Preparation of Conductive Polymer Based Composite Materials and Their Electrophysiological Response in Myocardial Tissue Repair

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Abstract: It is challenging to employ conventional insulating biomaterials to repair the irreversible damage to the myocardial electrical conduction network induced by myocardial infarction, which may quickly result in arrhythmia and cardiac failure. Because of their conductivity and biocompatibility, composite materials based on conductive polymers have drawn attention from researchers studying cardiac healing. This article examines the common preparation techniques (solution blending, in-situ polymerization, and electrospinning) and examines how different techniques affect the materials' electrophysiological characteristics by controlling their microstructure (conductive particle dispersion, matrix-conductive phase interface bonding, fiber arrangement). This kind of material can achieve directional electrical conduction, low interface impedance coupling, or stable electrical signal transmission, encourage the synchronization of myocardial cell electrical activity, and aid in the repair of damaged myocardial electrical networks. This paper investigates and separates the relationship between preparation techniques and electrophysiological response, offering theoretical justification for the creation of bioelectric materials for cardiac repair and supporting the clinical management of myocardial damage.

1. Introduction

1.1. Research Background

The electrical conduction network of heart tissue is permanently damaged after ischemia or infarction. Biomaterials that are not insulated can't repair electrical connection, which leads to arrhythmia and a reduction in systolic performance. Conductive polymers contain characteristics of both metals and polymers, which implies they may be blended with elastic matrices and treated to form scaffold electrode integrated patches. They can control how action potentials go across cardiac cells in vitro, synchronize calcium transients, and connect scar tissue and surviving myocardium in vivo, bringing back the channels for electrical signals. Recent research has demonstrated that the conductivity, topology, and surface charge of this composite material can profoundly influence the maturation, pulsation frequency, and conduction velocity of myocardial cells via mechanisms including membrane potential, ion channels, and gap junction protein 43. This lays the groundwork for the next generation of cardiac repair materials with bioelectric function, both in theory and in practice.

1.2. Research Significance

Cardiovascular disorders, including myocardial infarction, may result in irreversible necrosis of myocardial cells, and the intrinsic reparative capacity of myocardial tissue is markedly deficient. After damage, the electrical conduction network is broken and the electrical coupling function is lost. This can lead to serious problems like arrhythmia and a decline in heart function, which can eventually lead to cardiac exhaustion. This makes it very difficult for the patient to live, stay healthy, and get treatment. Conventional cardiac repair biomaterials, owing to their non-conductive nature, might only provide mechanical support and fail to restore the electrophysiological channels of injured myocardium, hence hindering substantial enhancement of myocardial function.

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Conductive polymer-based composite materials integrate metallic conductivity with polymer biocompatibility, and may be amalgamated with elastic matrices to provide repair materials appropriate for cardiac tissue. They can control the conduction of action potentials in myocardial cells in vitro, synchronize calcium transients, encourage cell maturation and functional maintenance, and connect scar areas and surviving myocardium in vivo, restoring pathways for electrical signal transmission and fixing the core insulation problems of traditional materials. Researching this type of material can not only help with the lack of knowledge in the area of myocardial electrophysiological functional repair using biomaterials, but it can also help with the creation of the next generation of myocardial repair materials that have bioelectrical functions. It may also provide new technical ideas for treating myocardial damage in the clinic and make patients' prognosis better. It has great medicinal and societal value.

2. Basic Understanding of conductive Polymer Based Composite Materials

2.1. Core Types of Conductive Polymers

There are core types of conductive polymers, namely, Polypyrrole (PPy), Polythiophene (PTh) and its derivatives and Polyaniline (PANI), as shown in Figure 1.

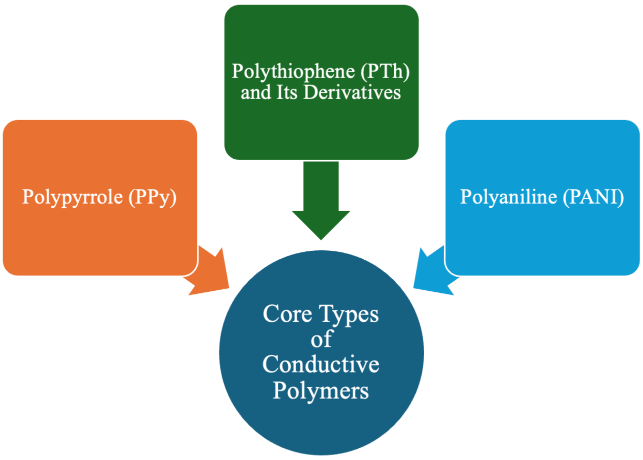

Figure 1: Core types of conductive polymers.

2.1.1. Polypyrrole (PPy)

In the field of myocardial repair, polypyrrole is one of the most commonly used conductive polymers. It has a molecular structure made up of alternating conjugated double bonds, which makes it stable at room temperature (conductivity can usually reach 10^{-2}-10^{2}S/cm). This meets the basic requirements for transmitting electrical signals in myocardial tissue. When it comes to biocompatibility, pure polypyrrole is not very toxic to cardiomyocytes. It can also change its conductivity and surface hydrophilicity by adding small molecules like chloride ions and sulfonic acid groups, making it suitable for different repair situations. Polypyrrole, on the other hand, has brittle mechanical properties and breaks easily when used on its own [1]. So, it is often used with elastic matrices like gelatin and polycaprolactone to repair the heart muscle. This keeps the material conductive and makes it more flexible, which is what the heart muscle needs to contract and relax.

2.1.2. Polythiophene (PTh) and Its Derivatives

The primary chain of polythiophene consists of a thiophene ring conjugated structure; nevertheless, its conductivity in a pure form is low (about 10^{-8}-10^{-4}S/cm), and its solubility is inadequate, which restricts its direct applicability. At this time, poly (3,4-ethylenedioxythiophene) (PEDOT), a derivative of it, is more often utilized to fix heart muscle. This derivative not only greatly boosts conductivity (up to 10^{0}-10^{2}S/cm) because it has ethylenedioxythiophene groups on the thiophene ring, but it also lowers oxidation potential and lowers the danger of degradation in the biological environment. The best thing about PEDOT is that it is very biocompatible, which may help cardiac cells stick to it and grow. It can also be mixed with polymers like poly (styrene sulfonate) (PSS) to make it more soluble and help it form films. This makes it easier to make thin films or fibrous repair materials that mimic the structure of the extracellular matrix in myocardial cells and help with rebuilding electrophysiological function [2].

2.1.3. Polyaniline (PANI)

Polyaniline is an early studied conductive polymer that is cheap to make and has a wide range of adjustable conductivity (by changing the doping state, the conductivity can be increased from 10^{-10}S/cm to 10^{2}S/cm). There are many variations of its molecular structure, such as the emerald base state and the emerald salt state. The emerald salt state is the conductive state and may be made by adding acid. For cardiac healing, polyaniline is useful since it is easy to get the basic ingredients and make (for example, via chemical oxidation polymerization). However, unaltered polyaniline does not dissolve well in water and is harmful to certain cells. To improve biocompatibility and dispersibility, it is necessary to add biocompatible groups (like polyethylene glycol) or natural polymers (like chitosan) to the surface. Polyaniline's conductivity changes with pH, thus in simulated bodily fluid conditions, it's important to keep the conductivity steady by doping it with something like phosphate ions to make sure that electrical signals can be sent.

2.2. Basic Composition of Conductive Polymer Based Composite Materials

The matrix material and the conductive filler are the two main parts of conductive polymer-based composite materials, as shown in Figure 2. Together, they meet the needs of repairing the heart. Most of the matrix materials are biocompatible polymers, which may be either synthetic or natural. Synthetic polymers such as polycaprolactone (PCL), polylactic acid hydroxyacetic acid copolymer (PLGA), and others exhibit robust mechanical stability, a controllable degradation rate, the capacity for long-term structural support, and the potential to enhance the processability of conductive polymers (including film formation and spinning) . In contrast, natural polymers like collagen, gelatin, chitosan, and others possess unique cell adh [3]esion sites and can replicate the extracellular matrix microenvironment of myocardial cells, thereby promoting cell adhesion and proliferation. Conductive polymers (polypyrrole, PEDOT, polyaniline, etc.) make up the majority of conductive fillers, to which auxiliary fillers like graphene and carbon nanotubes are added. The former is essential for electrical signal transmission, while the latter can improve composite materials' conductivity by creating a three-dimensional conductive network, increasing mechanical strength, and preventing the mechanical brittleness of single conductive polymers. To guarantee stable material qualities, the two ingredients must be combined uniformly to prevent filler agglomeration.

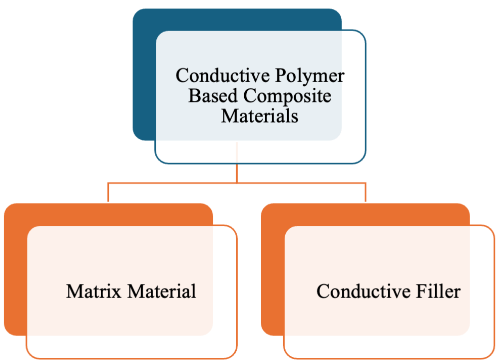

Figure 2: Basic composition of conductive polymer based composite materials.

2.3. Key Performance Requirements for Composite Materials

To be useful for repairing cardiac tissue, conductive polymer-based composite materials need to achieve three main performance criteria, as demonstrated in Figure 3. One is the adapted conductivity:

the conductivity needs to be close to natural myocardial tissue (about 0.1-1S/cm), too low cannot effectively transmit electrical signals, and too high may cause excessive local electrical stimulation; And in the simulated body fluid environment, it is necessary to maintain stable conductivity to avoid interruption of electrical signal transmission due to degradation or ion loss. The second is great biocompatibility: the material needs to be safe, not cause immune rejection reactions in the body, and have good cell adhesion. It does this by controlling how hydrophilic the surface is or adding bioactive sites (like RGD peptides) to help myocardial cells attach, grow, and mature, creating a friendly microenvironment for tissue repair. The third is that the mechanical properties should match: the elastic modulus should be close to that of the myocardial tissue (about 10-100kPa), and the tensile strength should be able to handle the repeated mechanical effects of the heart's contraction and relaxation without causing the material to come loose or damage the surrounding healthy myocardium because of differences in mechanical properties. The material should also be flexible enough to meet the heart's changing activity needs.

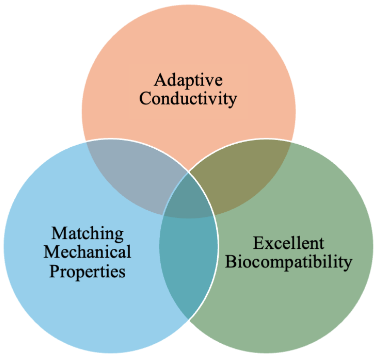

Figure 3: Key performance requirements for composite materials.

3. Preparation Method of Conductive Polymer Based Composite Materials

There are preparation method of conductive polymer based composite materials, namely solution blending, in-situ polymerization method, and electrospinning, as seen in Figure 4.

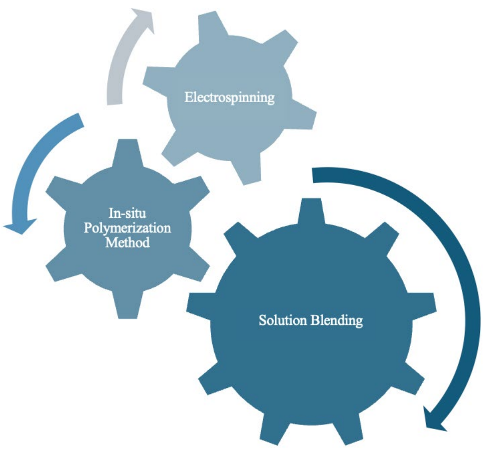

Figure 4: Preparation method of conductive polymer based composite materials.

3.1. Solution Blending

The most common way to make composite materials out of conductive polymers is to mix the solution. It uses solvents to mix the conducting parts and the matrix materials evenly. It is essential to ensure that all required solvents are readily available prior to commencing any work-related tasks. Some examples of solvents are water, N, and N-dimethylformamide. The matrix materials, such as gelatin or PCL, and the conductive polymers or their precursors, such as polypyrrole powder or PEDOT solution, should be mixed together in separate containers [4]. In order to ensure that the conductive particles are distributed uniformly, the two solutions should be mixed together in the appropriate proportions, and either magnetic stirring or ultrasonic treatment should be used. In this way, they will not be able to adhere to one another. Casting, spin coating, or tape casting are the methods that are used to apply the solution to the mold or substrate once it has been well mixed. These composite materials may be made into thin films or blocks as a result of this process. Next, the solvent is eliminated by allowing it to dry at room temperature or in a vacuum after it has been removed.

This approach is awesome since it is simple to implement and does not need a large number of instruments; rather, it just requires fundamental equipment such as mixers and drying ovens. It's easy to make a lot of it, and you can change the amount of conductive polymer added to change how conductive the material is. But there are two things to keep in mind. In order to prevent phase separation, the solvent must first be compatible with both the substrate and the conductive component. Secondly, the amount of solvent that remains must be carefully regulated to prevent myocardial cell toxicity and to influence subsequent biocompatibility.

3.2. In-situ Polymerization Method

Increased interfacial compatibility of composite materials may be achieved by the use of an essential technology known as in situ polymerization. Inducing the polymerization of conductive polymer monomers inside the matrix material is the main component of this approach. The creation of a robust connection between the matrix and the conductive phase is the consequence of this circumstance. The following is a list of the specific actions that need to be taken: First, in order to generate a matrix system that is consistent throughout, the matrix ingredients, which include chitosan solution and collagen gel, should be dissolved or dispersed in the suitable medium. The next step is to include conductive polymer monomer, which includes pyrrole monomer and aniline monomer, as well as oxidant, which includes ferric chloride and ammonium persulfate, into the system. Last but not least, the pH of the system should be adjusted as required (for instance, polyaniline polymerization necessitates an acidic environment, whereas polypyrrole polymerization can be carried out in a neutral environment), and the temperature (which typically ranges from room temperature to fifty degrees Celsius) should be adjusted as required. In the ensuing stage, the monomers are subjected to a number of oxidative polymerization reactions that take place inside the matrix [5]. As a consequence of these interactions, conductive polymer chains are produced. These chains then interweave and entangle with the molecules of the matrix, which ultimately leads to the production of an integrated composite material.

This technique has the potential to significantly reduce the resistance of the interface and to promote the long-term stability of conductivity. This is due to the fact that the conductive polymer is intimately linked to the matrix interface without any obvious phase separation. This is the most important advantage for using this strategy. This is a very critical aspect in the continuing transmission of electrical impulses throughout the process of heart tissue mending, which is taking place. Having said that, it is essential to have exact control over the response circumstances. An excessive use of oxidants may result in an excessive polymerization of monomers, which can cause the material to become brittle. If the reaction temperature is too high, it may cause deterioration of the matrix material, which can have an effect on the material's mechanical qualities as well as its biocompatibility [6].

3.3. Electrospinning

Electrospinning is the most often used technique for the production of biomimetic conductive composite materials. These materials have the potential to duplicate the nanofiber structure of the extracellular matrix of the heart and satisfy the requirements of cell development. It is necessary to prepare a spinning solution before beginning the operation. In order to do this, conductive polymers, such as PEDOT/PSS composites, must be combined with matrix materials, such as PLGA and gelatin, in the appropriate proportions. In addition, you will need to include solvents such as chloroform and dimethylformamide mixed solvents in order to perfectly get the desired viscosity. For the purpose of maintaining the jet's stability, it is customary to maintain the viscosity in a range of 5 to 20 Pa·s. The second step, which involves loading the solution into a syringe using a metal needle, involves setting a high-voltage electric field (often between 10 and 30 kV), a distance between the needle and the collecting plate (between 10 and 20 centimeters), and a solution flow rate (between 0.1 and 1 milliliter per hour). The force of the electric field presses the solution out of the needle, resulting in the formation of a very tiny jet. In addition, the solvent experiences rapid evaporation while the flight is taking place. Because of this, the solvent accumulates on the collecting plate, which results in the formation of a nano- or micro-scale fiber film composed of composite fiber material that is based on conductive polymer [7].

A great deal of porosity, a large specific surface area, and the ability to vary the orientation of the fibers are all characteristics that are conferred onto the fiber membrane by this procedure. This technique has the potential to do all of these incredible things. By imitating the organized structure of real heart tissue, the oriented fibers have the potential to stimulate myocardial cell growth in the direction of the fibers. Also, the conductive fiber network can send electrical impulses in a certain direction without any breaks. It is also very important to pay special attention to how well the spinning parameters match. If the viscosity of a solution is too low, it may readily break fibers. If the viscosity is too high, it can create structures that seem like beads. If the voltage or flow rate is wrong, it may affect the uniformity of the fiber diameter. This can then influence the material's conductivity and how well cells stick to it.

4. Electrophysiological Response of Conductive Polymer Based Composite Materials in Myocardial Tissue Repair

4.1. Electrophysiological Response of Composite Materials Prepared by Solution Blending Method

By spreading conductive polymer particles throughout the matrix, the solution blending approach creates conductive pathways. The electrophysiological response of this method is dependent on the homogeneity of the dispersion of conductive particles. The material is able to form a continuous electrical signal transmission network when the conductive particles are well dispersed. This network is capable of uniformly conducting external electrical stimulation or myocardial self-electrical signals, with the ability to avoid local signal attenuation and provide a stable electrical microenvironment for myocardial cells.

This sustained electrical signal transmission has the potential to increase the expression of gap junction proteins in cardiac cells, improve the capacity of intercellular electrical connection, decrease the heterogeneity of individual cell electrical activity, and therefore lower the risk of arrhythmia. Because of the uneven distribution of the conductive particles, the material will have local conductive blind spots, which will lead to the discontinuous transmission of electrical signals [8]. This will not only prevent the myocardial electrophysiological function from being improved, but it may also disrupt the normal pulsation of the cells due to signal disorder. When taken as a whole, the electrophysiological response stability of the materials that were made using this process is directly connected to the dispersion of conductive particles.

4.2. Electrophysiological Response of Composite Materials Prepared by In-situ Polymerization Method

A high level of electrical conductivity stability and a low interface impedance are both characteristics of the in-situ polymerization process. This is because of the strong bonding that occurs between the matrix interface and the conductive polymer. In the environment that simulates myocardial fluid, conductive polymers are not easily detached from the matrix. Furthermore, the electrical conductivity of the material can be maintained for an extended period of time in a range that is comparable to that of natural myocardial tissue. This makes it possible for the material to perform continuous transmission of electrical impulses and to provide assistance for the process of cardiac tissue healing over an extended period of time [9].

The tight interface bonding allows the material to better create an electrical connection with heart tissue. This also decreases the loss of electrical impulses at the interface and significantly lowers the impedance of the interface between the conductive phase and the substrate. In addition, the material is able to better build an electrical connection with cardiac tissue. It is possible for cardiac tissue to generate electrical activity, which enables the material to be able to react quickly and synchronously, effectively transmit electrical impulses to the scar region, assist in activating dormant myocardial cells that are surrounding the scar, and increase the function of local myocardial contractions. Because this material is more sensitive to external electrical stimulation, the application of low-intensity electrical stimulation has the ability to regulate the conduction speed of action potentials in myocardial cells, promote the synchronization of cellular electrical activity, and better meet the electrophysiological requirements of myocardial repair. This is because this material is more sensitive to the stimulation of electrical currents from the outside.

4.3. Electrophysiological Response of Composite Materials Prepared by Electrospinning Method

The fiber membrane that is created using electrospinning has a nanofiber structure that is biomimetic, and its electrophysiological response is centered on the directed conduction of electrical signals and the guiding of cell arrangement. Through the use of directional arrangement of fibers, myocardial cells may be directed to grow in the direction of the fibers, resulting in the formation of an ordered cell layer. In order to prevent disorderly signal diffusion and significantly improve the synchronicity of myocardial cell electrical activity, the conductive fiber network has the ability to construct directional conductive pathways along the cell arrangement direction. This makes it possible for electrical signals to be transmitted along the natural conduction direction of myocardial tissue.

The fibrous membrane has a large specific surface area, which enhances the contact area between cells and materials. This makes it easier for cells to adhere to one another and transmit electrical signals, which further improves the electrical coupling that exists between cells [10]. This material has the ability to accurately manage the calcium transient synchrony of cardiac cells via directed conductive pathways when it is subjected to the action of electrical stimulation. This, in turn, promotes the development of cell contraction function. Through the experiment, it is possible to see that myocardial cells that have been inoculated on this material have a pulsation frequency that is more stable, a contraction amplitude that is bigger, and they are less likely to have local pulsation disorder. Its electrophysiological response is more similar to the electrical signal transmission mechanism of normal cardiac tissue, and the auxiliary influence that it has on the functional rebuilding of myocardial tissue is more important.

5. Conclusion and Outlook

5.1. Research Summary

The purpose of this research is to investigate the fabrication of composite materials based on conductive polymers and the electrophysiological response of these materials in the context of cardiac tissue restoration. A summary of the essential information may be broken down into three parts. The features of three common preparation techniques are elucidated by one of them, which are as follows: solution blending method is simple to operate and easy to scale, but its electrophysiological response depends on the uniform dispersion of conductive particles; The in-situ polymerization method significantly improves the stability of material conductivity and interface electrical coupling ability by tightly bonding the matrix and conductive phase; Electrospinning can construct biomimetic fiber structures, achieve directional transmission of electrical signals, and better conform to the electrophysiological patterns of natural myocardial tissue.

The second substantiates the fundamental significance of this particular composite material, which is able to overcome the constraints that are associated with conventional insulating natural materials. Providing a material basis for the reconstruction of myocardial tissue electrical networks can be accomplished by regulating the electrical conductivity of the material through a variety of preparation methods. This allows for stable electrical signal transmission, low interface impedance coupling, directional electrophysiological regulation, and other functions to be accomplished.

Thirdly, it clarifies the correlation logic between preparation methods and electrophysiological response: the preparation process directly determines the electrical signal transmission efficiency and cell electrical activity regulation effect by affecting the microstructure of the material (such as dispersibility, interface bonding, fiber arrangement), providing a clear direction for subsequent material design.

5.2. Future Prospects

Research in the future may be advanced from three different perspectives. To begin, in order to optimize performance, it is necessary to further enhance the long-term in vivo applicability of the material. This can be accomplished by addressing the issue of conductivity degradation during in vivo degradation by means of surface modification or novel doping techniques. Additionally, it is necessary to introduce cardiomyocyte specific adhesion sites (such as RGD peptides) in order to improve biocompatibility and the ability to differentiate cells in a cell-directed manner.

When it comes to functional expansion, the synergistic mode of electrophysiological regulation and active repair can be investigated. For example, the combination of composite materials with drug delivery systems can be used to release repair factors like vascular endothelial growth factor while simultaneously transmitting electrical signals, which in turn promotes myocardial vascular regeneration. Alternatively, intelligent responsive materials can be developed that are able to adjust their electrical conductivity characteristics based on the electrical activity status of myocardial tissue, thereby avoiding excessive stimulation.

Finally, in clinical translation, it is necessary to break through the bottleneck of large-scale preparation technology, optimize the production process of fiber membranes, patches and other dosage forms, and carry out longer-term animal in vivo experiments to verify the safety (such as immune rejection, long-term degradation product toxicity) and repair effect of materials, laying the foundation for their ultimate application in clinical myocardial injury treatment and promoting the transition of such materials from laboratory to practical medical scenarios.

References

[1] Shokrollahi, P., Omidi, Y., Cubeddu, L. X., & Omidian, H. (2023). Conductive polymers for cardiac tissue engineering and regeneration. Journal of Biomedical Materials Research Part B: Applied Biomaterials, 111(11), 1979-1995.

[2] Meyers, K., Lee, B. P., & Rajachar, R. M. (2021). Electroactive polymeric composites to mimic the electromechanical properties of myocardium in cardiac tissue repair. Gels, 7(2), 53.

[3] Ul Haq, A., Carotenuto, F., De Matteis, F., Prosposito, P., Francini, R., Teodori, L., ... & Di Nardo, P. (2021). Intrinsically conductive polymers for striated cardiac muscle repair. International Journal of Molecular Sciences, 22(16), 8550.

[4] Jalilinejad, N., Rabiee, M., Baheiraei, N., Ghahremanzadeh, R., Salarian, R., Rabiee, N., ... & Zare, E. N. (2023). Electrically conductive carbon-based (bio)-nanomaterials for cardiac tissue engineering. Bioengineering & Translational Medicine, 8(1), e10347.

[5] Alamdari, S. G., Alibakhshi, A., de la Guardia, M., Baradaran, B., Mohammadzadeh, R., Amini, M., ... & Sahebkar, A. (2022). Conductive and semiconductive nanocomposite-based hydrogels for cardiac tissue engineering. Advanced Healthcare Materials, 11(18), 2200526.

[6] Khidr, W. A., Al-Hussainy, A. F., Sanghvi, G., Ballal, S., Singh, A., Sabarivani, A., ... & Mushtaq, H. (2025). Polymeric bio-scaffolds in combination with conductive materials for cardiac tissue engineering. Polymer Bulletin, 1-32.

[7] Mousa, H. M., Ali, M. G., Rezk, A. I., Nasr, E. A., & Hussein, K. H. (2022). Development of conductive polymeric nanofiber patches for cardiac tissue engineering application. Journal of Applied Polymer Science, 139(32), e52757.

[8] Li, J., Fang, W., Hao, T., Dong, D., Yang, B., Yao, F., & Wang, C. (2020). An anti-oxidative and conductive composite scaffold for cardiac tissue engineering. Composites Part B: Engineering, 199, 108285.

[9] Ghovvati, M., Kharaziha, M., Ardehali, R., & Annabi, N. (2022). Recent advances in designing electroconductive biomaterials for cardiac tissue engineering. Advanced healthcare materials, 11(13), 2200055.

[10] Li, S., Yin, W., Liu, Y., Yang, C., Zhai, Z., Xie, M., ... & Song, X. (2025). Anisotropic conductive scaffolds for post-infarction cardiac repair. Biomaterials Science, 13(3), 542-567.