

Applications of biomaterials in reconstructive gynecology

Zastosowanie biomateriałów w ginekologii rekonstrukcyjnej

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Polymers in Medicine, ISSN 0370-0747, eISSN 2451-2699

Polim Med. 2025;55(1):59–65

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Funding sources

None declared

Conflict of interest

None declared

Received on January 4, 2025

Reviewed on January 29, 2025

Accepted on April 11, 2025

Published online on June 27, 2025

Abstract

This review comprehensively describes the applications of biomaterials in gynecology, focusing on their role in treating gynecological disorders, reconstructive procedures and minimally invasive surgeries. It highlights the latest advancements, such as biocompatibility, innovative implants and biodegradable materials. This article also provides information about biomaterials used for vaginal and pelvic wall reconstruction in pelvic organ prolapse patients, as well as its use in minimally invasive surgical procedures and infertility treatment (including assisted reproductive technologies (ART)). The application of biomaterials in gynecological oncology is also discussed, as biomaterials – particularly those incorporating nanotechnology – enable selective drug delivery and targeted cancer therapy.

We highlight the current clinical challenges and unmet needs while offering a forward-looking perspective on the potential of biomaterials in advancing regenerative medicine, personalized treatments and improving outcomes for women's health. We aim to provide some directions for future research and the development of novel biomaterials that can improve gynecological care.

Key words: biomaterials, regeneration, gynecology, implantation

Streszczenie

W pracy przeglądowej opisano zastosowania biomateriałów w ginekologii, ze szczególnym uwzględnieniem ich roli w leczeniu schorzeń ginekologicznych, procedurach rekonstrukcyjnych i operacjach małoinwazyjnych. W artykule przedstawiono informacje na temat biomateriałów stosowanych do rekonstrukcji ścian pochwy i miednicy u pacjentek z obniżeniem/wypadaniem narządów płciowych, a także ich zastosowania w małoinwazyjnych zabiegach chirurgicznych oraz w leczeniu niepłodności (w tym technologiach wspomaganego rozrodu). Omówiono także zastosowanie biomateriałów w onkologii ginekologicznej, ponieważ biomateriały umożliwiają selektywne dostarczanie leków i ukierunkowaną terapię przeciwnowotworową przy zastosowaniu biomateriału opartego na nanotechnologii. Artykuł podkreśla najnowsze osiągnięcia, takie jak biokompatybilność, innowacyjne implanty i materiały biodegradowalne, a także przedstawia obecne wyzwania w zastosowaniu klinicznym biomateriałów oraz potencjalne przyszłe możliwości ich zastosowania w medycynie rekonstrukcyjnej i spersonalizowanych metodach leczenia. Naszym celem było wskazanie kierunków przyszłych badań i rozwoju nowych biomateriałów, które mogą poprawić skuteczność leczenia w ginekologii.

Słowa kluczowe: biomateriały, ginekologia, regeneracja, implanty

Cite as

Blok R, Myszczyński G, Wiatrowski A, Tomiałowicz M, Pomorska M, Florjanski J. Applications of biomaterials in reconstructive gynecology. *Polim Med.* 2025;55(1):59–65. doi:10.17219/pim/203964

DOI

10.17219/pim/203964

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Introduction

Biomaterials play a fundamental role in contemporary medicine, enabling the treatment of disorders and supporting tissue regeneration. Their wide range of applications includes surgical procedures, reconstructive interventions, minimally invasive approaches, and combined cancer therapies. The development of biomaterials is grounded in advanced knowledge of biology, chemistry and materials science, allowing for the design of materials with specific properties such as biocompatibility, mechanical strength and biodegradability. The use of biomaterials in gynecology dates back to the 1960s, when synthetic materials were first introduced for the treatment of gynecological disorders. Early implants made from metals or polymers often triggered immune reactions and complications. Advances in technology have since enabled the creation of biomaterials that better mimic natural tissues, becoming increasingly biocompatible and safe for patients.¹

Modern biomaterials used in gynecology can be categorized into the following groups:

- Synthetic polymers (e.g., polycaprolactone, polylactide): used in implants and biodegradable structures;
- Natural materials (e.g., collagen, elastin): ideal for tissue regeneration due to high compatibility with human tissues;
- Composite materials: combining the properties of synthetic and natural components for greater application flexibility.

The introduction of biomaterials into gynecological practice has significantly enhanced treatment effectiveness and patient comfort. Notable applications include: 1) synthetic surgical sutures replacing natural materials; 2) mesh implants for treating hernias, such as pelvic floor disorders in women; and 3) drug delivery systems, including biodegradable implants for hormone or chemotherapy drug release.

As research and technology progress, biomaterials in gynecology are becoming more advanced and accessible, opening new therapeutic possibilities.^{2,3}

Biocompatibility and biodegradability

Biocompatibility and biodegradability are 2 critical aspects of biomaterials in gynecology, determining their efficacy and safety. Biocompatibility refers to a material's ability to coexist with human tissues without causing adverse reactions such as inflammation, rejection or scarring. Biodegradability refers to a material's ability to break down within the body into metabolizable and excretable byproducts, thereby eliminating the need for surgical removal.⁴ Biocompatible biomaterials must meet several criteria, including:

- Biological neutrality, preventing immune responses;
- Adequate mechanical strength to provide structural stability during tissue regeneration;

- Chemical safety, ensuring no toxic degradation products.

Materials like polymer meshes and collagen implants in gynecology are designed to support tissue regeneration while minimizing infection risks.⁵ Biodegradable materials have found various and extensive applications in gynecology due to their ability to be absorbed by tissues after fulfilling their function. We can include the following examples:

- Polycaprolactone (PCL) is frequently used in implants for pelvic floor reconstruction;
- Polylactide (PLA) is mostly utilized in drug delivery systems and surgical meshes that degrade over time;
- Collagen and gelatin, which are natural polymers used in membranes that aid wound healing following gynecological procedures.

The biodegradability of these materials is particularly valuable in procedures requiring temporary mechanical support or precise drug release over time. Challenges in this field include controlling the degradation rate and preventing adverse biological reactions. Examples of widely used long-term drug delivery systems are implants and intrauterine devices releasing synthetic progesterone derivatives over 3–7 years.^{5,6}

Biomaterials used for vaginal and pelvic wall reconstruction

Biomaterials used in reconstructive surgery of the vaginal and pelvic walls can be classified into synthetic, biological and composite materials.⁷ Most frequently, biomaterials are used in pelvic floor dysfunction,^{3,8,9} and transvaginal mesh repair.³ Synthetic materials, such as polypropylene meshes, are widely used due to their mechanical strength and durability. Biological materials, such as human- or animal-derived collagen matrices (allografts and xenografts), offer superior biocompatibility and can enhance the immune response through stimulation of cytokine release and activation of immune cells.¹⁰ Composite materials combine the benefits of both synthetic and biological components to enhance biocompatibility while maintaining structural integrity. The available studies indicated that graft synthetic and biological materials could be efficiently used in pelvic reconstruction. Jeon and Bai categorized synthetic grafts into absorbable and non-absorbable types and further divided them into 4 subgroups based on their physical characteristics. In contrast, biological grafts are classified into 3 categories: autologous grafts (e.g., rectus fascia, fascia lata, vaginal mucosa), allografts (e.g., cadaveric fascia lata, dermis) and xenografts (e.g., porcine dermis, small intestinal submucosa).¹¹ Another interesting approach is to combine drug release and biomaterials. Mangır et al.¹² indicated in their research that polypropylene meshes used in pelvic floor repair may lead to severe complications. Accordingly, the authors emphasized the need for biomechanically compatible alternatives. Their study developed an estradiol-releasing electrospun PLA mesh to enhance extracellular matrix (ECM) production and angiogenesis.

Polylactic acid meshes contained varying concentrations of estradiol, and were tested in vitro and in vivo, indicating sustained estradiol release over 4 months. Finally, it was observed that the meshes promoted ECM production, including collagen I, collagen III and elastin, and doubled angiogenesis in chick models. These findings suggest that estradiol-releasing PLA meshes are promising candidates for pelvic floor repair, warranting further investigation in advanced animal models.¹² Table 1 shows the possible biomaterials used in pelvic therapy.^{7,13,14}

Despite the growing utility of biomaterials, their clinical use still presents challenges such as erosion, infection and chronic pain. These complications are well documented for polypropylene meshes, as they are the most commonly used synthetic materials in pelvic organ prolapse surgery. The occurrence rate of polypropylene mesh-related complications currently ranges from 5% to 29%. The U.S. Food and Drug Administration (FDA) has issued multiple warnings regarding the use of polypropylene mesh in pelvic organ prolapse surgery and, in 2019, officially ordered the cessation of sales of surgical mesh devices for transvaginal prolapse repair in the USA.

The underlying cause of mesh-related complications, such as erosion, infection and pain, is the tissue inflammatory response to mesh implantation. It was previously believed that the peak inflammatory response to polypropylene mesh occurs within 24–48 h after implantation, followed by a continuous decline. However, recent studies have revealed that polypropylene degradation over time promotes a persistent inflammatory response, primarily driven by neutrophil granulocytes, T-lymphocytes, and both M1 and M2 macrophages.^{15,16} Additionally, mesh degradation leads to the formation of microcracks on its surface, which favors the development of bacterial biofilms, as the mesh can be easily contaminated by vaginal microbiota. As polypropylene mesh degradation progresses over time following implantation, the local inflammatory response also intensifies, contributing to a higher incidence and severity of mesh-related complications.

Despite these risks, modern innovations, such as coated or resorbable meshes, have improved outcomes by reducing adverse effects. Future research focuses on developing bioactive materials that promote tissue regeneration and reduce complications. Recent studies suggest that patient-specific approaches may further enhance the effectiveness of biomaterials in reconstructive surgery.^{9,11,17}

Treatment and prevention of pelvic organ prolapse

As previously mentioned, biomaterials play a crucial role in providing structural support to weakened pelvic tissues, particularly in cases of pelvic organ prolapse (POP). Currently, polypropylene meshes are commonly used for surgical interventions,¹⁸ while bioengineered scaffolds and absorbable meshes are gaining attention for their reduced risk profiles. However, improved materials such as electrospun nanofibers¹⁹ and hydrogels,²⁰ offer promising alternatives for POP repair. The most important aspect of biomaterial use in POP surgery is risk prediction, particularly concerning complications such as erosion, mesh exposure and infection. Emerging strategies include the use of bioresorbable materials and tissue-engineered scaffolds that integrate with native tissues to mitigate complications. Current research emphasizes optimizing material properties such as elasticity, porosity and biocompatibility to enhance outcomes.^{21,22}

Minimally invasive surgery

In recent years, biomaterials have also been increasingly used in laparoscopic and endoscopic procedures. Such techniques, called minimally invasive gynecological procedures,²³ benefit from advanced biomaterials such as biodegradable polymers, hydrogels and lightweight meshes.¹³ These materials reduce scarring, promote healing and enhance surgical precision. Examples include absorbable fixation devices and bioadhesive materials for tissue approximation.⁹ It was noticed that biomaterials play a significant role in reducing the invasiveness of gynecological procedures. Biomaterials help reduce procedure invasiveness by promoting faster healing and minimizing postoperative complications. One study exemplified this by successfully treating Fallopian tube obstructions, a common cause of infertility, using a novel self-expandable biodegradable microstent. The authors fabricated the microstent from PLA using femtosecond laser cutting, achieving an outer diameter of 2.3 mm and precise strut dimensions of 114 µm in thickness and 103 µm in width. As was indicated, mechanical tests confirmed its ability to crimp to 0.8 mm and recover to 1.8 mm upon release, demonstrating its self-expanding properties. This proof-of-concept revealed the potential of microstent technology as a minimally

Table 1. Overview of biomaterials used in gynecological applications^{7,13,14}

Type of biomaterial	Examples	Applications	Advantages	Challenges
Synthetic	polypropylene, polyester	vaginal mesh, pelvic organ support	high durability, cost-effective	risk of erosion, infection, rejection
Biological	collagen, allografts	pelvic floor repair, prolapse repair	biocompatibility, tissue integration	limited availability, higher cost
Composite	hybrid meshes	pelvic reconstruction	improved integration and strength	complex manufacturing

invasive solution to restore the natural lumen of the Fallopian tube, offering a promising therapeutic option for infertility treatment.²⁴

Hydrogels, for instance, are used for adhesion prevention in laparoscopy, while shape-memory polymers called “smart” materials enable precise tissue reconstruction.²⁵ Tang et al. evaluated a shape memory polymer (SMP) device for Fallopian tube occlusion in a rabbit model. The device, made of poly(dl-lactic acid)-based poly(urethane urea), is a spiral-shaped cylinder that reverts to its permanent shape within 60 s at 37°C. Authors implanted their polymer in 48 rabbits. As observed, the SMP device induced aseptic inflammatory reactions and achieved complete Fallopian tube occlusion in all cases, with no resulting pregnancies. Additionally, SMP device demonstrated progressive biodegradation. This research demonstrates biodegradable and biocompatible potential of SMP devices as a possible permanent contraceptive solution.²⁶ Future innovations in this field aim to integrate nanotechnology and drug-eluting systems into surgical biomaterials.^{27–29}

Infertility treatment and assisted reproductive technologies

Biomaterials are increasingly used in assisted reproductive technologies (ART) to enhance embryo implantation and improve pregnancy outcomes. Examples include biodegradable scaffolds for endometrial regeneration, hydrogels for embryo culture and bioactive coatings for embryo transfer catheter.^{30,31}

As is known, the endometrium plays a crucial role in embryo development and pregnancy. Lin et al. used human umbilical cord mesenchymal stem cells (HUCMSCs), known for their rapid self-renewal and painless collection, in combination with spermidine (SN), a polyamine essential for cellular function, demonstrating promising potential in the repair of intrauterine adhesions. Authors explored the potential of hydrogel-loaded exosomes derived from HUCMSCs and spermidine to improve conception rates in mice model with thin endometrial lining. The obtained results revealed that HUCMS cells and SN enhanced endometrial function, with hydrogel-incorporated exosomes showing potential for intrauterine treatment and improving pregnancy outcomes.³² In another study, ECM hydrogels derived from decellularized tissues were applied for endometrial regeneration, offering potential therapeutic benefits for conditions such as Asherman's syndrome and endometrial atrophy. A proteomic analysis of porcine endometrial ECM hydrogels (EndoECM) was performed, revealing a significant presence of proteins essential for tissue repair. Authors used murine model of endometrial damage, and treated animals with EndoECM supplemented with growth factors (GFs). Improved regeneration was observed, marked by increased gland formation, cell proliferation, angiogenesis, and pregnancy rates, along with reduced collagen deposition. These findings

highlight bioengineered EndoECM hydrogels with GFs as a promising therapeutic option for endometrial-related infertility.³³

The female reproductive system is strongly dependent on the precise hormonal and uterine coordination to support implantation and fetal development, with pathologies in any organ or process potentially compromising fertility. Thus, there are potential benefits of biomaterials in embryo implantation and development, e.g., advanced biomaterials can mimic the ECM, improving the interaction between embryos and the uterine lining. The available studies highlight the role of nanofibers and growth-factor-laden hydrogels in creating an optimal microenvironment for implantation.^{27,28}

Gynecological oncology

Biomaterials are used not only for regeneration in gynecology but also in treating cervical, ovarian and other gynecological cancers. In this field, biomaterials are used mainly for drug delivery, tissue reconstruction and targeted therapy. Examples include nanoparticle-based carriers for chemotherapeutics, injectable hydrogels for localized drug release and scaffolds for reconstructive surgery.^{28,34–36}

Biomaterials enable selective drug delivery and targeted cancer therapy through the application of nanotechnology-based systems, such as liposomes and dendrimers, which allow for the precise delivery of anticancer drugs while minimizing systemic toxicity. Stimuli-responsive materials offer targeted therapies triggered by pH or temperature changes within the tumor microenvironment.³⁷ Ovarian cancer's high mortality necessitates innovative treatment strategies, including natural compound-based therapies. Thus, researchers continue to develop more promising nanocarriers to transport drug molecules more effectively. The recent study examined the anticancer effects of resveratrol (RSV)- and curcumin (CUR)-loaded in newly developed core-shell nanoparticles in ovarian cancer cell lines model (MDAH-2774, SKOV-3). Authors observed that RSV-loaded systems showed limited cytotoxicity, but CUR-loaded nanoparticles significantly reduced cell viability, with MDAH-2774 cells being more sensitive. Moreover, confocal microscopy showed enhanced cellular uptake and mitochondrial localization of CUR. These results underscore the potential of CUR-loaded nanoparticles for ovarian cancer treatment, warranting further investigation into their biological effects.³⁸ Another major challenge in ovarian cancer is the phenomenon of drug resistance, which is associated with mechanisms such as efflux transporters, apoptosis dysregulation, autophagy, and the presence of cancer stem cells. Multi-drug resistance (MDR) occurs in more than half of patients. Currently, the first-line treatments include the combination of surgery and chemotherapy, which is not effective against drug-resistant cancer in long-term therapies. One study developed an innovative nanotechnology-based targeted drug delivery system,

where hyaluronic acid-modified gold nanorods were used for functionalization of mesoporous silica nanoparticles (HA-PTX/let-7a-GNR@MSN) to deliver paclitaxel (PTX) and the microRNA let-7a. This new nanosystem specifically targeted CD44 receptors on drug-resistant SKOV3TR human ovarian cancer cells. An enhancement in tumor permeability by 150% was observed, along with effective delivery of therapeutic agents. In terms of MDR phenomenon, the results revealed a significant P-glycoprotein down-regulation, induction of apoptosis and inhibition of tumor growth, with mTOR-mediated pathways identified as key mechanisms in reversing drug resistance. Consequently, these nanoparticles demonstrated a promising strategy for overcoming MDR and improving ovarian cancer therapy.³⁹ Another promising technology worth developing is theranostic nanosystems, which combine both therapeutic and diagnostic capabilities, enabling a more efficient anticancer effect.⁴⁰ Emerging targets such as MUC16/MSLN and FOLR1 have been reported, showing promising effects in enhancing the personalization of ovarian cancer treatment. For instance, MUC16/MSLN interactions activate survival pathways in cancer cells, but anti-MSLN antibodies and engineered CAR-T cells effectively reverse these effects. Remarkably, FOLR1-targeted therapies, including ADCs and CAR-CIK cells, have proved a significant anti-tumor activity in preclinical and clinical studies. Other biomarkers, such as CHI3L1, nectin-4, CXCR4, and STAT3, also offered potential theranostic applications through targeted therapies and molecular profiling. These strategies highlight the potential for personalized, biomarker-driven approaches to ovarian cancer diagnosis and treatment, paving the way for improved outcomes.^{41,42} In summary, targeted nanoparticle-based delivery systems, including lipid, polymeric and inorganic nanoparticles, are designed to enhance specificity and efficacy in overcoming drug resistance, improve therapeutic outcomes and simultaneously serve as diagnostic tools in ovarian cancer.^{42,43}

Future perspectives on biomaterials in gynecology

Recent developments in biomaterials, including stem cell-laden scaffolds and bioactive hydrogels, have shown promising effects in regenerating endometrial tissue and repairing gynecological damage. These biocompatible materials support cell proliferation, angiogenesis and tissue integration.^{19,32} Another promising direction for development is tissue engineering involving 3D bioprinting and bioactive scaffolds to create personalized regenerative solutions. For instance, there are currently developed biomaterials that release growth factors to enhance the repair of damaged uterine tissues, offering potential treatments for conditions such as Asherman's syndrome.^{33,36} Another challenging issue is ovarian aging, characterized by the progressive decline of ovarian function with advancing age.

Biomaterial-based solutions can serve as a promising way in ovarian aging (OA). Ovarian aging involves a complex interplay of genetic, environmental and molecular factors, with several biomarkers, such as AMH, estrogen and follicle-stimulating hormone (FSH), serving as indicators of ovarian function. Biomaterials like extracellular vesicles, synthetic polymers and 3D scaffolds show the ability for development of artificial ovaries, enhancing follicular development and delivering therapeutic agents.⁴⁴ However, despite advancements, challenges are still present in clinical translation, including safety concerns, regulatory barriers and limited large-scale studies. Future perspectives should focus on integrating innovative biomaterials with advanced diagnostics like machine learning^{45,46} and molecular imaging to enhance early detection and treatment efficacy, and demonstrate full potential in gynecology.

Biomaterials in magnetic resonance imaging

The most commonly used biomaterials in pelvic organ prolapse surgery are polypropylene meshes. Polypropylene is a non-ferromagnetic material and therefore does not pose significant risks to patients in terms of heating, magnetic attraction or image distortion during magnetic resonance imaging (MRI) scans. As a non-ferromagnetic material, polypropylene implants typically do not produce significant artifacts in MRI scans. However, some implants may contain additives, such as metallic traces, which can cause mild artifacts. Additionally, the shape and size of polypropylene implants may contribute to local image distortions.

Regarding the visualization of polypropylene implants using MRI, polypropylene-based meshes do not interact with the MRI signal and therefore typically appear as areas of low signal intensity on MRI images. This can lead to difficulties in visualization of the implants, especially when the imaging focus is on the surrounding tissues.

In conclusion, polypropylene-based meshes used in pelvic organ prolapse surgery are MRI-compatible; however, mild imaging artifacts and difficulties in implant visualization may still occur.

Conclusions

Our review highlights significant developments in the applications of biomaterials for gynecological procedures, with a focus on minimally invasive surgeries, infertility treatments and gynecological oncology. As indicated, in minimally invasive procedures, biomaterials such as hydrogels and SMP show great potential for treating conditions like Fallopian tube obstructions and pelvic floor disorders, offering reduced complications and faster recovery times. The development of biodegradable and bioresorbable materials personalized to patient-specific needs is crucial for further improvements of surgical outcomes

while minimizing adverse effects. In the context of infertility treatments, new biomaterials like hydrogel-loaded exosomes and ECM scaffolds are emerging as effective solutions for regenerating damaged uterine tissues and addressing conditions such as endometrial atrophy and intrauterine adhesions. These technologies enhance tissue regeneration and implantation success rates, but more clinical trials are needed to establish their long-term efficacy. In the case of gynecological oncology, nanoparticle-based drug delivery systems provide a promising approach to overcome challenges like MDR and systemic toxicity in ovarian cancer treatments. These systems enable precise targeting of cancer cells, thereby reducing harmful side effects and improving treatment outcomes. In particular, theranostic strategies, combining diagnostic and therapeutic functions, show significant potential for personalized treatment approaches. Table 2 summarizes the applications of biomaterials in gynecology.

It can be stated that integrating biomaterial development with nanotechnology, molecular imaging, and machine learning offers a promising pathway to enhance both diagnostic and therapeutic efficacy in gynecology. However, several challenges remain, including addressing regulatory and safety concerns, ensuring cost-effectiveness and conducting large-scale clinical studies to translate these advancements into routine clinical practice. The findings emphasize the crucial role of biomaterials in advancing gynecological care and the necessity of continued interdisciplinary research to improve and expand their clinical application.

Table 2. Biomaterials in gynecology

Application	Biomaterials used	Benefits	Challenges
Minimally invasive surgery	hydrogels, SMPs	reduced invasiveness, faster healing	managing biodegradation rates
Infertility treatment	ECM scaffolds, hydrogel-loaded exosomes	tissue regeneration, improved implantation	limited clinical trials, cost
Gynecological oncology	nanoparticles, liposomes, ADCs	targeted drug delivery, reduced toxicity	overcoming drug resistance, scalability
Pelvic floor repair	PLA meshes, composite scaffolds	enhanced biocompatibility, tissue integration	risk of erosion, infection

ECM – extracellular matrix; PLA – polylactide; ADCs – antibody-drug conjugates; SMP – shape-memory polymer.

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