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Article

Application of infrared and near-infrared photosensitive pi-conjugated materials in the diagnosis and rehabilitation of sports injuries in aerobics

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Abstract: According to a survey in 2021, around 12% of people were injured during the exercise, and they require the immediate healing process. Several tissue healing materials are incorporated into the sports rehabilitation process. However, the materials have a high rejection reaction rate, poor effect, and low healing speed, which affects aerobics rehabilitation training. The research difficulties are overcome by applying infrared and near-infrared photosensitive pi-conjugated materials to tissue healing procedures to maximize the result of sports rehabilitation. The research analysis discusses the conjugated materials composition and biocompatibility properties which helps to manage the skin healing drug release rate and durations. In addition, the pi-conjugated materials having a high Nearer-Infrared (NIR) observation rate between 600 nm to 1000nm then the materials are suitable for the photobiomodulation therapy wavelength. Then, NIR triggers the drug release from conjugated materials that are used to locate the injured area for treatment and rehabilitation process. Therefore, infrared and NIR-based conjugated materials effectively support injury rehabilitation and damaged tissue regeneration processes. The system efficiency is evaluated using various skin healing rates with different experiments and experimental groups.

Keywords: sports injuries; conjugated materials; infrared; nearer infrared; photo biomodulation therapy; rehabilitation; tissue regeneration

1. Introduction

Nowadays, most people follow aerobic exercises to strengthen their heart muscles, blood circulation, healthy blood flow, and lung function [1,2]. During the exercise, cells endure cellular respiration in which molecules and oxygens are transformed into Adenoise Triphosphate (ATP) [3], which is the main resource for the cells. Aerobic exercise helps to improve body functioning, heart function, lung function, oxygen supply and minimizes hypertension, inflammation, diabetes, stroke, high cholesterol, blood sugar, and heart disease [4]. Aerobics requires the continuous movement of muscle groups according to the rhythmic activities. The combination of hybrid activities creates severe and low impacts on human health. Exercise is directly linked with several sports injuries, which are categorized into two types such as traumatic injuries and overuse injuries [5]. Traumatic injuries [6] occur due to falls and twists, and the most common injuries are occurred in the knee or ankle. The overuse injuries develop gradually, which creates changes in the aerobics because of training errors. The shin pain, knee, and foot are the common pain overuse injuries. Therefore, participants should avoid injuries by proper preparations, utilizing good techniques, wearing the right gear, environment checking and understanding the sports. However, the participants faced several injuries like a sprained ankle, shoulder injury, shin splint, knee injuries, wrist sprain, tendinitis, muscle pull, and strain [7]. If the participant is affected by injuries, they must follow the Rest Ice Compression and Elevate (RICE) [8] method to minimize injury impacts. Initially, rest the injury, then apply the ice on the injury to minimize the bleeding, inflammation, and swelling. Afterward apply the compression bandage to reduce the swelling. Finally, elevate the injury to minimize the swelling. However, most aerobic injuries [9,10] require a healing time of up to 4 weeks, and in some situations, injuries require detailed medical assistance to improve their health.

The rehabilitation [11] process begins after the injuries, which includes pharmaceutical medications with therapeutic activities. The rehabilitation process restores the anatomy and physiological functions, which help to improve fitness, functional capacity, and performance. The participants' main intention is to return to the activities by following the rehabilitation strategy [12]. Participants expect their functional capacity must be similar to before injuries, which is strongly associated with the rehabilitation strategies. Therefore, rehabilitation strategies must developed by understanding the sports injuries that help to minimize the injury's severity and incidence [13]. The framed rehabilitation strategies are used to avoid reinjuries, reduce time away from aerobics, and enhance the entire recovery. The injury risk factor and level of injuries are frequently assessed to improve the treatment and rehabilitation process. The injuries are highly treated with the help of the pi-conjugated materials. The conjugated materials are referred to as double-bond compounds, which consist of molecular backbone and form with overlapping p-orbitals. The extended conjugation [14] is the electron delocalization with pi orbits. The pi-conjugated materials have several characteristics, such as electron delocalized, planned structure, unique electronic properties, semiconducting properties, and organic semi-conductors. The specific optical and electronic properties of the pi-conjugated materials lead to their importance in various applications like sensing devices, photonics, biological systems, electronics, and different scientific applications.

In photobiomodulation therapy (PBMT) [15], the pi-conjugated materials are designed to assimilate the near-infrared (NIR) light wavelength. The conjugated material absorption properties are more applicable to the cellular process, promote tissue restoration and minimize inflammation. Therefore, the pi-conjugated materials are utilized for fast recovery by diminishing oxidative stress, inflammation modulation, and improving mitochondrial function.

The rehabilitation process uses wearable devices to monitor the patient's activities during the aerobic exercises. The conjugated materials [16] are merged with wearable devices that give lightweight sensors and flexible sensors, which help to monitor the physiological parameters of participants in injury recovery. The pi-conjugated material-embedded sensor devices optimize the participant's movement while rehabilitating. In addition, the material incorporated in the drug delivery systems responds to particular stimuli like temperature and light. This process is highly linked with the therapeutic agents and helps in the rehabilitation process. The scaffold with pi-conjugated materials improves the overall healing procedure in aerobic injuries because it is widely applied in damaged tissue regeneration. The NIR-activated heating elements in pi-conjugated materials are highly employed in thermotherapy, alleviating muscle stiffness and enhancing blood circulation in the aerobic injury rehabilitation process. Finally, the pi-conjugated material merged devices are utilized to monitor the patient activities that helps to maximize the recovery speed in aerobic activities. Several materials are incorporated into the recovery process, but they have a poor impact on serious injuries, low healing speed and high rejection reaction rate. These difficulties affect the rehabilitation procedure and minimize the recovery rate. The advantage of pi-conjugated materials is considered in this study to maximize tissue healing and rehabilitation. This study explores the pi-conjugated material functions and processes to observe the damaged tissue regeneration process in photobiomodulation therapy. During the analysis, Near-Infrared (NIR) and infrared photosensitive pi-conjugated materials are examined to improve the recovery and skin healing rate in various periods.

2. Related works

This study examines the various researcher's opinions and contributions about the conjugated materials in the rehabilitation process. The research work, contribution, and limitations are described in **Table 1**.

Table 1. Literature analysis of conjugated material in injury analysis.

Author	Objective	Contribution	Materials	Limitations
Yu et al. [17]	Increasing the wound healing and skin regeneration rate.	Applying wound dressing, electrotherapy, and wound assessment to achieve a high wound healing rate.	Conductive biomaterial (conductive polymers and nanoparticles).	Require detailed description of wound phases.
Talikowska et al. [18]	Using conductive polymers to faster the wound healing speed.	Combining conductive polymers with biomolecules to maximize the biocompatibility and physical properties.	Polythiophene, polypyrrole, polyaniline, and ethylenedioxythiophene conductive polymers.	Consume more time to heal the wounds.
He et al. [19]	To eliminate the difficulties in the tissue regeneration process.	Utilizing the nanocomposites with multimodal material combinations to identify the difficult process in wound healing.	Photothermal antibacterial materials.	Difficult to manage the safety factor while handling the photothermal material.
Zong et al. [20]	To monitor and identify the diabetic related wounds.	Near-infrared (NIR) fluorescent probe imaging systems.	Hydrogel, vascular endothelial growth factor.	High computation time for real-time monitoring the diabetic wounds.
Li et al. [21]	To develop and exploration of therapeutic agents to reduce the toxic side effects and drug resistance.	Therapeutic strategies are created using conjugated polymers.	Conjugated polymers.	Metabolism and absorption range of light range in the human body are degradable.
Jia et al. [22]	To address the challenges involved in wound dressing in antibacterial hydrogel fabrications.	Antibacterial method, antibacterial component, and crosslinking method.	Antibacterial hydrogels.	Clinical efficiency is still one of the major challenges.

According to the various discussions, conjugated and conductive materials are highly involved in the skin tissue healing, repair, and regeneration process. However, the traditional methods consume high computation time and minimum healing rate. Therefore, this study uses photosensitive pi-conjugated materials to improve the tissue healing process in aerobic exercise related injuries.

3. Analyzing Tissue Healing and training for exercise rehabilitation

Tissue healing is one of the important phases in aerobic exercise injuries, which includes inflammation, vascular reconstruction, congulations, repair stages, and cell proliferation. During normal healing, every stage performs perfectly, and tissue recovery is done effectively. However, if any problem presents in the healing process, the tissue healing process is more complicated. The first stage is inflammation, which is initiated after then few days of tissue injury. In this stage, blood vessels dilate, causing the blood and then cytokines to be transmitted to the injured area. The inflammation process is used to minimize the waste and pathogens; however, the high inflammation leads to creating a negative impression on healing. The second stage is blood coagulation-vascular reconstruction, in which blood clots are formed on the wound, and blood vessels are grown to improve the flow of oxygen and nutrients. Afterward, new cells are proliferative and travel to the infected area to complete the cell proliferation and repair stage. During this process, fibroblasts create collagen to make the structural support. The generated cell splits and restores the epidermal layer integrity effectively. Then college is rearranged to manage the tissue durability and flexibility and reshape the structure. The tissue healing stages are affected by several factors, such as poor blood supply, infection, severity, lack of nutrition, abnormal scar creation, and ischemia. Once these factors influence the treatment process, the entire healing process is affected, which leads to maximizing the recovery time. For example, if the healing process is disturbed in inflammatory stages, then the intensity and healing process are completely affected. Therefore, for aerobic injuries related to rehabilitation, trainers and care takers should give maximum attention to maximize the tissue healing efficiency. The rehabilitation training should concentrate on physical therapy, nutritional support, dressing replacement, wound monitoring, infection, and scar analysis.

4. Photosensitive pi-conjugated materials in sports injury rehabilitation process

The photosensitive pi-conjugated materials are developed using the dispersion polymerization of either pre-synthesized conjugated polymers. The pre-synthesized materials are developed in terms of self-assembly, reprecipitation, and miniemulsion. The miniemulsion process requires the biphasic immiscible solvent that has water and chloroform. The developed polymers are melted in the solvent, which is named miniemulsified. During stirring, nanoparticles are generated by collapsing the hydrophobic polymers into micelles. Then, the surfactants are removed from the solution to stabilize the nanoparticles. In this process, conjugated polymer concentrations are affected due to the nanoparticle size because it varies from 20 nm to multiple hunderds of nm. If the nanoparticle minimum than 20 nm size is named single the polymer chain is represented as semiconducting polymer dots. The described polymer dots are generated with the help of nanoprecipitation or reprecipitation. Then, the nanoparticles are created by using a good solvent for dissolving the conjugated materials in the water. The single polymer chain does not require stabilizing agents because the particles are less than 5 nm. The developed particles are coated using an extra polymer layer which helps to decorate the material surface and stabilize the particle properties.

Consider the nonstructured particles like vesicles, micelles, nanoparticles, and hollow capsules developed with the help of amphiphilic pi-conjugated polymers via water-based self-assembly. This polymer has hydrophilic pendants and hydrophobic conjugated materials, which also self-assemble in water. Few conjugated polyelectrolytes contain ionic groups, which are complex with negative charging conjugated polyelectrolytes. The complex nanoparticle materials are named coacervates. In most cases, nanoparticles are developed from monomers, which are polymerized and collapsed with nanoparticles. During the dispersion process, polymerization is approved in the solvent of monomers but has poor performance in conjugated polymers; therefore, conjugate polymers fail in the nanoparticles. Therefore, this kind of nanoparticle requires an additional stable process by including the surfactant. Functional groups of conjugated polymers help to generate the nanostructure preparation. In addition, the hybrid nanoparticles-based conjugated polymers with metal are utilized in the sensing, photocatalysis, and plasmonic lashing.

The created pi-conjugated polymers have photophysical properties that cause them to be utilized in various sensing applications. During the preparation, the hydrophobic polymers collapsed with water and developed as pi-conjugated material, which has close interactions. The interactions are accountable for the inter-chain and intra-chain energy transformation in excited state dynamics. The interactions are carried out according to the conjugated polymer's chemical and structure-property. Then, the nanoparticle wavelength is compared with the organic solvents spectrum which helps to understand the conjugated material energy transfer. The photosensitive pi-conjugated polymers have special properties like conjugation & delocalization, optical properties, semi-conductor behavior, photovoltaic properties, light and responsive conductivity, and tuning electric properties. The pi-conjugated polymers are the main support to produce the extended pi-electron. The single and multiple bond-based developed extended electron cause to the delocalization with polymer chain. Then, the polymers effectively absorb and emit the light of the near-infrared region, which helps to process the light-responsive process.

4.1. Skin trauma analysis

The pi-conjugated poly material properties are the main reason the material is utilized in the sports injury rehabilitation process. In aerobic exercise, skin trauma happens due to prolonged interaction with the surface, repetitive motion, and friction between clothing and skin. The skin trauma severity depends on skin sensitivity, hygiene practices, environmental conditions and exercise types. Generally, skin injuries are categorized into deep trauma and shallow trauma, in which abrasions, cuts, and burns have happened in shallow trauma. In deep trauma, tissue-skin damage, gunshot wounds, collisions, and cuts may happen. Therefore, pi-conjugated polymaterials are highly utilized in the skin tissue healing process to improve the tissue healing rate. During this process, composite conjugated materials are utilized as the protective barrier to block pollutants, viruses, and external bacteria, which minimize the risk of inflammation and infection. In addition, composite materials are good in wettability and permeability, which are used to absorb and manage the injury area moisture and humid value. The humidity in the wound region is used to improve the proliferation, promote cell movement, and minimize scabbing and dryness. The conjugated materials control the drug releases that maximize the wound healing rate and regulate the release rate. The drug-release-related surface and mass values are computed for estimating the Drug Release Rate (DRR). The DRR value is computed using Equation (1).

$$\mathrm{D_r} = \frac{\mathrm{M}}{\mathrm{A}} \times \mathrm{t} \tag{1}$$

In Equation (1), the dissociated drug mass value is represented as M, the drug release surface area is denoted as A, and t is denoted as t. The computed material release rate controls the drug releases on wounded surfaces, which helps to achieve the targeted therapeutic and sustained effect. Then, the wound cell migration $\mathrm{Cell_m}$ is estimated using equation (2).

$$\mathrm{Cell_m} = \frac{\mathrm{D_j}}{\mathrm{t}} \tag{2}$$

According to the Equation (2), cell migration $\mathrm{Cell_m}$ distance $\mathrm{D_j}$ is estimated at time t. If the $\mathrm{Cell_m}$ is high value, then the conjugated materials are highly helpful for wound closure and cell movement. In addition, the pi-conjugated materials promote cell differentiation and proliferation. The conjugated material components deliverances bioactive substances that stimulate cell activity and enhance wound healing. The successive computation of drug release rate and cell migration distance helps to maximize cell proliferation, generate new blood vessels, and prevent scar formation and wound infection.

4.2. Fracture healing analysis

The next important problem in aerobic exercise is fracture healing, in which infected tissues must be regenerated. The pi-conjugated matrials enhance the bone tissue repair and regenerations. The combination of materials encourages bone cell differentiation and proliferation, also preventing osteolysis and infections. The conjugated materials have photosensitive, antimicrobial, and antibacterial properties, which reduce the infection and manage the wounds. The conjugated materials have fibroblast growth factors and bone morphogenetic proteins that have a particular molecular structure. Therefore, materials have participated in cell receptors; therefore, they activate cell differentiation and proliferation via pathways. Then, the relationship between cell differentiation and proliferation is computed using Equation (3).

$$\mathrm{Cell_y} = (\mathrm{G_F} + \mathrm{E_m}) \times \mathrm{O_F} \tag{3}$$

In Equation (3), the relationship between bone differentiation and proliferation $\mathrm{Cell_y}$ is estimated from the growth factor $\mathrm{G_F}$, the extracellular matrix component $\mathrm{E_m}$ and bone proliferation and differentiation affected other factors $\mathrm{O_F}$. The conjugated material has several components like hyaluronic acid and collagen based extracellular matrix components. These components have a unique structure that gives physical support and encourages cell proliferation, cell attachment, migration, and scaffold structure to cells. The extracellular components are associated with the receptors that regulate cell behavior and function. In addition, it has silver ions and antibiotics activities, which protect the injuries from the environment and ensure interactions with deoxyribonucleic and bacterial proteins, which provide antibacterial effects.

4.3. Analysis of soft tissue injury

In medical applications, conjugated materials are utilized to cure soft tissue injuries like joints, ligaments, tendons, and muscle-related soft tissue damage. The pi-conjugated material supports soft tissue repair cell generation and promotes the injury rate because it has fillers and scaffold properties. In addition, composite material has biocompatibility and adhesion properties, which is the main reason to cure tissue injury very fast. The efficiency of the conjugated material repair rate is computed from the damaged tissue repair value, which is mentioned in Equation (4).

$$\mathrm{R_r} = \frac{\mathrm{A_2} - \mathrm{A_1}}{\mathrm{A_1}} \tag{4}$$

In Equation (4), the damaged tissue repair rate is denoted as $\mathrm{R_r}$ which is computed with the help of the ratio between the initial size of the affected tissue area $(\mathrm{A_1})$ and the difference between the size of damaged tissue after a particular area$(\mathrm{A_2})$ and the initial size of the damaged tissue. According to the above analysis, the pi-conjugated materials are highly participated in the extensive applications to improve tissue healing and wound healing. The successive and photosensitive properties are the main reason to observe and cure wounds during aerobic exercises. In addition, the integration of new materials in conjugated materials also creates a huge impact on healthcare applications to heal wounds with minimum difficulties. The pi-conjugated materials are utilized in the inflammatory response in which the body reacts to the external stimuli and reduces the damage during the activities. The inflammatory response should be minimal else it causes various pathological effects like bowel disease, cardiovascular disease, arthritis, and neuritis. The conjugate material-based generated inflammatory response reduces the drug-related issues and side effects. The conjugated material has several components and medical properties like hormonal drugs and anti-inflammatory drugs, etc. These properties and molecular structure lead to minimizing inflammation-related issues and regulating the immune response to tissue damage.

5. Experimental analysis to evaluate the effect of pi-conjugated materials on tissue healing in aerobic exercise

5.1. Experimental subject and samples

This section evaluates the effect of pi-conjugated materials on the tissue healing process in aerobic exercise. In this study, sophomore and freshman aerobic students

[23] in a particular city were used for the research analysis. During the analysis, 60 girls were selected, in which two subjects had acute sports injuries and 58 subjects are confirmed as fitted to this analysis. Hence, this study uses 58 girls with no significant difference in their age, weight, and height. The girls are instructed to perform the aerobic squat in which they stand straight with their feet shoulder-wide or slightly wider and their toes pointed straight front. Adjust your hands to make the elbow joint 90° and elevate the test rod to the head by extending both arms simultaneously. Then, gradually squat until your thighs are parallel to the ground, keeping your heels on the ground, raising your head and chest, keeping your back straight, not bending your waist, and holding the test rod as high as possible. The knees on both sides are in the same plane as the feet when squatting. Never bend your knees, and keep your toes pointed forward. This squat test was done three times. This type of exercise leads to muscle strain, sprain, and joint strain[24,25].

Another type of exercise is an active straight-leg raise. The participant lies on his back with arms on his side, palms up, and flat; the test board is beneath the knees with toes pointing up. Perpendicular to the ground, it is between the anterior superior iliac spine and the patella midway. The individual elevated one leg fully with a straight knee. The second knee joint should be as close to the test board as possible, with toes pointed upward, and the other side should be the same. This type of exercise also leads to muscle strain, sprain, and joint strain. During the study, subjects were divided into two groups: the control group was fixed with non-conjugated materials, and the experimental group subjects were implanted with pi-conjugated materials. The experimental study is conducted at five weeks and the various materials are utilized for observing the tissue healing during the aerobic exercise.

5.2. Experiment analysis based on material characteristics

The excellence of pi-conjugated materials in tissue healing is evaluated according to their biocompatibility property. Biocompatibility consists of blood and tissue compatibility; this property is used to interact with the tissue to cure the injury without affecting the tissue's function, rejection reaction and prevent the inflammation process of tissues. This study monitors the biocompatibility value of experimental and control groups in the form of decreased cell function, adverse reaction, implantation material inflammation, and minimized tissue function. According to the terms, the obtained biocompatibility value of the control group is shown in **Table 2**.

Table 2. Biocompatibility observation values—control group.

Terms	Number of subjects	Percentage (%)
RR	11	24%
DCF	9	20%
DTF	12	27%
IC	13	29%

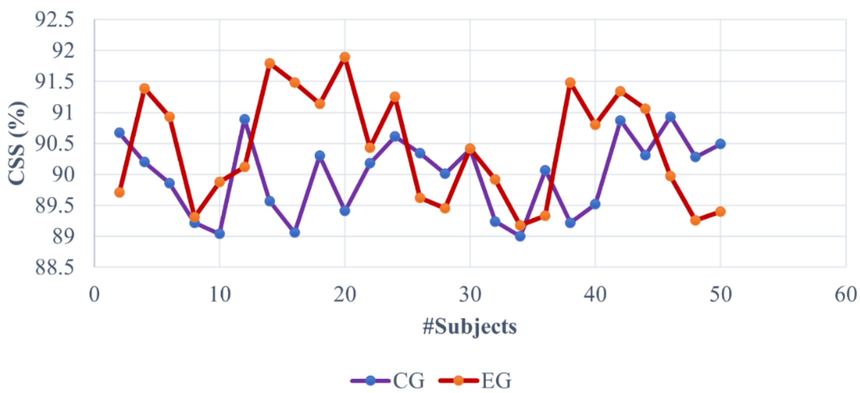
Note: RR—Rejection Reaction, DCF—Decreased Cellular Function, DTF—Decrease Tissue Function and IC—Inflammation Occurs.

Table 2 illustrates the percentage value of biocompatibility observed value of the control group (CG). In this analysis, 11 subjects in CG have a 24% RR value, nine subjects have DCF with 20%, 12 subjects with 27% of DTF, and 13 subjects with 29% of IC value. Then, the study further analyzed the Experimental Group (EG) to explore the biocompatibility observed value.

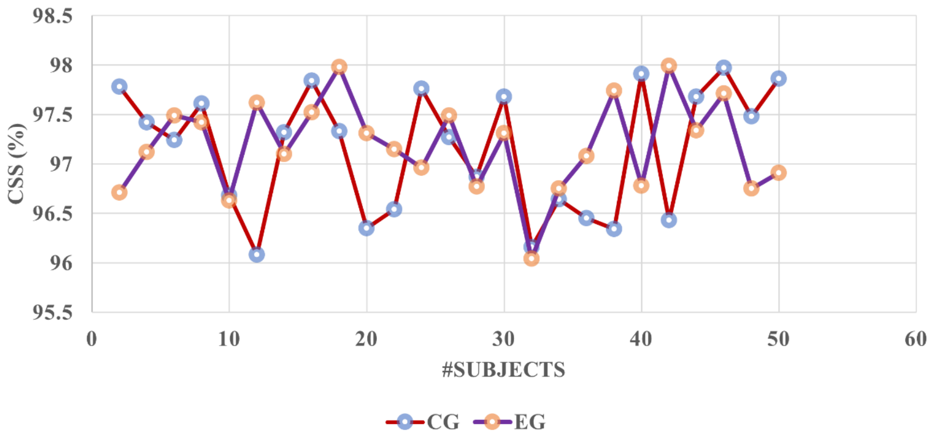
Table 3. Biocompatibility observation values—experimental group.

Terms	Number of subjects	Percentage (%)
RR	5	11%
DCF	2	4%
DTF	4	9%
IC	2	4%

Table 3 illustrates the percentage value of biocompatibility observed value of the Experimental Group (EG). In this analysis, five subjects in CG have an 11% RR value; two subjects have DCF with 4%, four subjects with 9% DTF, and two subjects with 4% IC value. From the analysis, pi-conjugated material has a attain effective biocompatibility property than ordinary materials because of the cytocomptability, physicochemical, and immunocomptability properties. In addition, the conjugated material's antibacterial properties need to be analyzed because it is used to prevent infection by killing microorganisms and bacteria. Generally, the wound occurs because the microorganisms and bacteria present in the injury lead to a reduction in the healing rate. Applying pi-conjugated materials along with antibacterial characteristics avoided the infection and microorganisms promote the wound healing rate. Then, the effectiveness of conjugated material-based Cell Survival Score (CSS) computed on both groups is examined. The maximum CSS value indicates that conjugated material minimizes cell cytotoxicity. Then the CG and EG value of CSS is shown in **Figure 1**.



(a)



(b)

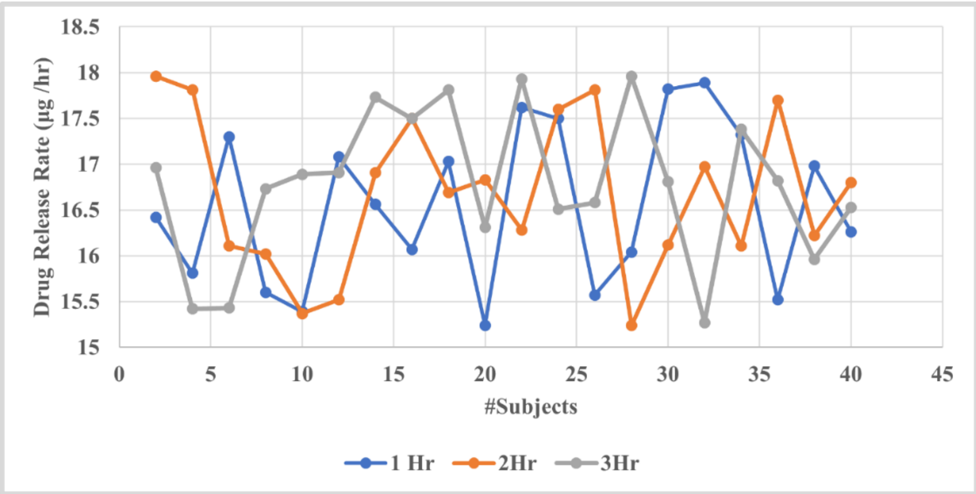
Figure 1. Cell survival score analysis **(a)** CSS value before implanted pi-conjugated material; **(b)** CSS value After implanted pi-conjugated material.

Figure 1 illustrates the cell survival score value of the control group and experimental group while treating the injuries. Here, **Figure 1a** is the graphical representation of the before implanting the conjugated materials on injuries. The results clearly show that the CG attains 89.94% and EG has 90.40% before implanting the materials on tissue treatment. **Figure 1b** is the representation of after implanting the conjugated material-based CSS value. The results clearly show that the CG attains 96.84% and EG has 96.96% after implanting the materials on tissue healing treatment. The analysis clearly states that EG subjects have attained maximum CSS value compared to CG. Therefore, the incorporation of pi-conjugated material with antioxidant characteristics leads to protecting the cell from oxidative damage [26,27].

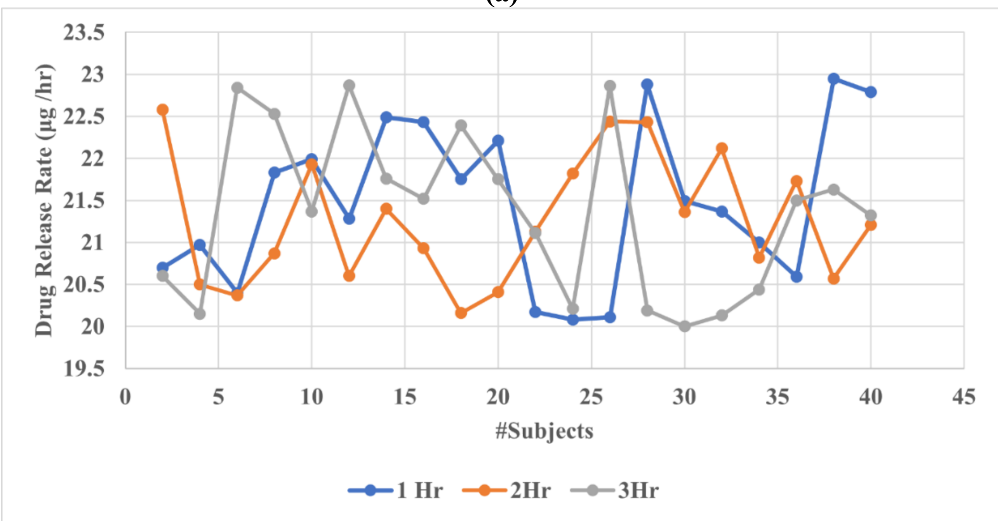
5.2.1. Analysis of skin healing

The skin healing degree is measured via the drug release rate, which is computed from the drug provision and sustained rate that is used to encourage the wound healing and repair rate. The conjugated materials control the inflammatory reactions, infection occurrences, and wound side effects during skin healing. The pi-conjugated material is given to the two groups with a drug release rate is 5 µg/h to 20 µg/h. The higher drug release rate provides a better improvement in the healing process. Then, the graphical analysis of the drug release rate for CG and EG is illustrated in **Figure 2**.

Figure 2 illustrates the graphical analysis of the drug release rate during the skin healing process in both the control group and experimental group subjects. **Figure 2a** is the control group drug release rate in which the system ensures the 16 µg/h to 16.5 µg/h drug release rate for 40 subjects. **Figure 2b** shows that the EG drug release rate system attains 21 µg/h to 21.5 µg/h drug release rate for 40 subjects. The analysis clearly states that EG attains the maximum drug release rate compared to the control group. Therefore, in the sports rehabilitation process, the traditional recovery process is influenced due to pressure, greater friction, and stress. When the conjugated material is incorporated with the healing process, the drug release rate leads to maximizing the recovery rate during the tissue damage. Then, the degree of skin healing of CG and EG is illustrated in **Table 4**.



(a)



(b)

Figure 2. Drug release rate analysis in skin healing **(a)** graphical analysis of control group drug release rate; **(b)** graphical analysis of experimental group drug release rate.

Table 4. Analysis of skin healing rate.

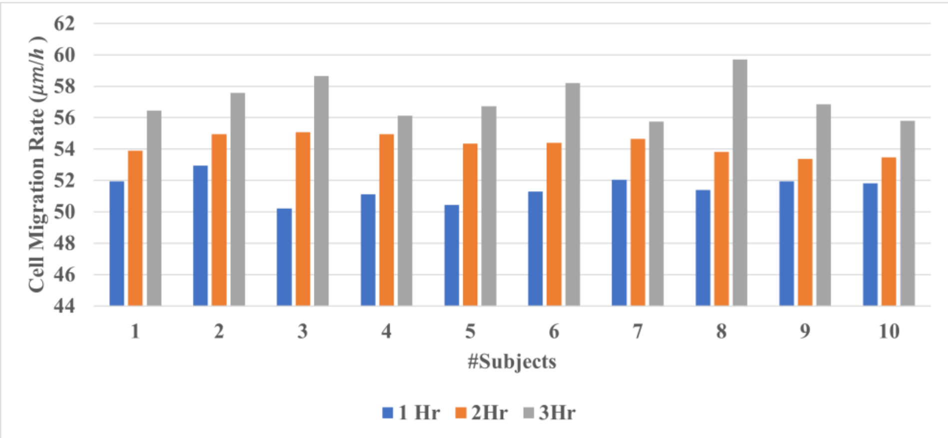
Week	CG	EG
1	45.27	59.29
2	48.389	60.2
3	49.28	62.34
4	50.2	70.29
5	52.80	79.7

Table 4 illustrates the rate of skin healing of two groups at different weeks. In week 1, CG ensured 45.27%, and EG had 59.27%. After five weeks of the experiment, the skin healing rate increased gradually to 52.80% and 79.7%. The analysis clearly shows that the skin healing rate of both group subjects gradually increased because of effectively utilized pi-conjugated materials in the recovery process. Photosensitive conjugated materials have wetting properties that are used to coat the wounds to prevent the wounds from wetting environment. The safeguard

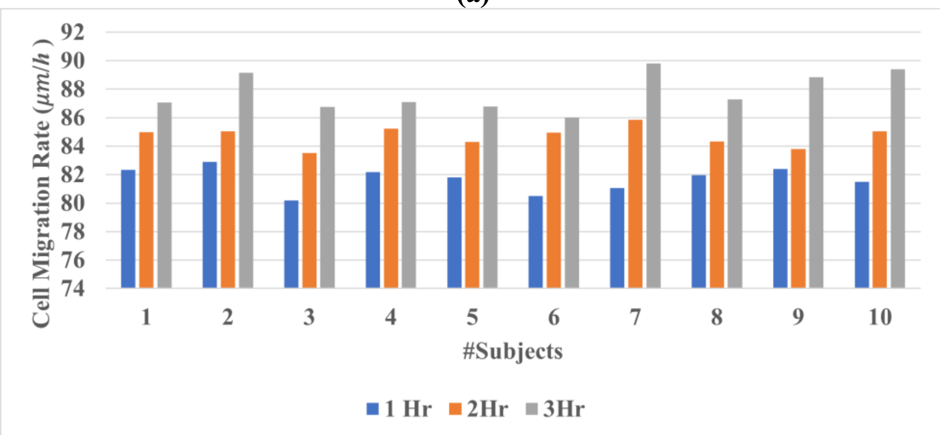
property of conjugated material encourages the healing process. Then conjugated materials have strong ingredients and components, which are the main reason the material has a maximum drug release rate and accelerates the healing very fast. Therefore, the pi-conjugated materials are highly utilized in the deeper wounds that are sprained in sports-related skin injuries. In addition, conjugated materials encourage material exchange and cell movement that is directly linked with the wound healing process. Therefore, the conjugated material improves their cell differentiation and proliferation within a certain period [28,29].

5.2.2. Analysis of fracture healing

The next important factor is to analyze the fracture healing rate, which is computed from the cell migration rate. If the conjugated material encourages wound closures and cell movement, then the process has a maximum cell migration rate. The migration rate is measured as µm/h and has a value from 60 µm/h to 100 µm/h. This analysis uses the ten subjects in two groups to explore the cell migration rate. Then, the obtained cell migration rate in the fracture healing process is shown in **Figure 3**.



(a)



(b)

Figure 3. Fracture healing analysis **(a)** cell migration rate of control group; **(b)** cell migration rate of experimental group.

Figure 3 illustrates the fracture healing analysis of the control and experimental group for different subjects. For the control group described in **Figure 3a**, ten subjects are examined at different hours of medication in which 1hr attains 51.99 μm/h, 2 hr–55.037 μm/h and 3rd hr–57.296 hr. **Figure 3b** shows the cell migration rate of EG of ten subjects at various hours of medications in which 1 hr attains 81.68 μm/h, 2 hr–84.13 μm/h and 3rd hr–88.09 hr. The analysis clearly shows that EG subjects attain a high cell migration rate after the successful medication of 2 hours. Then, the degree of fracture healing rate is shown in **Table 5**.

Table 5. Analysis of fracture healing.

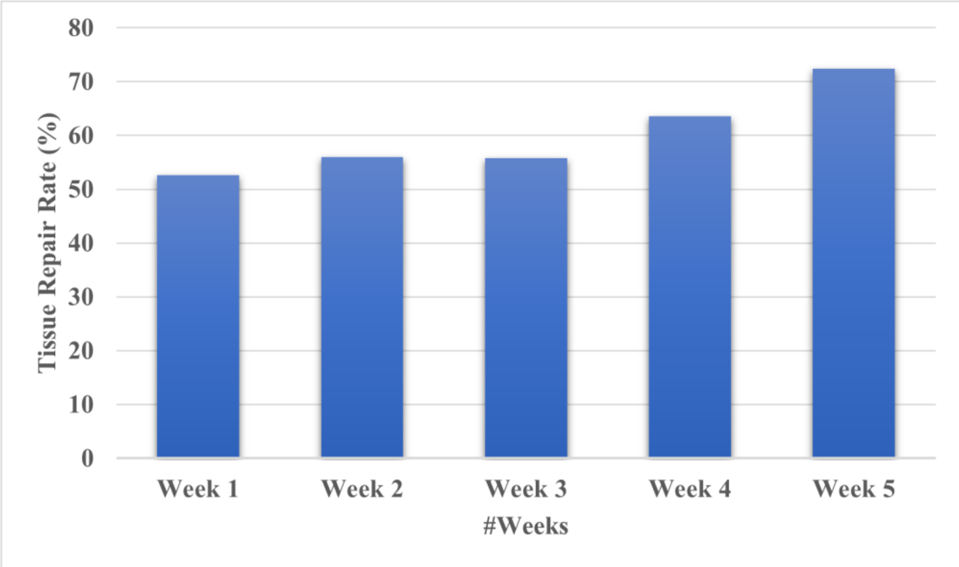
Week	CG	EG
1	55.99	63.29
2	59.2	74.23
3	64.20	80.2
4	69.3	89.2
5	76.39	94.5

Table 5 illustrates the fracture healing rate of several-week medications, which is evaluated in both control and experimental groups. In the first week 1, CG attained 55.99%, and EG had 63.29%, whereas in week 5, CG had 76.39% and EG had 94.5%. From the comparison, the fracture healing rate increased from week 1 to week five in both groups. The pi-conjugated materials encourage the fracture healing process via external and internal applications. The materials are highly involved in the tissue regeneration process in internal applications because of the scaffold properties. In addition, the conjugated materials give the growth and support for bone tisse repair and regeneration process. For external applications, conjugated materials help to promote the wound repair process via dressing and patches. The materials attached to the skin release the drug slowly, which helps to improve the tissue repair and regeneration process [30,31].

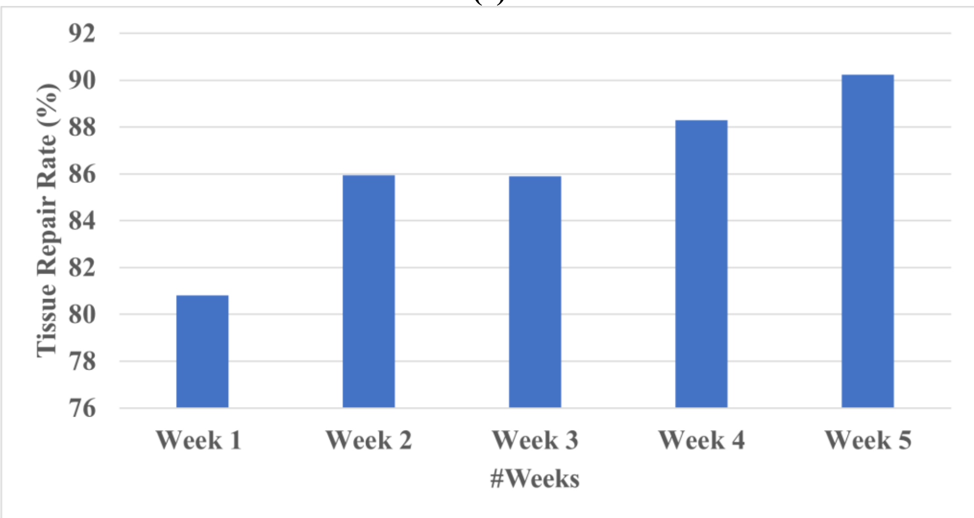
5.2.3. Analysis of tissue damage repair

The tissue repair rate must be higher when utilizing the correct conjugated material for tissue damage. Then, the tissue repair rate for control and experimental groups is frequently analyzed week by week to explore the efficiency of conjugated material. Then, the obtained tissue repair rate graphical analysis is shown in **Figure 4**.

Figure 4 illustrates the tissue repair rate analysis of various weeks of medications for both control and experiment groups. From the analysis, the tissue repair rate changed from week 1 (52.4%) to week 5 (72.4%) in the control group (**Figure 4a**). Same as in the experimental group, the tissue repair rate changed from week 1 (80.81%) to week 5 (90.23%) (**Figure 4b**). The pi-conjugated materials encourage vascular regeneration, which is directly linked with wound healing. If the aerobic participants face injury, the blood vessels are damaged, which affects the blood flow and causes delays in wound healing and tissue necrosis. Therefore, pi-conjugated materials are applied to the wound that has angiogenesis ability, which regenerates the vascular and improves the wound healing rate. In addition, conjugated material maximizes exercise safety in the rehabilitation process and minimizes the risk factors during training. Therefore, effective utilization of photosensitive conjugated material provides support and growth for proliferation and minimizes the injury level in exercise [32,33].



(a)



(b)

Figure 4: Graphical analysis of tissue repair rate **(a)** control group tissue repair rate; **(b)** experimental group tissue repair rate.

6. Discussion

The following enhancements and future suggestions may inform the theoretical study of the suggested article:

Adaptive Tissue Healing Processes: This work may lead to intelligent materials and infrared and near-infrared (NIR) materials improving tissue restoration. This material may self-adjust medication delivery in real-time in response to biological cues from the body, providing continuous feedback. Materials may improve recovery by adjusting their release mechanisms in response to temperature, tissue oxygenation, and healing.

Biofeedback-Driven Rehabilitation: If biofeedback drives rehabilitation, advanced biofeedback devices may be used in therapeutic materials. These devices may measure tissue response and deliver bioelectrical impulses for pain control or muscle repair by linking to the patient's neurological system. This might lead to a paradigm change in self-regulating therapy that substantially reduces healing times, particularly for sports injuries.

Nanomaterial-Enhanced Regeneration: Pi-conjugated polymers with nanoparticles may enable more accurate tissue regeneration in this hypothetical situation. Customising these nanoparticles to deliver therapeutic chemicals exactly where cellular damage is identified may improve regeneration without systemic negative effects. AI-Powered Predictive Healing: In this other reality, AI may determine the best times and places to use near-infrared (NIR) radiation for healing. Artificial intelligence (AI) might use patient profiles and historical data to generate personalised therapeutic regimens for each patient's metabolic and tissue response characteristics to promote recovery.

Addressing the study's weaknesses and integrating the results with current research requires expanding the discussion section. How to proceed:

Relationship between results and knowledge Advancements in photo biomodulation and medication delivery combined with using photosensitive π-conjugated materials in sports rehabilitation. Our work contributes to the literature since these technologies may enhance sports injury healing and rehabilitation. NIR technology has been examined for tissue regeneration, but this study shows it may improve medication release control and sports injuries.

The study's limitations include not fully addressing negative consequences such as tissue irritation, immunological responses, and hazardous breakdown products from π-conjugated compounds.

Future research might examine the long-term impact of π-conjugated polymers on various tissue damage types. Long-term usage, especially with several treatments, requires biocompatibility.

7. Conclusion

Thus, the paper analyzes the photosensitive conjugated material contribution to aerobic exercise-based tissue damage and rehabilitation process. This study uses the sophomore and freshman aerobic students' exercise and tissue damage information for analyzing the efficiency of conjugated material in the recovery process. The collected subjects are divided into control and experimental groups; they are frequently monitored to observe the conjugated material efficiency in wound repair. The subjects, cell migration rate, tissue repair rate, and fractural healing rate are computed because it is directly related to the cell movement in wounding repair and tissue regeneration process. According to these tissue growth factors, fracture healing rate, damaged tissue repair, and skin healing process are computed at different weeks of experiments. From the analysis, the effective utilization of pi-conjugated material increases the skin repair rate up to 90.23%, fracture healing to 94.5%, and skin healing rate to 79.7% in experimental groups. Hence, the conjugated material effectively works to reduce the risk and increases the tissue healing rate in the treatment process. In the future the conjugated materials will be composed with other materials to improve the performance in wound healing procedures.

The following enhancements and future suggestions may inform the theoretical study of the suggested article:

Adaptive Tissue Healing Processes: This work may lead to intelligent materials and infrared and near-infrared (NIR) materials improving tissue restoration. This material may self-adjust medication delivery in real-time in response to biological cues from the body, providing continuous feedback. Materials may improve recovery by adjusting their release mechanisms in response to temperature, tissue oxygenation, and healing.

Biofeedback-Driven Rehabilitation: If biofeedback drives rehabilitation, advanced biofeedback devices may be used in therapeutic materials. These devices may measure tissue response and deliver bioelectrical impulses for pain control or muscle repair by linking to the patient's neurological system. This might lead to a paradigm change in self-regulating therapy that substantially reduces healing times, particularly for sports injuries.

Nanomaterial-Enhanced Regeneration: Pi-conjugated polymers with nanoparticles may enable more accurate tissue regeneration in this hypothetical situation. Customising these nanoparticles to deliver therapeutic chemicals exactly where cellular damage is identified may improve regeneration without systemic negative effects.

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