**Review Article**

# Abdominal Wall Defects: Hydrogel based solutions in abdominal wall reconstruction

**Alook Kumar Ajay[1]*, Shashi Ranjan[2], Rajendra Singh[3], Shalini Kapoor Mehta[4]**

[1]Department of Medicinal Chemistry, Rajputana college of Pharmacy, Bangalore, Karnataka, India.

[2]Department of Pharmaceutical Sciences, Rajputana college of Pharmacy, Bangalore, Karnataka, India.

[3]Department of Pharmacology, Rajputana college of Pharmacy, Bangalore, Karnataka, India.

[4]Department of Phytochemistry, Rajputana college of Pharmacy, Bangalore, Karnataka, India.

*Correspondence: alook2me@gmail.com

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**Abstract**

Abdominal wall defects, including hernias and congenital anomalies, are complex conditions that require practical and durable repair strategies. While commonly used, traditional synthetic meshes often face limitations such as poor integration with host tissue and complications like infection or adhesion formation. This paper presents hydrogel-based materials as a novel approach to addressing these abdominal wall defect repair challenges. Hydrogels, characterized by their biocompatibility, tunable mechanical properties, and ability to support tissue regeneration, offer a promising alternative to existing methods. This paper explores the design and application of these hydrogels, highlighting their potential to improve surgical outcomes through enhanced tissue integration, reduced inflammation, and minimized postoperative complications. Preclinical and clinical evidence suggests that hydrogel technology could revolutionize the standard of care for abdominal wall defects, offering a more effective and patient-friendly solution.

**Keywords:** Hydrogel; Abdominal wall defects; hernia; electrospinning; nanotechnology; tissue regeneration

## Introduction

Abdominal wall defects (AWDs), a congenital disability, occur when the digestive organs such as the stomach or intestines- protrude from the body through an abnormal opening in the abdomen. The abdominal wall plays a crucial role in fetal development, as it should enclose these organs as they move into the abdomen. An abdominal wall defect occurs when this process is disrupted, allowing some organs to remain outside the abdomen [1]. The abdominal wall is undeniably a crucial weight-bearing structure in the body, playing a pivotal role in supporting respiratory mechanics and providing an indispensable protective barrier for internal organs. It dynamically adjusts to intra-abdominal and external pressures, constituting an indispensable component for normal physiological functions. Abdominal wall defects predominantly involve the absence of one or more components of the abdominal wall, and it is essential to note that postoperative incisional hernias are the prevailing type, representing over 65% of all abdominal wall defects [2,3]. These defects can arise from congenital anomalies, trauma, surgical procedures, or infections, and they present significant challenges in clinical practice due to their impact on patient quality of life and the complexity of repair strategies [4-5]. The two most common types of AWDs are gastroschisis and omphalocele, each with distinct characteristics and associated clinical challenges. They are of significant concern in neonatology and pediatric surgery due to the complexity of management and the long-term outcomes associated with these conditions [6,7].

## Gastroschisis

Gastroschisis is an abdominal wall defect on the right side of the umbilicus. The absence of a protective covering over the protruding abdominal contents characterizes it. The exact cause is not fully understood, but it is believed to result from an abnormality in the lateral ventral body folds migration during early embryonic development, leading to a defect near the midline. Usually, the developing intestine moves outside the abdominal cavity around the sixth week of gestation. Over the next four weeks, the intestine undergoes a process of midgut rotation and returns to the abdomen. However, if the abdominal wall fails to form correctly, the intestine may remain outside the abdomen in the amniotic cavity [8,9].

**Omphalocele**

Compared to gastroschisis, which is characterized by a defect in the abdominal wall, omphalocele manifests as a herniation at the abdominal midline, explicitly involving the umbilical ring. This results in forming a 3-layer sac that encases the herniated abdominal contents. The layers of this sac consist of an inner layer of peritoneum, a middle layer of Wharton's jelly, and an outer layer of amnion. From an embryological standpoint, omphalocele is postulated to arise from a folding defect occurring during the bowel's return to the abdominal cavity during normal development [7].

While both conditions occur in approximately 4% of live births, omphalocele, which is detected during the second trimester of pregnancy, can have an incidence of up to 1 in 1,100. It is important to note that omphalocele is often accompanied by a high rate of intrauterine foetal death [8-10]. However, gastroschisis has become more common globally in the last several decades. In addition to gastroschisis and omphalocele, other less common abdominal wall defects include umbilical hernias and bladder exstrophy. Each of these conditions results from the failure of the abdominal wall to close properly during fetal development, leading to varying degrees of herniation of abdominal contents [11]. A large number of people around the world are affected by abdominal wall abnormalities, which are becoming more common as a clinical condition. Between 9% and 20% of the global population suffers from this illness. Healthcare expenditures exceed 10 billion USD annually due to over 400,000 reconstructive surgeries to correct internal soft tissue anomalies [12,13].

In the 19th and 20th centuries, medical science began to approach these defects with a more systematic and scientific methodology. Early surgical interventions were attempted, but these were often crude and fraught with high mortality rates due to the lack of anaesthesia, asepsis, and an understanding of the pathophysiology of these defects [6,7,14]. The development of pediatric surgery as a specialized field in the mid-20th century marked a turning point in managing abdominal wall defects. Surgeons like William Ladd [6] and Robert Gross [15], pioneers in pediatric surgery, contributed significantly to advancing surgical techniques and postoperative care, greatly improving survival rates.

At present, several options for the management of abdominal wall defects include tension-free mesh repair [16], abdominal wall tissue separation [17], flap reconstruction [18], abdominal wall expansion techniques [19], and temporary abdominal closure measures [20, 21]. However, these technologies can partially reconstruct, restore, or even compensate for the lost function while revealing the essential vulnerabilities. They include infection and immune rejection, high recurrence rate, and potential risks of reoperation, which set limits to reconstructing the advanced functions for humans and limit their clinical application [22-24].

To address the limitations of current treatments, researchers have explored the development of advanced biomaterials that promote tissue regeneration and integration with host tissues [25]. Tissue engineering is gradually becoming an innovative technique in managing abdominal wall defects (AWDs), delivering novel solutions for restoring the abdominal wall. Conventional repair methods involve using synthetic meshes or harvesting autogenous tissues, which bear several problems, such as infection, rejection and poor integration with the surrounding tissue. Tissue engineering aims to overcome these drawbacks by creating new constructs that will mimic the native tissue of the abdominal wall [26,27]. These new techniques currently in use depend on the carrying capacity of scaffolds to translocate cells and for the delivery of bioactive molecules. This dynamic approach increases tissue healing and regeneration, thus creating a stage for further development of tissue engineering [28,29-31].

Another promising avenue in tissue engineering is the incorporation of bioactive molecules, such as growth factors, into the scaffold material. These molecules can be released in a controlled manner to enhance cellular processes critical for tissue repair, including angiogenesis, cell proliferation, and ECM production. Growth factors like vascular endothelial growth factor (VEGF) and essential fibroblast growth factor (bFGF) have been shown to accelerate the formation of new blood vessels and improve the overall healing response in tissue-engineered constructs, leading to better outcomes in abdominal wall repair [32]. Tissue engineering scaffolds are designed to offer mechanical support and determine favourable local conditions to promote cell attachment, mobility, proliferation, and differentiation [33]. Hence, efforts to develop and manufacture a novel bio scaffold for abdominal wall tissue engineering are an active research focus on rebuilding the mechanical and biological features of the abdominal wall tissue.

**Hydrogels**

Hydrogels are crosslinked polymeric structures that provide three-dimensional hydrophilic structures capable of holding a massive amount of water or biological fluids. Due to their hydrophilic property and flexible nature, they are highly similar to natural tissues, which is why they are widely employed in the biomedical field for drug delivery, wound healing and tissue engineering. Hydrogels have been a topic of interest in recent years because of their multi-faceted characteristics and their possible application in enhancing several therapeutic interventions [34,35]. Some of the tunable properties associated with hydrogels, irrespective of whether they are composed of natural polymers, synthetic polymers, or a combination of both, include the following: This is particularly important for applications that need to interface with living tissues since gelatin, alginate, and chitosan are all biocompatible and biodegradable natural polymers. Polyethylene glycol (PEG), polyvinyl alcohol (PVA), and polyacrylamide are few examples of synthetic polymers which are used for specific Biomedical applications due to their ability to control mechanical properties, swelling behavior, and degradation rates [36,37]. Hydrogels have a three-dimensional crosslinked polymer network and can swell in water without dissolving, converting into a gel-like substance. Crosslinking can be done by physical contact (hydrogen bonds, ionic interactions) or by chemical means (covalent bonds). Crosslinking density is one of the most significant factors controlling the mechanical properties, pore size, and swelling behaviour of hydrogels used for biomedical applications [34]. Hydrogels have been used in many novel applications to manage abdominal wall defects. The one that holds much promise is their application as a scaffold for cell delivery. Thus, when stem cells or other types of regenerative cells are incorporated into a hydrogel structure, it becomes possible to produce a scaffold that fosters tissue healing. These cellular and nutrient-containing hydrogels can be applied directly to the defect area, where they offer the physical environment and encourage the formation of new, healthier tissue [38,39]. Growth factors and cytokines involved in the repair process have also been incorporated into hydrogels. For example, once introduced into hydrogels, angiogenic factors like vascular endothelial growth factors (VEGF) improve blood vessel formation, which is essential for supporting tissue nutrition under regeneration. Likewise, the hydrogels containing anti-inflammatories could prevent the immune response that leads to fibrosis and scarring that could hinder the repair [40].

Hydrogels have been extensively utilized in abdominal wall defects, mainly in regeneration, which involves providing scaffolds to hold tissues. This is because hydrogels can be designed to stimulate cell attachment, growth, and development into functional tissue. The hydrogel further enables this regenerative capacity to help retain moisture known to support healing and deliver bioactive molecules like growth factors at the site of the wound [41,42]. For example, when injury damages the abdominal wall extensively, the body may not be capable of growing enough new tissue to cover the gap; hydrogels can be used to provide a framework for tissue regeneration until the affected area is once again intact. These scaffolds can be designed to self-diminish in a time scale matching tissue regeneration, thereby minimizing the need for follow-up surgeries to remove the implant [43]. Hydrogels are also being considered drug delivery vehicles in the repair of the abdominal wall. They can be pre-dosed with antibiotics or anti-inflammatory drugs or with another therapeutic agent programmed to be released gradually to control the infection or inflammation at the surgical site. This ability to provide a slow release is exceptional and is mainly used in preventing infections after surgery or adhesion formation in operations involving the abdominal wall [44]. For example, a hydrogel containing anti-microbial agents may be applied after surgery to minimize bacterial growth on the repair site, hence minimizing infection chance, which is a considerable issue with synthetic meshes [45].

**Nanotechnology**

Nanotechnology has brought significant advancements in developing new reparative techniques for abdominal wall defects and utilizing the subsequent innovative scaffolds and biological meshes widely applied in hernia repairs. Substantial progress has been made in developing synthetic and biological meshes in this critical area [26,46]. The traditional use of synthetic meshes in repairing these defects has been associated with complications such as infection, adhesion, inflammation, and poor integration with surrounding tissues. The application of nanotechnology in treating abdominal wall defects has emerged as a promising approach to address these issues. Nanotechnology involves manipulating materials at the nanoscale to enhance their physical, chemical, and biological properties, thereby offering improved outcomes in surgical repair [47].

The marked study has shown that myoblast-seeded bovine tunica vaginalis can be a scaffold to reconstruct major and extensive abdominal wall defects and regenerate skeletal muscle tissue [48]. In another study by Song et al., a modified plasma polymerization method generated A composite scaffold with acellular dermal matrices (ADM) and VEGF-loaded multi-walled carbon nanotubes (MWNTs). Controlled release of VEGF by the plasma polymerization treatment offers a method to accelerate early revascularization, and the 3% MWNT composite scaffold was able to repair abdominal wall defects [49].

Although synthetic meshes have been studied and proven helpful in certain studies, Synthetic meshes are commonly used for abdominal wall reconstruction, specifically for support of weakened or damaged tissue. These meshes can be fabricated from polypropylene, polyester, or polytetrafluoroethylene (PTFE). They aim to be biocompatible, compliant, and robust so that the surgical mesh can be integrated into the body tissues without causing infection or even sometimes rejecting the mesh by the body [50,51]. Hernandez-Gascon and their colleagues have extensively researched computational modelling of hernia-repaired abdominal walls. Their use of finite element (FE) models of the abdomen with three synthetic meshes has revealed that surgical repair fails to fully restore normal physiological conditions in the abdominal wall [52]. On the other hand, biological meshes, including meshes made from human or animal-derived tissues, can attract blood vessels and regenerate through the infiltration of native fibroblast cells; they are superior to synthetic meshes [49].

In addition, electrospinning has become another well-liked approach in tissue engineering for creating fibrous membranes with a large surface-area-to-volume ratio and fibers of the nano-micro range [53,54]. Owing to its diversity in composition, electrospun fibrous membranes have been investigated in various tissue engineering fields, such as cardiac patches [55], wound dresses [56], and drug-delivering carriers [53]. The ideal mechanical strength of the fibres is also one of the significant advantages of this technique, which made it an ideal mesh option for abdominal wall hernia reconstruction in the past decade [57,58]. However, the row material for electrospinning is less receptive, and the final fibres developed are primarily hydrophobic, which may hinder their histological integration in hernia repair. To this end, the researchers have incorporated 3D-printed scaffolds in managing abdominal wall hernia reconstruction [59,60]. Thus, 3D printing, based on its flexibility and variability of changes in the structure and a large number of printing sources, can be considered a promising trend for creating complex hernia repair materials in the future [61]. This potential makes us optimistic about the future of hernia repair with enhanced biocompatibility and mechanical strength. It is essential to mention that in recent years, much attention has been paid to hydrogels, electrospun fibrous membranes, and three-dimensional scaffoldings, as shown in Figure 1 [25].

This review will identify the advantages of hydrogel and nanotechnology and their use in reconstructing and remodelling defective abdominal walls. It will expound on new developments appearing in this branch of study; they give information about how they improve the design, development, and challenges in hydrogel and nanotechnology-based repairs for abdominal wall defects, emphasising their application in regenerative medicine and surgery.

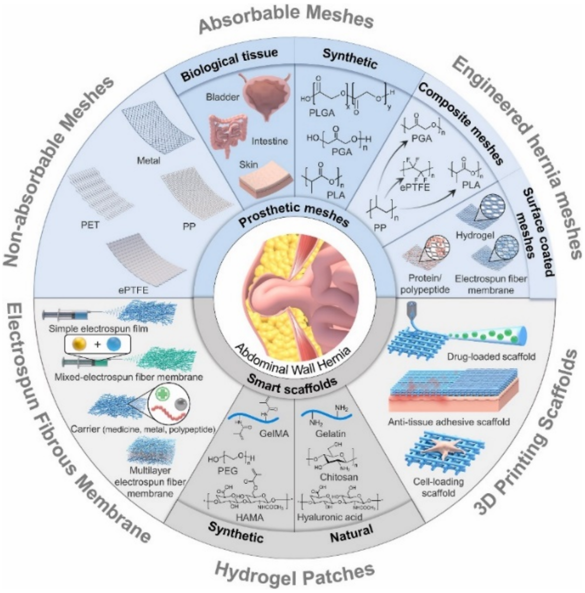


**Figure 1.** Schematic illustration of abdominal wall hernia repair meshes: from prosthetic meshes to smart materials [25].

### Abdominal wall anatomy

The abdominal wall structure involves the skin, subcutaneous tissue, fascia, muscle, and peritoneum layers. The muscles are in layers; the big one is the rectus abdominis in the middle and the external, internal and transversus abdominis muscles on the sides. The muscles are also anchored by the fascia, especially the transversalis fascia, which offers more support. However, the anterior abdominal wall has the primary function of shielding the organs and ensuring appropriate positioning of abdominal organs as well as maintaining integrated intraabdominal pressure but at the same time is accountable for the majority of the abdominal wall injuries [62-64]. It is important to emphasize that hernias and other kinds of injury of the abdominal wall are not rare and can be caused by numerous factors, such as congenital abnormalities, trauma, surgery, and chronic diseases. They include hernias, which are a condition that results from the protrusion of abdominal contents through a hole in the abdominal muscles and traumatic injuries that lead to the tearing or injuring of the abdominal muscles [65-67].

To meet the needs of diagnosis and treatment, depending on the severity of abdominal wall defects, they can be divided into three different types: (a) Partial thickness defect of the abdominal wall is thus defined as those situations where only the skin and a part of the subcutaneous tissue is lost. These injuries may be due to trauma, surgical excisions, or ulcers and generally affect only the skin and subcutaneous tissue in the abdominal wall up to the dermal layer and occasionally the subcutaneous fat. These defects typically do not penetrate the deeper layer of the fascia or muscular layer. Consequently, they are usually not as extensive as they necessitate more complicated surgeries, such as free flap reconstruction, but only moderate surgery that may include skin grafting or local flap [68-72]. (b) Muscle and fascia atrophy or aplasia is another condition defined by the fact that the abdominal wall muscles and fascial tissues are missing while the skin remains. For instance, this condition might be congenital in prune belly syndrome, where the abdominal muscles are poor or absent. Skin, though, has lost deeper investing musculature and cutaneous fascia, and the integrity of skin tissue continues to be unperturbed, which creates certain biomechanical enigmas for the abdominal wall [73,74]. (c) Abdominal wall agenesis or abdominal wall aplasia is a condition where the abdominal wall is not formed at all (agenesis and aplasia means that an organ, tissue or body part failed to develop naturally; in some cases, it means that it is missing) [75-78]. Abdominal wall defect patients often have symptoms and signs of the primary disease and possible complications like adhesion and intestinal obstruction. Such complications stem from multiple abdominal injuries and infections [79-81]. The method of separating the adhesions may cause damage to the adjacent intestinal wall tissues and eventually lead to the formation of intestinal fistulas [82,83]. For instance, patients suffering from an open abdomen often undergo numerous abdominal operations and recurrent abdominal lavage that continuously injures the abdominal wall. For instance, prolonged bed rest, prolonged abdominal surgery, and limited mobility lead to the atrophy and loss of contractile strength of the abdominal wall muscles, making it challenging to reconstruct the abdominal wall [84,85] effectively. This means definitive abdominal wall repair and reconstruction should be performed immediately.

**Hydrogel-based abdominal wall repair**

Thus, there has been an increasing focus on tissue-engineered scaffolds for better biocompatibility and functionality in abdominal wall repair. Among these, hydrogels have renewed interest in their application due to their versatile properties. Hydrogels are relatively more biocompatible and can be synthesized to disintegrate over time as the new tissue grows, thereby reducing the chances of post-surgery complications [86,87]. Different kinds of hydrogels have been investigated for AW repair, and each has unique characteristics that make it appropriate to be used in specific situations [87,88]. Bio-natural hydrogels like collagen-based, gelatin, or hyaluronic acid hydrogels have better biocompatibility and are degradable in the body. These materials are most suitable in applications where close interaction with the tissues, as well as the regeneration of tissues, is required. However, in many cases, their mechanical strength is insufficient to support significant or highly stressed defects [41,89-91]. Polyethylene glycol, polycaprolactone, and polyvinyl alcohol-based synthetic hydrogels can be developed to achieve better mechanical properties and tunable degradation rates. These materials can then be tailored to provide mechanical strength in the range needed for abdominal wall reconstruction while being biocompatible.

Moreover, synthetic hydrogels, with relatively greater mechanical strength, can also be surface-modified with bioactive agents to augment the therapeutic potential of the scaffolds [92-94]. Moreover, cross-linking is the critical parameter that defines the hydrogel's characteristics and potential fields of usage, and various approaches to cross-linking result in hydrogels with various physicochemical properties and network morphologies. The cross-linking of hydrogels may be categorized into two, namely, the physical cross-linking and the chemical cross-linking [95,96]. Physical cross-linking is formed through molecular interactions, including ion, hydroxyl and hydrogen bonds and crystallization was shown. Hydrogels prepared by this approach are generally stimuli-responsive and have good biocompatibility and degradability features. When hydrogels are applied to treat the defects of the abdominal wall, the biocompatibility of these materials is very low, significantly reducing the risk of inflammatory reactions [97]. The hydrogel's mechanical strength, porosity and degradation rate can be altered by controlling the parameters such as the polymer concentration, cross-linking mechanism and degree of cross-linking so that it mimics the defect site. This way, they can offer appropriate mechanical support and slowly dissolve as the repair process progresses and new tissue forms [98]. In light of this approach, the hydrogel can play a dual role of providing support to the tissue at the most necessary time during the healing process and then gradually disintegrating to let the tissue naturally regenerate, thus improving the repair process. Synthetic and natural hydrogels have attracted much attention for repairing abdominal wall defects because of the characteristic functional properties that can be designed for reconstructive surgery. Some of these properties are biocompatibility, high mechanical strength, controllable rates of degradation, and the possibility of incorporating bioactive molecules [99-101].

The following discussion provides an overview of the fundamental functional properties of hydrogels that make them suitable for repairing abdominal wall defects.

*Biocompatibility*

Biocompatibility is a critical property of any material used in tissue repair, and hydrogels excel in this regard. This property allows them to be safely employed in various medical applications, such as abdominal wall repair. Hydrogels' biocompatibility can be further divided into blood compatibility and tissue compatibility. Due to their direct contact with blood, the assessment of blood compatibility is an important criterion for the successful application of hydrogels in abdominal wall repair [100-102].

*Mechanical strength*

The mechanical properties of hydrogels are also relevant when it comes to their application in the repair of the abdominal wall since the material is subjected to continuous mechanical stress. As noted before, the stomach wall withstands various mechanical forces. Thus, the implant used to repair the abdominal wall needs to offer support in preventing hernia relapse and allow the muscles of the stomach wall to move with ease. Depending on the concentration of the polymer, the mode of cross-linking and the extent of cross-linking, hydrogels can be designed to have mechanical properties of the target tissue. This tunability makes it possible for hydrogels to be used as scaffolds to support tissues during the initial stages of healing. In contrast, the steady degradation of the hydrogel scaffold enables replacement by the newly formed tissue, which in most cases takes the entire load [25,102,103].

*Tunable degradation rates*

The best and most desirable characteristic of hydrogels is that these gels can be made biodegradable and degrade in a controlled manner. It is thus possible to control the degradation rate of a hydrogel via the alteration of the chemical characteristics of the polymer matrix and the cross-linking density. Specifically, for the application of abdominal wall repair, the hydrogel must degrade in a way compatible with the tissue healing process. Hydrogel with rapid degradation may not provide adequate support in the initial healing period; on the other hand, hydrogel with a slow degradation rate may hinder tissue formation or cause complications such as inflammation or fibrosis. Since the degradation rate is adjustable, hydrogels can also stabilize the wall of the abdomen for a certain period before it makes room and remodels with healthy new tissue [104,105]. A study on real-time monitoring the material degradation and tissue remodelling utilized near-infrared fluorescent dye Cy5.5 NHS ester for labelling ECM composites (ECMB) performed from small intestinal submucosa (SIS) and CS/elastin electrostatically spun nanofibers. After implantation, the Cy5.5 ECMB composite material showed substantial fluorescence and had a degradation period of 16 weeks before the total breakdown occurred. The Cy5.5 ECMB composite implant thickness substantially grew at 4, 8, and 16 weeks after implantation, reaching a thickness similar to the standard abdominal wall at 16 weeks. Furthermore, the decrease in fluorescence was significantly and positively correlated with the thickness of the implanted Cy5.5 ECMB composite implant ($r = 0.9832$), suggesting a strong link between the degradation of the ECMB composite and tissue remodelling. Therefore, it not only achieved real-time monitoring of material degradation but also employed the thickness of the implant as an intuitive indicator for assessing the efficiency of tissue remodelling in ECMB composites, which provides new insights for evaluating and monitoring the tissue repair effectiveness of hydrogel [102].

*Porosity and permeability*

The most relevant aspect in the abdominal wall repair case is the hydrogel's porosity. Hydrogels are hydrophilic networks with interconnected pores that enable the permeation of nutrients and oxygen needed for cell growth and tissue repair. The size of the pores and their distribution in the hydrogel can be regulated during fabrication to enhance the ability of the cells to penetrate the structure and promote the formation of vessels, which is also essential for tissue integration. Furthermore, depending on the type and application of hydrogels, their permeability can also be altered and designed to release specific therapeutic agents, such as growth factors or antibiotics, to improve the injured part's healing process and prevent infection [98,106-108].

*Bioactive molecule delivery*

Hydrogels as suitable carriers for bioactive molecules can pave the way for enhanced tissue regeneration in abdominal wall repair. These bioactive molecules can be encapsulated into the hydrogel network and delivered at the site of tissue repair, and in this way, stimulate tissue regeneration. This property makes it suitable when used in abdominal wall repair because the area is sensitive to infections due to the presence of the gastrointestinal system. Incorporating various antimicrobial agents directly into hydrogels is possible to prevent postoperative infections. Furthermore, hydrogels can incorporate growth factors that encourage further tissue reconstruction or anti-inflammatory drugs that reduce inflammation, thus preventing inflammation-induced chronic diseases. Thus, notwithstanding the synthetic nature of certain hydrogels, they have an advantage over synthetic meshes in releasing these therapeutic agents in a localized and sustained manner [109,110].

*Tissue adhesion prevention*

Another functional characteristic of hydrogels is that they help avoid adhesion formation between the abdominal wall and other tissues. Surgical adhesions occur frequently after abdominal operations and are associated with chronic pain, bowel obstruction and other complications. Designing hydrogels with anti-adhesive properties can be achieved by adding molecular agents, which reduce the ability of tissues to adhere to one another. For instance, hyaluronic acid-based hydrogels have demonstrated a decrease in adhesion formation because of their inherent property of lubrication and their ability to form a barrier to the tissues [25,41,87,111].

**Hydrogels to repair the abdominal wall defect**

Hydrogel has been widely applied for repairing abdominal wall defects because it has six unique characteristics that have contributed to this area's development. Yin et al. synthesized carboxymethyl chitosan and 4-arm poly (ethylene glycol) aldehyde for bio-multifunctional composite hydrogels for full-thickness abdominal wall defect. The histomorphological analysis reveals that as compared to the clinically used compact polypropylene mesh, the developed hydrogel patches promote the augmentation of enhanced thickness and integrity of the abdominal wall tissue by stimulating Ki67 expression, promoting the synthesis of collagen, promoting neovascularization, and reducing inflammation by down-regulating the levels of IL-6, TNF- $\alpha$ and IL -1β. The outcomes indicated that a bio-multifunctional hydrogel patch is feasible to be used on full-thickness abdominal wall defect treatment [112]. Another study was done by Wang et al. [113], where they developed a new biomaterial which is small intestinal submucosa coated with gelatin hydrogel containing essential fibroblast growth factor. They assessed the new biomaterials for use in abdominal wall reconstruction. It has been concluded from the results that the small intestinal submucosa coated with gelatin hydrogel incorporating basic fibroblast growth factor would be more effective in the regeneration and remodelling of host tissue to reconstruct the abdominal wall defects. Hu et al. fabricated a dopamine-modified hyaluronic acid and gelatin hydrogel with an acylation process. They further improved the hydrogel's antibacterial properties by incorporating silver nanoparticles [114]. Moreover, drugs can be loaded in hydrogels using their swelling characteristic, one in which the hydrogels are soaked in the drug-containing fluids. Moreover, drugs can also be impregnated in hydrogels by using the swelling character of the hydrogels through the use of liquid containing the drug.

Liu et al. synthesized a double-layer structured nanofiber membrane (GO-PCL/CS-PCL) of polycaprolactone (PCL), chitosan (CS) and graphene oxide (GO) through the process of continuous electrospinning. For enhancing the bio-functions (angiogenesis/reduction of ROS) of the patch (GO-PCL/NAC-CS-PCL), N-acetylcysteine here loaded was used to repair full-thickness abdominal wall defects (2 × 1. 5cm) in rat model. The results showed that double-layered nanomembranes described in this paper have notable anti-hernia and anti-adhesion capacities, and the in vivo micro-environment was significantly enhanced. It is thus applicable for repairing abdominal wall defects and has good features as a post-operative anti-adhesion key [115]. Dong et al. used the biodegradable polymer poly(lactic acid) PLA and poly(*N-isopropyl acrylamide*)-bpoly(ethyleneglycol) (PNIPAAm-b-PEG) to develop thermoresponsive hydrogel scaffolds that employed electrospinning technique. The composite electrospun scaffolds were seeded with rat adipose-derived stem cells (ADSCs). Scanning electron microscopy (SEM) assay for PNIPAAm-b-PEG/PLA scaffolds showed that its surface was covered with more adsorbed, well-spread, and stretched ADSCs in polygonal form compared to PLA and polypropylene (PP) scaffolds. It also showed that PNIPAAm-b-PEG/PLA mimetic hydrogel scaffolds enhanced the surface for cell adhesion. These outcomes predict the ability to boost cell adherence and growth rates by employing hydrogels with proficient cell loading capacity [116].

Hydrogels have proved to be preferred by surgeons because they are easy to manipulate, can be injected, stick to the tissue surfaces and offer mechanical support. These hydrogels can be formulated to have controlled viscosity and cohesiveness so that surgeons can easily apply or mould them. These hydrogels can be designed in injectable systems so they may be accurately placed in the defects of the abdominal wall by using endoscopic approaches with syringes or catheters [117]. Deng et al. synthesized a hydrogel with in situ cross-linked CS-HA via Schiff base reaction, which can be injected in situ to fill the defect site in the abdominal wall [118]. Moreover, hydrogels can possess attributes like shear thinning or self-healing abilities, depending on the design. To be used as injectable or diffusible materials into the tissue, shear-thinning hydrogels demonstrate a decrease in viscosity under shear stress [119]. Once the shear force no longer exists, the hydrogels regain their original viscosity and offer stability and support to the repaired tissue after abdominal wall defect closure. Hydrogels' self-repairing ability depends on the change of time and the dynamic interactions within the functional groups within them. This means that the hydrogels can change their structure without any external stimulus, improving the handling of the gels following mechanical injury. For instance, applying hydrogel that exhibits self-healing capabilities in a sutured postoperative incision helps avoid patch failure or cracking [112].

Surgical meshes from synthetic and biological materials are standard for repairing abdominal wall defects. However, existing meshes still need to fully meet clinical requirements due to issues with biodegradability, mechanical strength, and tissue-adhesive properties. Nishiguchi et al. developed biodegradable, decellularized extracellular matrix (dECM) patches reinforced with a water-insoluble supramolecular gelator to address these issues. The physical cross-linking networks formed by the gelator improved the mechanical strength of the dECM patches, making them more effective in treating abdominal wall defects. These reinforced patches showed higher tissue adhesion strength and stability than the original dECM. The reinforced dECM patches promoted collagen deposition and blood vessel formation during material degradation in animal studies using a rat model with abdominal wall defects. Significantly, they also suppressed the accumulation of macrophages compared to nonbiodegradable synthetic meshes. These results indicate that the reinforced dECM patches have great potential for repairing abdominal wall defects due to their tissue-adhesive and biodegradable properties and improved mechanical strength enabled by the supramolecular gelator [120]. Implantable meshes are revolutionizing tension-free repair operations for internal soft-tissue defects. Liang et al. have pioneered a groundbreaking biocompatible Janus porous poly (vinyl alcohol) hydrogel (JPVA hydrogel) for optimal internal soft-tissue defect repair. This innovative JPVA hydrogel patch is designed to combat visceral adhesion, promote defect healing, and resist deformation, making it a promising solution for addressing internal soft-tissue defects. Research has demonstrated the JPVA hydrogel's remarkable success in facilitating abdominal wall repair and driving substantial defect regeneration in experimental models [121]. The tissue engineering process includes methods of 3D bioprinting [122], electrospinning [123], microfluidics [124], and self-assembly [125] for the development of hydrogels with highly organized structures that would replicate the environment of abdominal wall tissues. These methods enable cells and bioactive substances to be incorporated into hydrogels in specific locations, thus improving hydrogel's potential for reparative tissue regeneration and managing defects in the abdominal wall. Also, recent advances in this area mean the work has progressed further with hydrogel applications. Nevertheless, further investigation is still required to evaluate the biocompatibility, efficacy and tensile strength of hydrogel indicators for treating abdominal wall defects and regeneration.

## Conclusions

The treatment of abdominal wall defects remains a significant challenge in surgical medicine, with conventional repair techniques often falling short due to limitations such as poor tissue integration, risk of infection, and postoperative complications like adhesion formation. The introduction of hydrogel-based materials as a novel solution has sparked considerable interest in the field, offering a promising alternative that addresses many of these shortcomings. This discussion delves into the conclusions drawn from current research on hydrogel-based solutions for abdominal wall defects and explores the prospects of this innovative approach in clinical practice. Hydrogels have emerged as a versatile and practical material for repairing abdominal wall defects due to their unique properties, including biocompatibility, tunable mechanical strength, and the ability to promote tissue regeneration. Unlike traditional synthetic meshes, which can elicit foreign body reactions and fail to integrate seamlessly with host tissues, hydrogels can be designed to closely mimic the extracellular matrix (ECM) closely, facilitating better interaction with surrounding tissues. One of the critical advantages of hydrogels is their ability to be engineered with specific mechanical properties that can be tailored to match the dynamic environment of the abdominal wall. This adaptability is crucial, as the abdominal wall undergoes constant movement and pressure changes, necessitating a repair material that can flex and adapt without compromising structural integrity. Studies have shown that hydrogels can be formulated to provide the necessary mechanical support while remaining sufficiently flexible, thus reducing the risk of complications associated with rigid synthetic materials.

Moreover, hydrogels can be loaded with bioactive agents such as growth factors, cytokines, or antimicrobial peptides, which can further enhance tissue regeneration and reduce the risk of infection. This multifunctionality allows hydrogels to serve as a physical barrier and an active participant in the healing process, promoting faster and more effective recovery. For example, hydrogels incorporating vascular endothelial growth factor (VEGF) have significantly enhanced angiogenesis, which is vital for tissue repair and regeneration. In addition to promoting tissue integration and healing, hydrogels offer a more favourable biocompatibility profile than traditional materials. The risk of chronic inflammation, a common issue with synthetic meshes, is significantly reduced with hydrogels, as they are designed to degrade over time into non-toxic byproducts easily resorbed by the body. This controlled degradation aligns with the natural healing process, allowing the hydrogel to provide support during the critical early stages of healing and gradually transfer the load to the newly formed tissue as it matures. Clinical studies have provided encouraging results, demonstrating that hydrogel-based repairs can lead to fewer complications and better overall outcomes than traditional methods. Patients treated with hydrogel materials have shown reduced infection rates, lower incidence of adhesion formation, and improved functional outcomes, such as greater flexibility and reduced pain during recovery. These findings suggest that hydrogel-based solutions could become the new standard in the surgical repair of abdominal wall defects.

**Future Perspective**

While the current research on hydrogel-based solutions for abdominal wall defects is promising, several areas require further investigation before these materials can be widely adopted in clinical practice. One of the primary challenges is the need for long-term studies to assess the durability and safety of hydrogel implants over extended periods. Although short-term results are favourable, it is essential to understand how these materials perform over the years, particularly in terms of their mechanical stability, biodegradation rates, and potential for late-onset complications. Future research should also focus on optimizing the composition of hydrogels to match the specific requirements of different types of abdominal wall defects. For example, hydrogels' mechanical properties and degradation rates may need to be adjusted depending on whether they are used to repair a small hernia or a significant, complex defect.

Additionally, incorporating advanced bioactive agents within the hydrogel matrix could be further refined to enhance their therapeutic potential. The use of personalized medicine approaches, where hydrogels are tailored to the specific biological environment of each patient, represents a promising direction for future development. Another exciting prospect for hydrogel-based solutions is their potential application in minimally invasive surgery. As surgical techniques continue to evolve, there is a growing emphasis on reducing patient morbidity and recovery times through less invasive procedures. Hydrogels are well-suited for such applications due to their flexible and injectable nature.

Injectable hydrogels could be delivered via laparoscopic techniques, allowing for precise placement with minimal disruption to surrounding tissues. This approach could significantly reduce recovery times and improve patient comfort, making hydrogel-based repairs an attractive option in modern surgical practice.

Moreover, developing "smart" hydrogels that respond to environmental stimuli, such as pH, temperature, or the presence of specific enzymes, could revolutionize how abdominal wall defects are treated. These innovative materials could be designed to release therapeutic agents in response to specific triggers, providing targeted treatment only when needed. For example, a hydrogel could be engineered to release anti-inflammatory drugs in response to early signs of inflammation, preventing complications before they arise. Such innovations would not only improve the effectiveness of the treatment but also reduce the need for additional interventions, further enhancing patient outcomes. The commercialization and regulatory approval of hydrogel-based products for abdominal wall repair will also play a crucial role in their widespread adoption. Collaborations between researchers, clinicians, and industry partners will be essential to translate the promising findings from the laboratory into commercially viable products. Regulatory bodies must establish clear guidelines for approving hydrogel-based materials, ensuring they meet safety and efficacy standards. Successfully navigating these regulatory pathways will be critical in determining the future availability of hydrogel-based solutions in the clinical setting. While challenges remain to be addressed, particularly regarding long-term performance and regulatory approval, the prospects for hydrogel-based solutions are highly encouraging. As research continues to evolve and more clinical data becomes available, hydrogels will likely become an integral part of the surgical toolkit for repairing abdominal wall defects, leading to improved outcomes and better quality of life for patients.

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**Authors contribution**

All the authors have contributed equally.

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