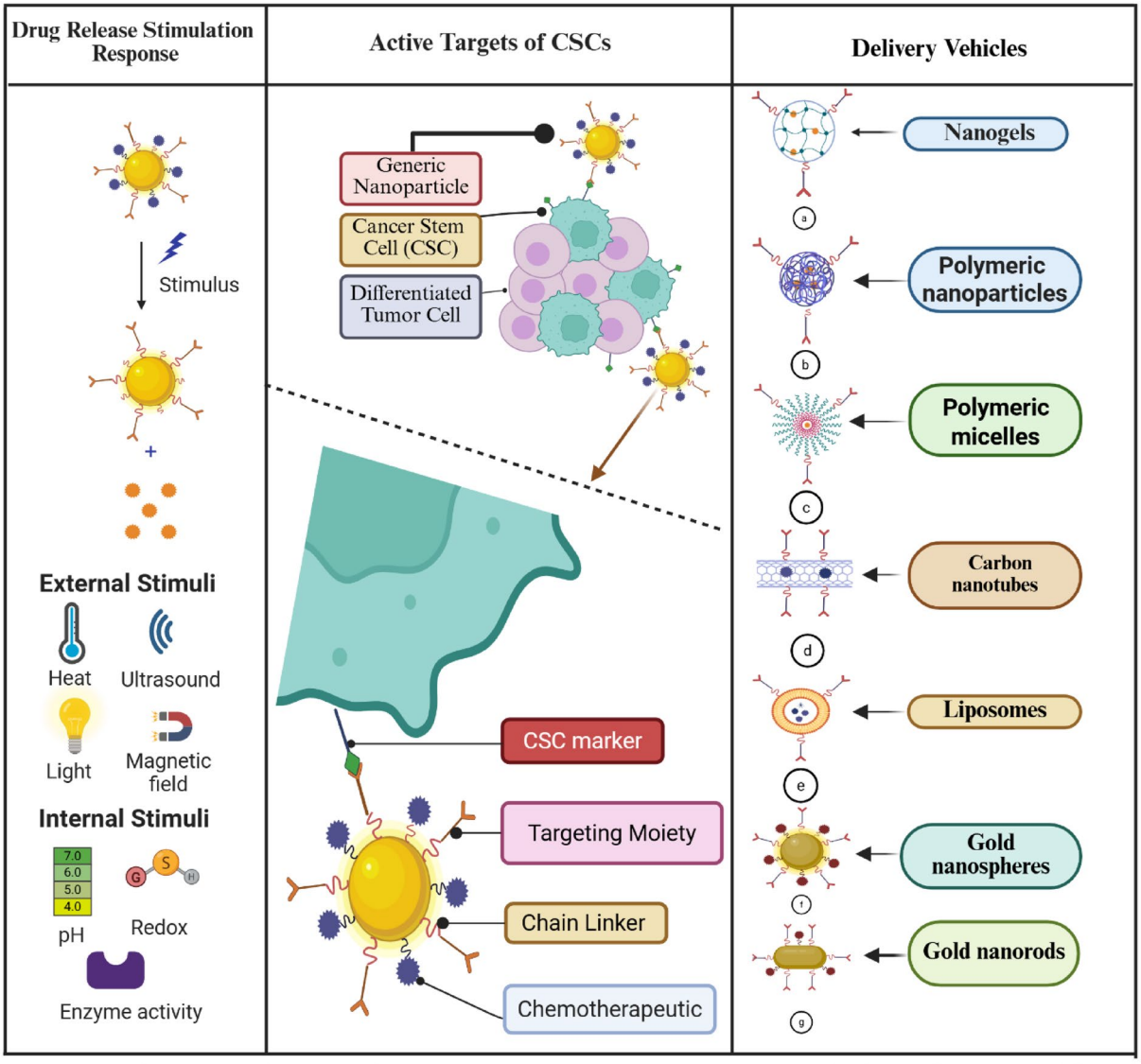

Fig. 6 The interaction of nanoparticles carrying drugs with ovarian cancer aims to prevent the proliferation of cancerous cells

and external sources [166–168]. Various nanoparticle-mediated distribution networks that rely on these technologies have been developed, as shown in Fig. 6(a – g).

The use of nanotechnology to transport therapeutic genes directly into cells offers hope for resolving genetic mutations and reestablishing normal function [169]. The potential of nanocarriers to increase gene transport efficiency, decrease off-target effects, and target with pinpoint accuracy makes them attractive alternatives to traditional reproductive therapy [170]. Zhao et al. effectively used a gene therapy technique to treat endometriosis by enclosing components taken from the pigment epithelium in lipid-grafted chitosan micelles within a plasmid [171]. Endometriotic infections, ectopic endometrial tissue atrophy, and degeneration are significantly reduced by nanoparticles packed with small interfering RNA (siRNA) [172]. Unlike cRGD-conjugated fifth-generation PAMAM dendrimers, gene therapy researchers may now deliver siRNAs precisely to spermatogonial stem cells (SSCs) [173]. The procedure for treating ovarian cancer with apoptosis-induced gene therapy is shown in Fig. 7. These technologies may facilitate targeted drug delivery to cancer cells, improving treatment efficacy while decreasing negative effects [161]. Finally, gene therapy using nanocarriers offers hope for resolving genetic mutations and reestablishing normal function in reproductive disorders.

Although the significant potential of nanotechnology in enhancing the detection and treatment of ovarian cancer via targeted medication delivery, imaging, and gene therapy, it encounters numerous major difficulties that hinder its clinical application. Attaining accurate targeting

Table 5 Nanomaterials utilized for anticancer integration

Drug	Utilization of Nanoparticles	Frequently Utilized Nanoparticles	Utilized Polymer	Refs
Bevacizumab	Liposomal (Avasin)	Liposomes NPs	Phospholipids (DSPC, Cholesterol)	[150]
Carboplatin	Polymeric Nanoplatin	PLGA NPs	Poly(lactic-co-glycolic acid (PLGA)	[151]
Cisplatin	Polymeric (Cisplatin -NP)	PLGA NPs	PLGA	[152]
Doxil	Liposomal - (Caelyx)	Liposomes	Phospholipids- (DSPC, Cholesterol)	[153]
Doxorubicin	Liposomal (Doxil)	Liposomes	Phospholipids- (HSPC, Cholesterol)	[154]
Gemcitabine	Liposomal-(Gemzar)	Liposomes	Phospholipids- (HSPC, Cholesterol)	[155]
Niraparib	Polymeric-(Zejula)	PLGA NPs	PLGA	[156]
Olaparib	Polymeric (Lynparza)	PLGA NPs	PLGA	[157]
Paclitaxel	Albumin-conjugated (Abraxane)	Albumin nanoparticles	Human serum albumin	[158]
Topotecan	Liposomal (Hycamtin)	Liposomes	Phospholipids (DSPC, Cholesterol)	[159]

of ovarian tumour cells is challenging because to the heterogeneity of tumour tissues and the intricate peritoneal milieu, which obstructs nanoparticle accumulation and penetration. The advancement of polymeric and stimulus-responsive nanocarriers has improved drug release regulation; nonetheless, concerns regarding biocompatibility, stability, and potential toxicity remain. Moreover, gene therapy employing nanocarriers, although promising for rectifying BRCA1/BRCA2 mutations and inhibiting carcinogenic pathways, encounters challenges including suboptimal transfection efficiency, off-target consequences, and immune activation. The manufacture, repeatability, and regulatory acceptance of multifunctional nanoplatforms continue to pose significant challenges. As a result, despite promising laboratory results with polymeric nanoparticles, micelles, liposomes, and dendrimers, the clinical applicability in ovarian carcinoma remains constrained due to biological, safety, and translational obstacles.

Employing nanoimaging techniques for the diagnosis of various issues related to the female reproductive system

Polycystic ovary syndrome (PCOS)

Among the many metabolic and endocrine disorders affecting women in the years leading to menopause, the incidence of polycystic ovary syndrome (PCOS) is high [174, 175]. In addition to decreased ovulation, which causes monthly abnormalities, impaired fertility, and

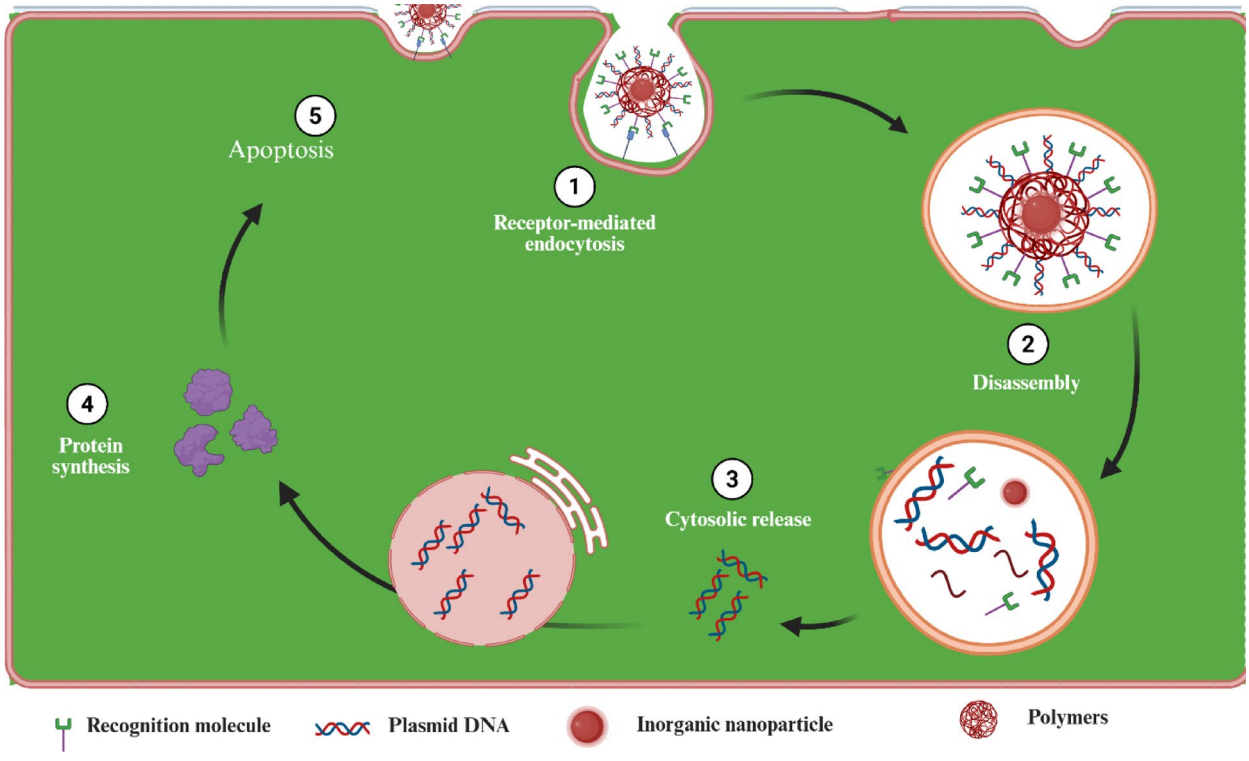

Fig. 7 Mechanism of action of Nano-mediated therapy in ovarian carcinoma in cells by inducing apoptosis

endometrial hyperplasia, hyperandrogenism is characterized by hirsutism, acne, alopecia, and seborrheic skin as clinical symptoms [53]. In addition to insulin resistance and metabolic diseases, PCOS is closely linked to both.

Ultrasound, optical imaging, MRI, and magnetic resonance elastography (MRE) are among the many imaging techniques that can be used to diagnose polycystic ovary syndrome (PCOS) [76]. An improved and more accurate method for diagnosing PCOS is the use of nanoparticles as contrast agents via ultrasonography [77]. It is possible to study and evaluate cysts or other aberrant changes in ovarian tissue by targeting nanoparticles to that area. Additionally, nanoparticles can improve the clarity of MR images by acting as contrast agents [48]. Improving diagnostic accuracy, nanoparticle integration with specific markers allows for the localization and identification of biomarkers associated with PCOS [49]. Furthermore, the pathogenic mechanisms of PCOS can be better understood with the use of fluorescently labeled nanoparticles, which allow for the identification and quantification of ovarian tissue cellular activity and metabolic irregularities. Finally, by combining MRE with nanoparticles as contrast agents, ovarian tissue elasticity can be measured, allowing for an evaluation of its functional condition and disease extent.

Herbal treatments such as curcumin, resveratrol, and berberine have demonstrated potential in alleviating PCOD symptoms. Encapsulating these substances within nanoparticles improves their absorption and stability. Nanocarriers such as dendrimers, polymeric and liposomal nanoparticles are capable of transporting drugs (e.g., metformin and clomiphene) directly to the ovaries or endocrine glands. NPs are capable of delivering siRNA or CRISPR-Cas9 elements to modify or correct genetic elements associated with PCOD, such as insulin resistance or elevated androgen levels.

Nanotechnology may improve polycystic ovarian syndrome (PCOS) diagnosis and therapy, however various obstacles limit its use. PCOS's complicated hormonal and metabolic environment makes nanoparticle uptake and distribution difficult to target to ovarian tissue. Nanoparticles improve imaging and drug absorption, but biocompatibility, long-term toxicity, and elimination remain problems. For consistent patient performance, nanoparticle production and functionalisation must be standardised and reproducible. Nanocarriers for herbal medicines or genetic materials like siRNA and CRISPR-Cas9 pose concerns about off-target effects, immunological responses, and stability in vivo. Despite promising experimental evidence, clinical translation is impeded by a lack of large-scale trials, regulatory clarity, and long-term safety reviews. Thus, nanotechnology has significant potential to improve PCOS care, but it must overcome biological, safety, and regulatory difficulties to be implemented in clinical practice.

Treating endometriosis with precise nanomedicine

Fibroids and endometriosis are the two most common reproductive disorders in women, with endometriosis affecting 10%–15% of reproductive-age women, 70% of whom experience severe pelvic discomfort [176]. Both the endometrial glands and stroma outside the uterus are affected by endometriosis, making it the most common pregnancy-related disorder. Delays in diagnosis cause symptoms such as nonmanstrual pelvic pain, dyspareunia, and infertility, which significantly reduce quality of life. Extensive studies have shown that endometriosis and uterine fibroids can be treated with methods based on nanomaterials. The authors of Chaudhury et al. emphasized the importance of targeting inflammatory mediators, such as prostaglandin E2 and cyclooxygenase-2 [177, 178]. One possible substitute for nonsteroidal anti-inflammatory medications is the administration of cerium oxide nanoparticles, which reduce the number of endometrial glands, microvessels, and endometrial lesions [179]. Singh et al. proposed a dual drug-loaded poly(lactic−coglycolic acid) (PLGA) nanoparticle strategy for treating endometriosis. This strategy combines the antioxidant and antiangiogenic properties of epigallocatechin gallate with the targeted matrix metalloproteinase inhibitory action of doxycycline [180]. A novel laser-mediated photothermal ablation treatment for endometriosis involves enhanced permeability and retention, along with the targeted delivery of gold nanoparticles to endometriotic sites via the TNYL peptide. This peptide has a strong affinity for the overexpressed EphB4 receptors found in endometriosis lesions [180]. The situation worsens when the ovaries are affected, leading to the development of cysts known as endometriomas [181]. Early screening is hindered by the invasiveness and significant patient discomfort caused by traditional diagnostic procedures such as laparoscopy and biopsy. NP-mediated endometriosis by drug-mediated apoptosis is illustrated in Fig. 8. Employing sensing approaches based on nanomaterials, which enable real-time disease assessment, could help mitigate such circumstances [182]. Various cytokines, angiogenic factors, matrix metalloproteinases, tumor suppressor genes, and circulating nucleic acid levels undergo changes in their expression, indicating significant alterations in the immunological milieu due to the inflammatory nature of endometriosis [183]. The levels of the proteases cathepsins B, D, and G in proliferative eutopic endometrium patients have been quantitatively examined via surface plasmon resonance (SPR) imaging, which revealed a favorable effect on endometriotic lesion formation [184]. Grzywa et al. developed a biosensor utilizing surface plasmon resonance (SPR) chips to

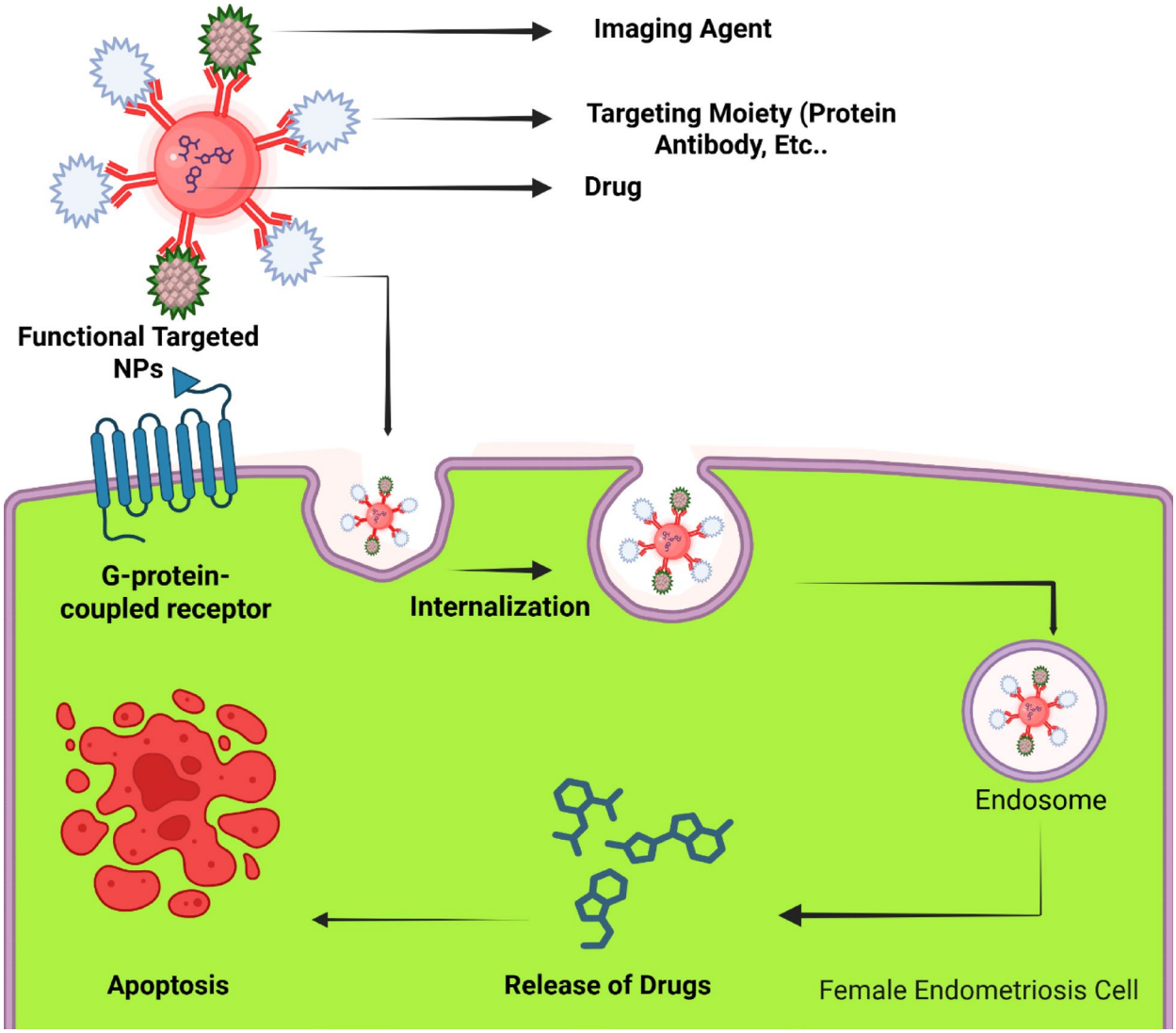

Fig. 8 The encapsulation of pharmaceuticals within nanoparticles for the treatment of endometriosis through the induction of drug-mediated apoptosis

detect CatG in endometrial samples collected from both healthy controls and patients. The study results suggest that hyperthermal treatment of endometriosis could be a promising option for patients in the future [185].

Due to the disease's heterogeneity and inflammation, and the complicated pelvic environment that limits nanoparticle penetration and retention, endometriotic lesions are hard to target. PLGA, gold, and cerium oxide nanoparticles may be used for anti-inflammatory, anti-angiogenic, and photothermal therapy, but their long-term safety, biodistribution, and removal are unknown. Nanomaterial-based biosensors, such as surface plasmon resonance (SPR) platforms, can detect early, but clinical validation and reproducibility are lacking. Translation is further hindered by multifunctional nanoplatform manufacturing scalability, cost, and regulatory approval. Despite promising preclinical results in targeted medication administration, imaging, and biosensing, nanotechnology in endometriosis is limited by biological complexity, safety concerns, and the absence of standardised clinical research needed for normal treatment.

Role of nanotechnology in assisted reproductive technology (ART)

Nanotechnology has influenced developments in reproductive science, and assisted reproductive technology (ART) has emerged as a well-respected and successful treatment option on a global scale. This comprehensive method includes a wide range of therapies for male and female infertility. ART encompasses various procedures that aid in conceiving a child, such as in vitro fertilization (IVF), zygote intrafallopian transfer (ZIFT), intracytoplasmic sperm injection (ICSI), and gamete intrafallopian transfer (GIFT). When a woman's ovarian

function is impaired or a man's sperm count is low, in vitro fertilization (IVF) becomes the preferred method for reproduction [186]. To stimulate the production of many eggs, women undergoing IVF are given a combination of medications. These eggs are then extracted and fertilized externally through in vitro fertilization before being implanted in the uterus. There has been promising progress in improving the effectiveness of in vitro fertilization therapies through the use of nanotechnology to mimic the ovarian microenvironment [187]. To recreate the ovarian environment in three-dimensional cell culture, isolated follicles and cells are housed in a synthetic matrix, namely, a functionalized polyethylene glycol (PEG) hydrogel enhanced with synthetic dextran fibers. The ovarian cells release ECM molecules after a long period of culture. In the beginning, the encapsulated cells are round and not attached to the matrix; furthermore, the cells and follicles are securely fastened to the fibers via the secreted and sequestered ECM components [188]. Figure 9 shows the detailed steps and processes needed to build ovarian microenvironments that improve the conditions for sperm and ovum fertilization by rearranging the hydrogel's extracellular matrix (ECM).

These materials are engineered to have specific properties, such as being able to release hormones or growth factors, being biodegradable, and having increased porosity [189]. In addition, the use of contrast agents based on nanoparticles is a prime example of how imaging techniques have advanced owing to research in nanotechnology [190]. By performing a thorough evaluation of the reproductive system, these technologies can identify abnormalities or factors that could affect fertility. There is great hope that the field of reproductive medicine can be revolutionized by the use of in vitro fertilization (IVF) procedures, which could ultimately lead to better results. Similar to in vitro fertilization (IVF), which is significantly different, the ZIFT method involves the insertion of mature eggs into the fallopian tube [191]. The term "GIFT" describes the well-known procedure that leads to fertilization: the transfer of sperm and eggs into the fallopian tube. The success rate of in vitro fertilization (ICSI) can be increased by the use of a chemical called hyaluronidase to directly inject a single sperm into an egg before either it is implanted into the uterus or transferred to the fallopian tube [192]. This chemical, when combined with nanopolymers such as polyethylene glycol (PEG), enhances the stability and vitality of the implanted sperm [193]. The nanopolymer acts as a protective barrier, allowing the sperm to remain viable during injection and increasing the likelihood of conception. To further increase the chances of a successful pregnancy, hyaluronidases and polymers work together to help fertilized eggs reach the right place in the reproductive system [194]. The intracellular DNA sequencing (ICSS) methods were made possible by hyaluronidase and PEG nanotechnology (Fig. 10).

Nanotechnology has improved assisted reproductive technology (ART), like in vitro fertilization (IVF), zygote intrafallopian transfer (ZIFT), and intracytoplasmic sperm injection (ICSI), but it still faces significant challenges that limit its clinical optimization and adoption. Nanomaterials like PEG-based hydrogels and synthetic dextran fibers struggle to replicate the complex ovarian microenvironment due to cell viability, differentiation, and functional hormone release issues. Nanoparticle-based imaging and nanopolymer-assisted sperm storage have improved diagnostics and fertilization, although biocompatibility, cytotoxicity, and long-term safety remain problems. To maintain consistency between ART labs, nanomaterial fabrication must be standardized, scalable, and reproducible. Clinical translation is further complicated by ethical and regulatory issues regarding nanotechnology in human reproductive systems. Despite promising laboratory advancements in improving fertilization efficiency and embryo survivability, nanotechnology in ART faces biological, safety, and ethical difficulties before it can be completely integrated into normal reproductive therapy.

Nanomedicine as a potential treatment for uterine fibroids

Uterine fibroids, also known as leiomyomas, are tumors that are composed of smooth muscle cells that typically develop during pregnancy. The size and number of fibroids can vary greatly, with some women experiencing a single fibroid and others experiencing multiple fibroids [195]. Shalaby et al. utilized a unique technique to explore the role of nanoparticles in treating uterine fibroids [196]. By combining virus-mediated gene transfer with nanotechnology, they developed a highly effective and noninvasive treatment strategy. This approach involves the use of magnetic nanoparticles with tailored features to achieve efficient viral transduction within an external magnetic field. By targeting and eliminating the fibroid stem cells responsible for tumor formation, this novel combinational approach represents a significant shift in the treatment of uterine fibroids.

One promising development in gynecology involves the use of nanosensing technologies for detecting uterine fibroids [197]. This cutting-edge method employs small sensors to spot and confine fibroids within the uterus. Furthermore, real-time data on electrical activity and changes in tissue composition caused by fibroids and nanosensing devices offer a painless and accurate way to diagnose and monitor these tumors. Omer et al. developed a sensor encasing silicon nanowires in a biocompatible material, polydimethylsiloxane, to improve the longevity and biocompatibility of the sensor in the uterus [198]. The sensor functions by detecting

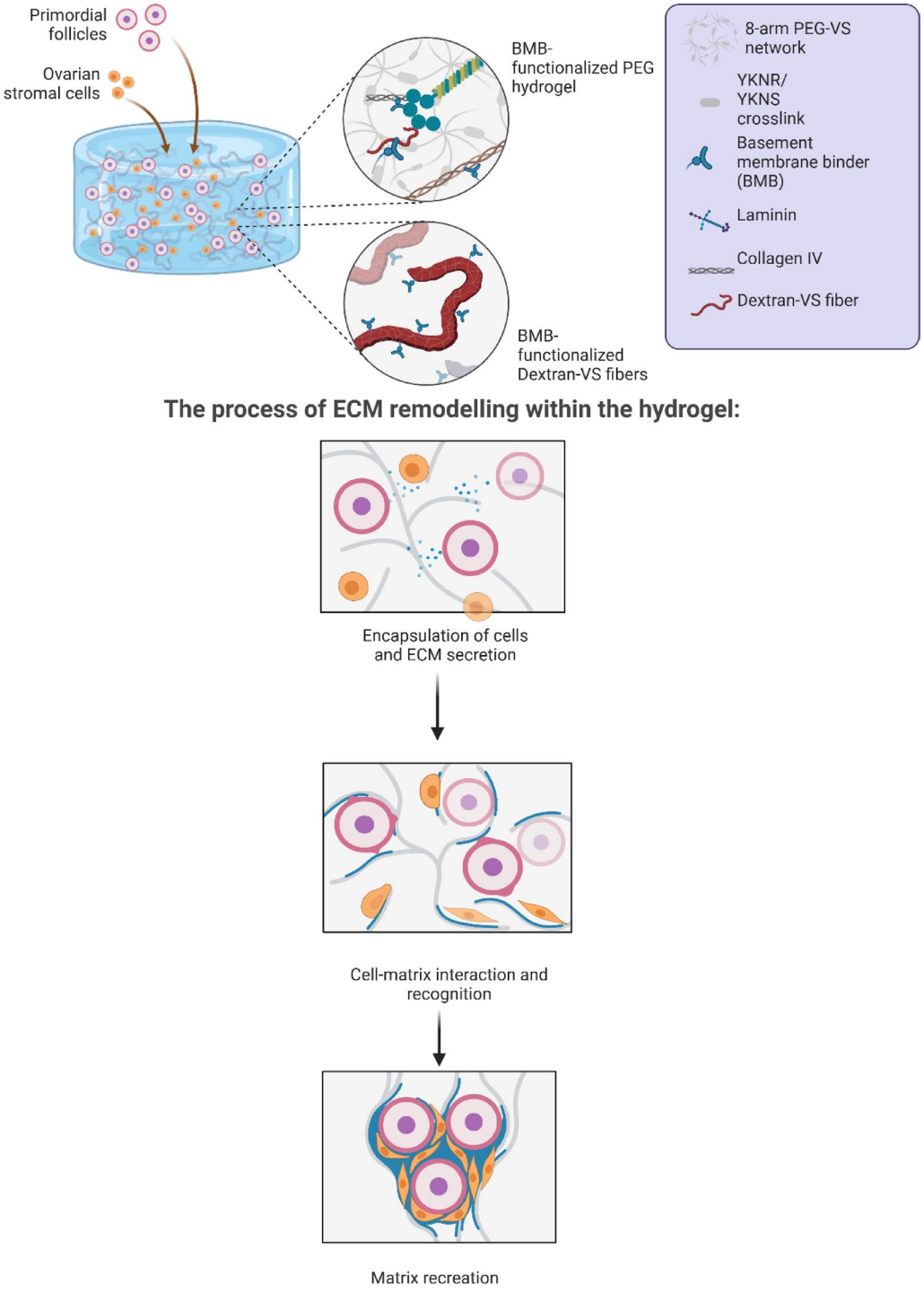

Fig. 9 Recreation of the ovarian milieu for best pairing of sperm cell and ovum in vitro by altering ECM with the hydrogel

specific biomarkers, such as proteins or genetic elements, secreted by fibroids, allowing for the quantification and analysis of changes in electrical conductivity [199]. This groundbreaking technology has the potential to transform the monitoring and diagnosis of uterine fibroids, providing patients with faster and more effective treatment options.

Uterine tumours' strong extracellular matrix and varied vascularization make nanoparticle penetration and retention problematic in fibroid tissues. For noninvasive treatment and early detection, magnetic nanoparticle–assisted gene therapy and nanosensing technologies show promise, but their long-term safety, biocompatibility, and impacts on healthy uterine tissue and fertility are

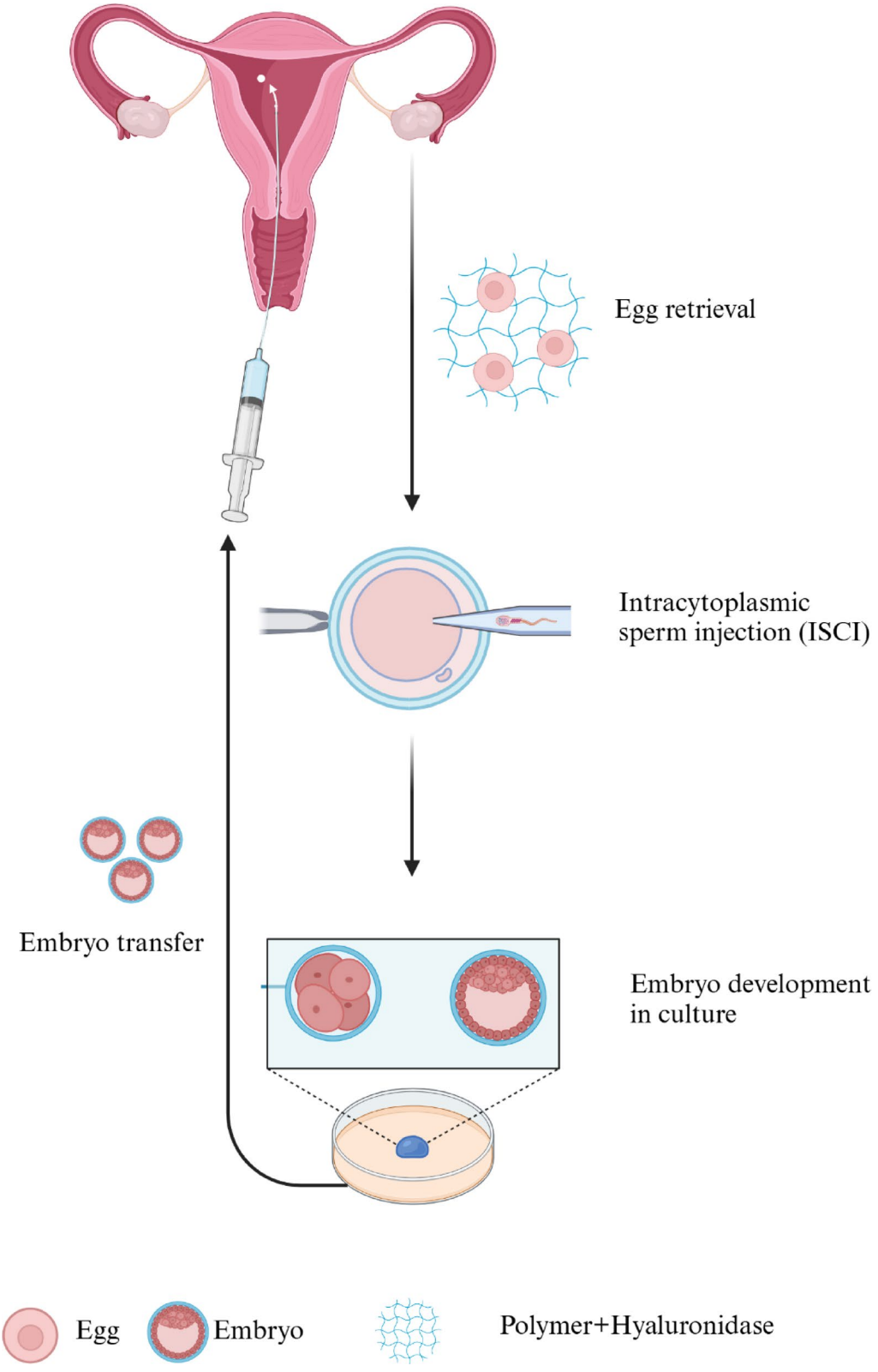

Fig. 10 Procedure for Intracytoplasmic Sperm Injection (ICSI) in humans to facilitate optimal fertilization of oocytes and sperm within the uterus, utilizing polyethylene glycol (PEG) and hyaluronidase

concerns. Nanosensors must also be tested for device stability, signal accuracy, and immune response risk before usage in vivo. Technical issues with scalable manufacturing, reproducibility, and regulatory approval impede clinical implementation. Thus, nanotechnology in uterine fibroid care is constrained by biological hurdles, safety concerns, and translational constraints that require multidisciplinary research to overcome, despite promising preclinical progress in targeting and detection.

Innovative nanomedicines in ectopic pregnancy care

Ectopic pregnancy, a condition in which the conceptus cannot survive outside the uterus, is a leading cause of mortality in pregnant women during the first trimester [200]. Nanotechnology offers promising solutions to increase the effectiveness of traditional medications for treating ectopic pregnancy [201]. Scientists have discovered the use of nanoparticles to deliver medications, such as methotrexate, at lower concentrations than conventional methods do, with studies demonstrating a significant reduction in trophoblastic tumor cell growth and an increase in apoptosis, indicating a potential alternative treatment for ectopic pregnancy [202]. By using sensitive surface plasmon resonance technology, researchers have developed chip sensors that employ electrical field-effect transistors and carboxy-graphene oxide sensors to detect ectopic pregnancies [203].

Pritchard et al. documented the application of nanocarriers to deliver medications such as mifepristone, misoprostol, and methotrexate to the site of an ectopic pregnancy [204]. These nanocarriers, which are made of biocompatible compounds such as lipids or polymers, improve medication stability, prevent degradation, and increase bioavailability at the intended site [205]. Additionally, a reduced frequency of drug administration with improved patient compliance has also been reported in a longer and more controlled treatment course of nanocarriers. Various nanomaterials, including scaffolds, hydrogels, bioprinting, and organoids, have been utilized in ectopic pregnancy treatment to aid in cell adhesion, tissue regeneration and drug delivery [206, 207]. These advanced technologies offer researchers the ability to create in vitro models that closely mimic human physiology, potentially improving drug discovery procedures and facilitating personalized medicine techniques [208]. Figure 11 illustrates the various nanotechnologies used in identifying and treating ectopic pregnancies.

Nanotechnology has significant potential to improve ectopic pregnancy diagnosis and treatment, but it faces numerous critical challenges that limit its clinical use. The fallopian tubes' intricate and delicate nature makes precise targeting and regulated drug distribution to the implantation location difficult, increasing tissue injury and inflammation risk. Nanocarriers for methotrexate, mifepristone, and misoprostol can improve stability, dose, and bioavailability, but biocompatibility, systemic toxicity, and reproductive tissue clearance remain problems. Nanosensors and surface plasmon resonance–based detection systems show promise for early diagnosis, but their sensitivity, repeatability, and in vivo safety need additional confirmation. Integration of these devices into normal ectopic pregnancy care is hindered by manufacturing consistency, regulatory approval, and ethical concerns. Despite promising laboratory and preclinical results, nanotechnology in ectopic pregnancy care has severe biological, safety, and translational obstacles before it can be safely adopted in clinical practice.

Advancements in nanotechnology for gestational trophoblastic disorders (GTDs)

One class of pregnancy-related complications is known as gestational trophoblastic disease (GTD), which is characterized by abnormal trophoblast growth in the uterine cavity. This process begins after conception. GTCs encompass various types of cancer, each with its own unique biological characteristics and the potential to metastasize [209].

Many cancer cells and placental trophoblasts express placental chondroitin sulfate A (plCSA), a glycosaminoglycan, suggesting therapeutic potential for GTDs. In a study utilizing lipid-based nanoparticles coupled with a synthetic peptide known as plCSA binding peptide (plCSA-BP), researchers investigated the delivery of methotrexate to placental cells [210]. They reported that plCSA-BP effectively attached to nanoparticles containing methotrexate, leading to efficient binding to mouse trophoblasts or human placental syncytiotrophoblasts throughout pregnancy. The specific route of drug delivery to the placenta in the mouse model facilitated this outcome, with no observed negative side effects on the baby. Furthermore, researchers have enhanced the targeted delivery of doxorubicin to JEG3 cells within the placenta by developing polymeric core–lipid shell nanoparticles coated with pICSA-BP [211]. Treatment for prenatal trophoblastic choriocarcinoma typically involves high doses of systemic anticancer medication, which may lead to systemic toxicity due to nonselective drug distribution to various organs. Zhang et al. conducted an experiment to explore potential adverse reactions associated with doxorubicin administration. They successfully delivered doxorubicin to choriocarcinoma cells via nanoparticles by leveraging the targeting properties of plCSA-BP, offering a promising approach for personalized cancer therapy [212].

Nanotechnology offers potential strategies for the treatment of gestational trophoblastic disorders (GTDs); however, it encounters notable challenges that hinder its clinical application. Achieving precise and selective drug

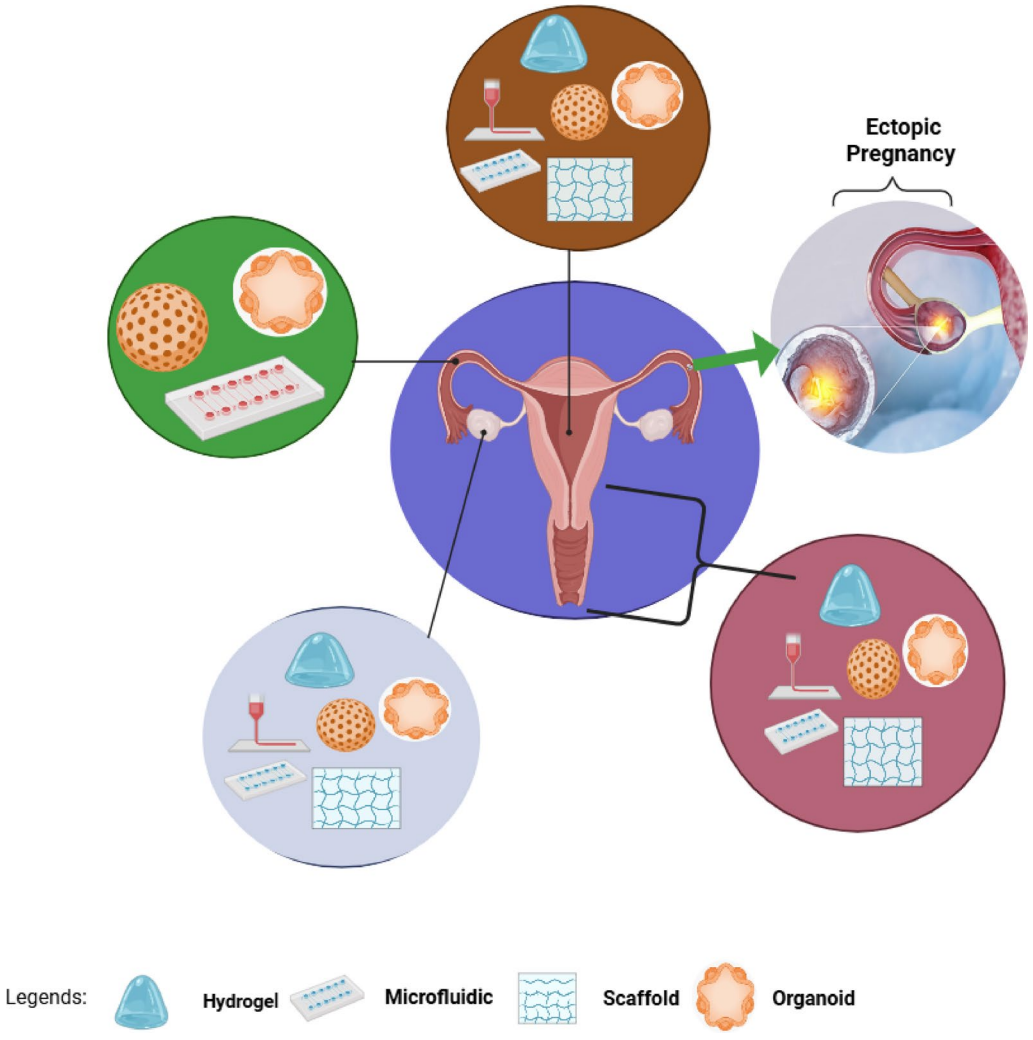

Fig. 11 Nanotechnology-targeted therapy for ectopic pregnancy in different regions of the uterus

delivery to trophoblastic tumour cells is complex due to the high vascularization, rapid proliferation, and invasive nature of these tissues, which elevate the risk of off-target accumulation and systemic toxicity. Targeted nanocarriers, including plCSA-binding peptide (plCSA-BP)–modified lipid or polymeric nanoparticles, have demonstrated promising efficacy in delivering drugs such as methotrexate and doxorubicin to placental and choriocarcinoma cells. However, concerns persist regarding their long-term safety, biodistribution, and potential impacts on foetal development. Additionally, the scalability, reproducibility, and regulatory approval of these specialised nanoplatforms pose persistent challenges. Despite promising preclinical findings that demonstrate enhanced drug targeting and reduced side effects, the application of nanotechnology in GTD management remains limited by biological complexity, safety concerns, and translational barriers that must be resolved prior to achieving widespread clinical implementation.

Role of nanotechnology in HIV/AIDS and other reproductive infections

Nanoparticle interventions for reproductive tract infections (RTIs), which affect people of all genders, are a major problem for global health and the economy. According to the World Health Organization (WHO), more than 200 million cases of sexually transmitted RTIs occur worldwide, with a higher prevalence observed among reproductive-aged women [213]. Nanomaterials have shown promise as a treatment and tracking tool for preserving reproductive well-being and the general standard of living, according to studies. For example, in one day, acyclovir was encapsulated in polyvinyl pyrrolidone–Eudragit RSPO hybrid polymeric nanoparticles. An in situ gel enhanced with nanoparticles was developed to treat genital herpes, achieving regulated drug release, improved permeability, and increased vaginal epithelial cell survival [214]. Compared with that of pure therapy, bioavailability was two times greater in the rat

models used for the experiments. A new treatment for genital herpes simplex virus type 2 infections was developed by Agelidis et al. Tailored zinc oxide tetrapodal nanoparticles inhibited viral infections of the vagina in female BALB/c mice. The established microbial-vacuum method can be employed to develop efficacious vaccines against viruses [215]. Lee et al.'s polymeric nanocarrier approach works, and peptide vaccines might be easier to develop [216]. A chlamydial glycolipid antigen-mimicking peptide (Pep4) was covalently linked to fourth-generation hydroxyl-terminated polyamidoamine (PAMAM) dendrimers (G4OH) as a component of the experimental design. By exposing the body to antigens through subcutaneous vaccination, the G4OH–Pep4 link in the intracellular milieu is broken, which in turn triggers the creation of antibodies specific to chlamydial Pep4, which become more immunogenic and remain that way after the formulation, since it increases the anti-chlamydial antibody response in mice. A possible explanation for this effect is that phagolysosomes cleave ester bonds [217]. This study indicates that the adhesive PLA-HPG nanoformulation may be beneficial for the intravaginal treatment of sexually transmitted infections. Wagner et al. developed a nanoparticle-based method to prevent STIs associated with the herpes simplex virus [218]. Researchers Soler et al. utilized a nanomonmonic biosensor to simultaneously detect *Chlamydia trachomatis* and Neisseria gonorrhea e. A set of gold nanohole sensors integrated within the nanosensor precisely identified and quantified the quantities of bacterial strains [219]. Nanotechnology-based preventative, therapeutic, and early diagnostic technologies may replace oral medications. Mandal et al. encased the antiviral agent emtricitabine into PLGA nanoparticles [220]. Cytotoxicity, poor absorption, a short plasma half-life, and widespread emtricitabine dispersion were the key concerns of this study. Enhancing the efficacy of emtricitabine as an HIV treatment was the driving force behind this research [221]. The new nanofabrication decreased cytotoxicity and in vivo biodistribution subsequent to topical intravaginal administration. Mirani et al. utilized a nanoformulation of lipidic microbialicide gel containing tetrahydrocurcumin to obtain comparable results [222].

Using surface-enhanced Raman scattering, Fu et al. developed a lateral flow test [223]. This study aims to positively identify and examine HIV-1 genetic material, a possible genetic indicator for retrovirus diseases. The authors prioritize usability in their tests. The use of fluorescence resonance energy transfer to detect viral DNA was the main focus of the investigation. Carbon nanoparticle energy absorption was achieved by coupling two silver nanoparticles with single-strand DNA (ssDNA). When the target analyte was present, fluorescence desorption occurred; however, once it was removed, the fluorescence was restored. The use of fluorescence quenching as a sensitive diagnostic tool allowed for the detection of HIV-1 DNA. Side flow strips based on fluorescent quantum dots and silver nanocrystals functionalized with surface DNA were utilized by Deng et al. and Fang et al. [224, 225]. The HIV-associated p24 antigen is now a very specific indicator for HIV detection. An optoplastic-based sandwich immunoassay was developed by researchers using a microcantilever nanoplatform for nanodetection [226]. With this method, the HIV-1 capsid antigen p24 may be reliably detected in blood samples. In this area, Cohen et al. conducted research to treat HIV and other reproductive tract disorders. The delivery of therapeutic payloads is typically accomplished via nanoparticles. These nanoparticles are engineered to deliver drugs to specific sick cells where they have the greatest impact. For enhanced stability and prolonged bloodstream circulation, incorporating sensors, targeting aptamers, fluorescence probes, targeting peptides, cationic chemicals, drugs, and polyethylene glycol is common [227]. By assisting in the identification of and binding to specific receptors on infected cells, the targeting antibody ensures correct medicine administration. By allowing real-time tracking of nanoparticle absorption and dispersion within the body, the use of a fluorescent probe improves therapeutic evaluation. Drug delivery specificity and efficiency are enhanced by the addition of targeting aptamers or peptides, which also decrease off-target effects. Taken together, these painstakingly made nanoparticles offer a promising approach to HIV-focused treatment [228]. Figure 12 shows the pharmaceutical payload technique that targets HIV-infected cells via multiple biological probes.

Nanotechnology offers potential strategies for the prevention, diagnosis, and treatment of HIV/AIDS and other reproductive tract infections (RTIs); however, it encounters various biological, technical, and translational challenges that impede its clinical implementation. Delivering targeted and safe nanoparticles to infected reproductive tissues is complicated by mucosal barriers, pH variations, and the diverse microbiota of the genital tract, all of which can influence nanoparticle stability and drug release. Nanoformulations, including polymeric nanoparticles, dendrimers, and lipid-based carriers, have enhanced drug bioavailability and decreased systemic toxicity; however, long-term safety, immune compatibility, and potential cytotoxicity continue to be significant concerns. Diagnostic nanoplatforms, such as biosensors and surface-enhanced Raman scattering assays, provide rapid and sensitive detection of viral or bacterial pathogens; however, issues related to standardisation, reproducibility, and cost-effectiveness hinder their widespread clinical application. Moreover, the scalability of manufacturing, the necessity for regulatory approval, and the

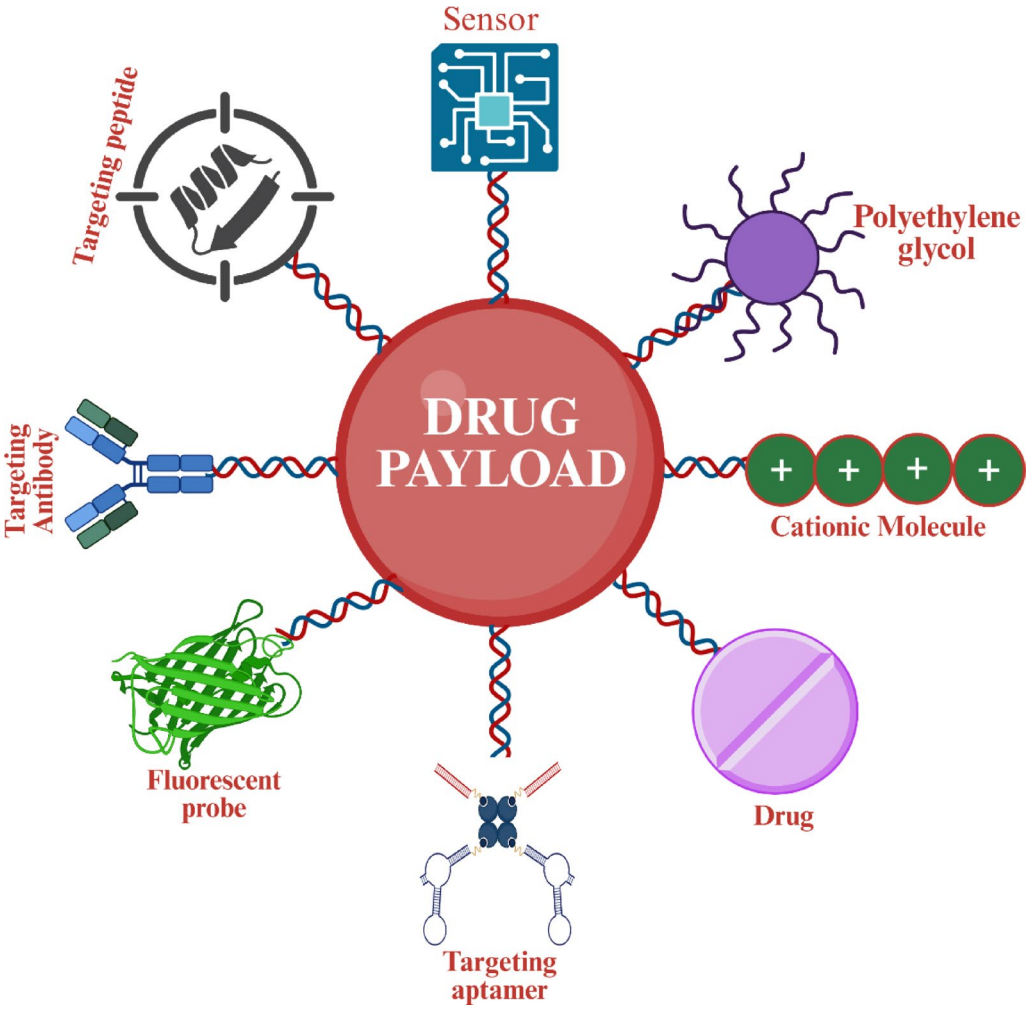

Fig. 12 Drug payload utilizing several biological probes for targeting HIV infections

ethical implications associated with the use of nanomaterials in reproductive health add complexity to the translation process. Despite notable preclinical advancements in enhancing targeted drug delivery and pathogen detection, the application of nanotechnology in HIV/AIDS and RTI care encounters substantial biological, safety, and regulatory challenges that must be addressed before it can be integrated into reproductive healthcare reliably.

Therapy for male reproductive disorders utilizing nanoparticles

An enlarged prostate, or benign prostatic hyperplasia (BPH), is one of several male reproductive issues. Other issues that can arise from an undescribed testicle include varicocele, hydrocele, prostatitis, erectile dysfunction (ED), and symptoms of testosterone inadequacy.

A novel approach to treating BPH via nanomedicine

An obstruction in the bladder's outflow can be caused by benign prostatic hyperplasia, which narrows the urethral passageways. Among the many potential side effects of this obstruction are urinary tract infections and urine retention. A new area of research called nanomaterial-based therapies has recently emerged to reduce the negative side effects of traditional medicine [229]. In their paper, de Sousa et al. outlined the procedure used to create PLGA nanoparticles and clay nanosystems using babassu oil [230]. Both methods demonstrated 90% encapsulation effectiveness and significant bioavailability, highlighting the promising use of these structures in treating benign prostatic hyperplasia (BPH). Recent studies have also shown that gold nanoparticles could aid in the development of new BPH treatments by specifically targeting inflammation and angiogenesis. Research has indicated a significant reduction in BPH, with the degree of reduction varying with respect to nanoparticle size. Additionally, this medication has shown potential benefits in preventing inflammation, angiogenesis, and cellular proliferation in the prostate gland [231].

Nanoparticles of poly(ethylene-alt-maleic anhydride) coupled with condition-specific T2 peptides were produced in a study by Cao et al. [232]. They utilized a mouse model of chronic prostatitis/chronic pelvic pain syndrome (CP/CPPS) in an attempt to find a cure for prostatitis. Research by Cheng et al. demonstrated the effective production of PLGA nanoparticles loaded with the autoantigen peptide T2 [233]. A mouse model was used to assess the efficacy of the nanoparticles in reducing CP and CPPS symptoms and promoting immunological tolerance. Both studies revealed an efficient and cost-effective method for treating CP/CPPS symptoms [233]. Studies have shown that gold nanoparticles (AuNPs) can inhibit the progression of testosterone-induced BPH in rats in a size-dependent manner, with 20 nm AuNPs being particularly effective [231]. Similarly, plasmonic silver nanoparticles (AgNPs) have been utilized in photothermal therapy to treat BPH, with studies indicating their potential in reducing prostatic hyperplasia [234]. Additionally, selenium nanoparticles (SeNPs) have exhibited both protective and curative effects against testosterone-induced BPH in rats, with the protective effects being more pronounced [235]. Furthermore, a study involving Cu–Mn@SiO_2 nanoparticles combined with localized sonodynamic therapy resulted in a substantial 60% reduction in prostatic hyperplasia in a testosterone-induced BPH rat model [236].

Progress in nanomedicine for erectile dysfunction

In men, the inability to achieve or maintain a strong enough erection for satisfying sexual activities is known as erectile dysfunction. Despite the availability of various therapeutic interventions, many men choose not to seek treatment. These interventions range from oral medications such as sildenafil, tadalafil, and vardenafil to more advanced methods such as intraurethral therapy and intracavernosal injections [237]. Many men have discontinued these therapies because of their high cost, pain, unnaturalness, prolonged erections, and risk of priapism [238].

The use of superparamagnetic iron oxide nanoparticles integrated with human mesenchymal stem cells (MSCs) allows the use of MRI in the diagnosis and treatment of erectile dysfunction, a technique known as SPION-MSCs [239]. In a previous study, cavernosal injections of SPION-MSCs were administered to rats, and four weeks after introduction, cavernous nerve damage was observed. This method, when combined with MRI, has shown promising results in treating erectile dysfunction because of its ability to assess therapeutic efficacy within living organisms [240]. A formulation called the nanoshuttle, which consists of embryonic stem cells derived from adipose tissue and magnetic nanoparticles, improved in vivo cell tracking within the corpus cavernosum after three days of exposure to a magnetic field in an animal model. This study evaluated the effectiveness of the nanoshuttle as a stem cell-based therapeutic intervention for ED [241].

An investigation by Tawfik et al. demonstrated the effectiveness of a vardenafil hydrochloride delivery method based on dendrimers [242]. Researchers have developed a sustained-release formulation of the medication, increasing its bioavailability by 3.7 times. Scientists in reproductive medicine have shown interest in lipid-based systems to increase the bioavailability, biocompatibility, and solubility of poorly water-soluble medications. This method of transdermal administration has shown success in treating impotence and erectile dysfunction [243]. A novel liposomal formulation called Nano Transferases has shown promise in diagnosing and treating erectile dysfunction through transdermal administration of papaverine to the penile region. This formulation has potential as a treatment approach for erectile dysfunction in men [244]. Improving the bioavailability and transdermal dispersion of the pharmacological substance avanafil is crucial for treating erectile dysfunction. It was delivered via a hydrogel film made of solid lipid nanoparticles [245]. Hydrogels have emerged as a promising platform for delivering therapeutic agents and supporting tissue regeneration in ED treatment. These materials can provide a scaffold for cell attachment and growth, release bioactive molecules in a controlled manner, and mimic the extracellular matrix. Studies have demonstrated that hydrogel-based therapies can improve erectile function by promoting tissue repair and reducing fibrosis in ED models [246].

Recent studies have developed biodegradable nanomaterials, like black phosphorus nanosheets, to deliver stromal cell-derived factor-1 alpha (SDF1-α). This chemokine plays a crucial role in recruiting endogenous stem and progenitor cells to the site of injury. In ED models induced by cavernous nerve injury, SDF1-α-loaded nanoparticles have been shown to enhance tissue repair and restore erectile function by promoting the recruitment of these cells [247].

The integration of nanomedicine into ED treatment strategies offers the potential for more effective, targeted, and personalized therapies. While preclinical studies have shown promising results, further clinical trials are necessary to validate the safety and efficacy of these novel approaches in human patients. Continued research and development in this field may lead to significant advancements in the management of erectile dysfunction.

Investigation into Nanoparticle-based therapy for male infertility

The inability to conceive, even after frequent, unprotected sexual encounters, is the hallmark of infertility.

One cause of male factor infertility is characterized by a diminished sperm count or suboptimal sperm quality [248]. Many researchers have recently expressed interest in nanotechnology because of the hope that it may help with infertility [249]. According to research by Moridi et al., the presence of cerium dioxide nanoparticles (CeNPs) significantly reduces the negative effects of the organophosphorus insecticide malathion on the male reproductive system [250]. When male rats exposed to malathion were treated with CeNPs, the abnormalities in their testicles were repaired. The nanoparticles also reduced the effects of stress on the viability, motility, and quantity of sperm ([250, 251]). Researchers subsequently utilized the magnetic characteristics of surface-charged Fe_3O_4 nanoparticles to devise an innovative and efficient approach for improving sperm motility and, consequently, fertility in infertile men [252]. The approach put forth by Vidya and Saji includes developing a streamlined screening process [253]. A colorimetric biosensor based on heparin gold nanoparticles, which is both highly sensitive and eco-friendly, is utilized in this method. To reliably diagnose male infertility, the biosensor can detect protamines in semen [254]. After the detection of protaminase in real sperm and serum samples, the plasmon absorption spectra of the nanobiosensor changed noticeably. Sun et al. analyzed human sperm via colorimetric nanobiosensing technology. The components of the nanosensor included ssDNA-functionalized gold nanoparticles (AuNPs) and frameworks made of zirconium and organic materials (Zr-MOFs) [255].

Future prospects

The future of nanomedicine in reproductive disorders is marked by exciting advancements poised to revolutionize reproductive medicine through personalized therapeutics. The potential of nanotechnology lies in its ability to deliver customized therapies, enabling precise targeting of reproductive organs and cells. This tailored approach may become standard practice, improving therapeutic efficacy while minimizing unwanted effects. Nanomedicine is anticipated to substantially improve diagnostic capabilities for reproductive disorders. The application of nanoscale imaging agents and sensors may enhance the early detection and accurate monitoring of conditions such as endometriosis or ovarian disorders, facilitating prompt and targeted treatments. The integration of nanotechnology in gene therapy for reproductive problems may advance to include advanced gene editing and repair methodologies. Engineered nanoparticles can deliver gene-editing tools directly to specific cells, correcting genetic defects and restoring normal function. Advancements in nanomedicine will likely focus on improving drug delivery systems for reproductive disorders. Intelligent nanocarriers with sensitive features, such as pH or temperature responsiveness, may enhance the precision and effectiveness of drug delivery, increasing therapeutic outcomes. Nanomedicine techniques may improve fertility preservation, offering innovative options for those with reproductive challenges. The conservation of gametes or reproductive organs via nanocarriers may prove to be a viable approach, especially for those receiving treatments that pose potential reproductive hazards. The future outlook requires further study and rigorous clinical trials to validate the safety and efficacy of nanomedicine applications in reproductive problems. Collaborative efforts among researchers, physicians, and regulatory bodies will be crucial for transforming laboratory innovations into approved therapeutic interventions. As nanomedicine advances, it will be essential to confront the ethical issues associated with its applications in reproductive health. Establishing a balance between scientific progress and ethical standards will enable the integration of nanotechnology into healthcare practices. The future of nanomedicine in reproductive disorders foresees a shift toward personalized, targeted, and innovative treatments. The ongoing progression of nanotechnology is poised to transform the diagnosis, treatment, and maintenance of reproductive health, thereby improving the quality of care for individuals with reproductive challenges (Fig. 13).

Regulatory and safety advances

Recent advancements in the regulation of nanomedicine have enhanced the framework for assessing safety and reproductive risks linked to nano-enabled therapeutics. The U.S. Food and Drug Administration (FDA) has released detailed guidance documents for drug products that incorporate nanomaterials and liposomal formulations, specifying standards for material characterisation, pharmacokinetic assessment, and reproductive toxicity evaluation ([256], – [257]) The European Medicines Agency (EMA) and the International Pharmaceutical Regulators Programme (IPRP) have produced harmonised reflection papers and horizon-scanning reports for 2025 to synchronise global regulatory expectations for nanomedicines [258]. The International Council for Harmonisation (ICH) concurrently revised its S5(R3) guideline to enhance testing strategies for developmental and reproductive toxicity (DART), focussing on mechanism-based, exposure-driven methodologies relevant to nanomaterials [259]. The International Organisation for Standardisation (ISO) has revised ISO 10993-1 to incorporate explicit evaluation of reproductive and developmental endpoints in medical devices, thereby ensuring the biological safety of intravaginal and intrauterine nanomaterial-based products (International Organization for Standardization [260]. In addition to these initiatives, the Organisation for Economic Co-operation and

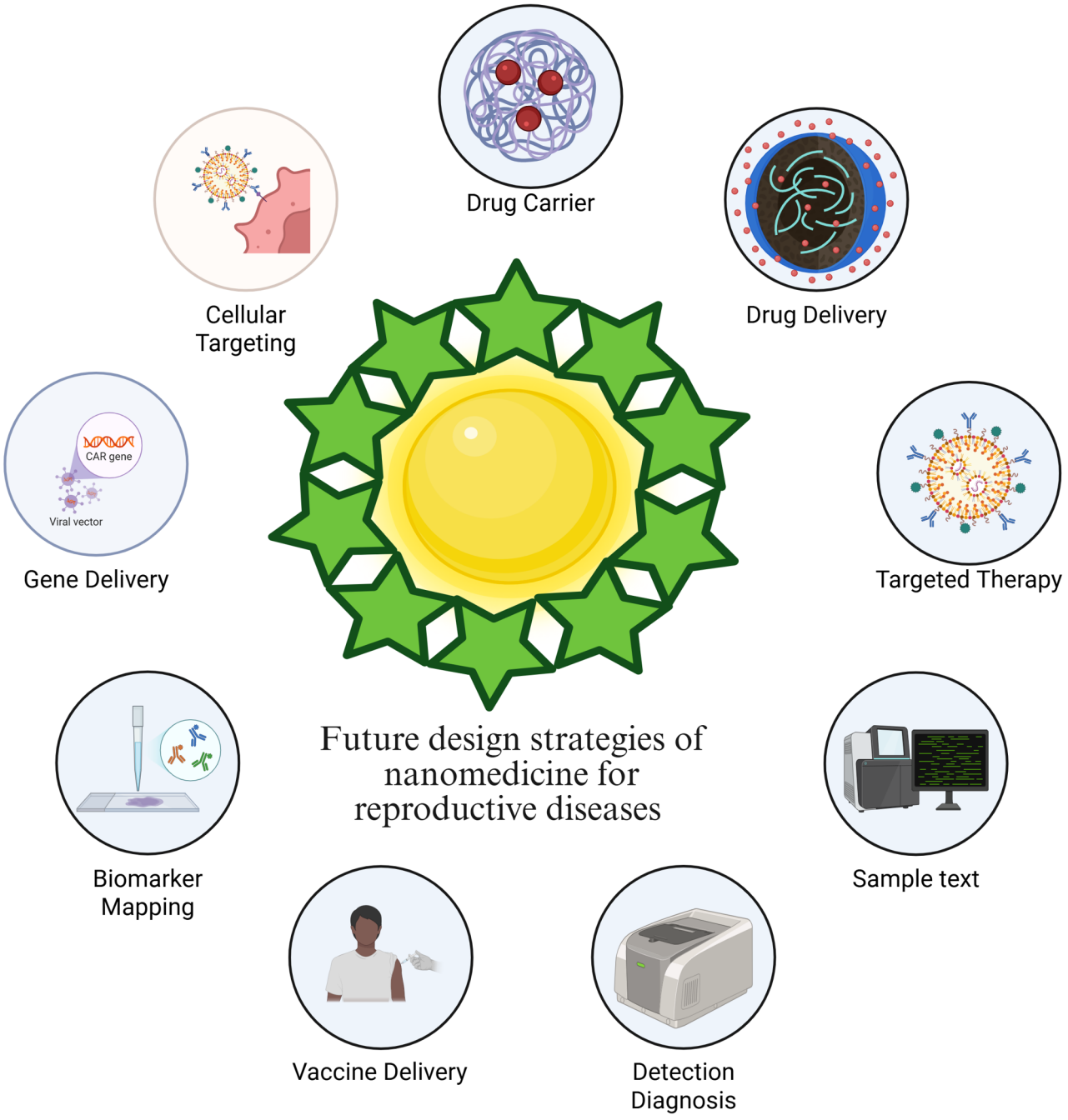

Fig. 13 Future potential of nanomedicine and nanotechnology in addressing diverse reproductive diseases

Development (OECD) has published revised Test Guidelines and Guidance on Nanomaterial Safety Testing, advocating for uniform physicochemical characterisation prior to in vivo studies [261] The advancements indicate a global trend towards evidence-based, risk-oriented regulation, aimed at ensuring therapeutic efficacy and reproductive safety in the application of nanotechnology within reproductive health.

Conclusion

Nanotechnology is revolutionizing female and male reproductive health by diagnosing, treating, and managing complex conditions such as PCOS, endometriosis, and uterine fibroids. NPs provide precise gene therapy, medication delivery, and imaging, allowing for unparalleled therapeutic control and minimal systemic adverse effects. Despite these advances, concerns have been raised about the biocompatibility and long-term safety of NPs in reproductive cells due to their unique properties.

Extensive research is needed to determine the safe utility of nanoparticles in reproductive medicine, taking into account oxidative damage, hormone disruption, and potential intergenerational effects. Future initiatives should focus on improving NP formulations to increase therapeutic effectiveness and reduce toxicity. Responsible integration of nanotechnology in health care requires adherence to safety, dosage, and ethical standards. NPs have the potential to improve reproductive health and personalize therapy as knowledge advances. The long-term impact of these advancements on women's health depends on their secure integration and adherence to safety standards.

Author contributions
R.K., P.R.R., G.J.M. and S.M. wrote the main manuscript text. R.K., A.M. and S.M. prepared Figs. 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12 and 13. P.R.R., G.J.M. and D.D. reviewed the manuscript .

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Declarations

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Competing interests
The authors declare no competing interests.

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