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Plasmonic Materials in Biohybrid Actuators: Medicinal applications

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Abstract:

Surface plasmonic nanomaterials are one of the key elements that take part in the process of light conversion with great efficiency while changing their shape to the desired surface plasmon resonance. Such materials are considered to be the main contributors for amplifying the sensor's stability and sensitivity. On the other hand, substantial drawbacks of surface plasmon resonance in actuators have been recognized, which mainly are the slow response of the actuators to the light stimuli. Therefore, it is important to study the other properties such as hot electron transfer, Plasmon Resonance Energy Transfer (PRET), and Plasmon Resonance Excitation Transfer (FRET), along with the surface plasmon resonance and the electron transfer, to overcome the limitations. The technologies surrounding these transfer phenomena of energy can lead to better light stimuli actuation and eventually soft robotics. In the end, this paper delivers a summary of the major precepts of utilizing SPR nanomaterials that will stimulate the search for more applications in soft robotics. It provides a comprehension of the energy transfer process that is taking place in SPR which can be incorporated and exploited in biohybrid actuators.

Keywords- Plasmonic, sensors, bio hybrid, soft robotics, actuators.

1. Introduction

Soft robotics has attracted a lot of attention because conventional rigid robotics is limited in sensitive situations like the human body. The capacity of soft robotics to mimic biological motions has garnered a lot of attention[1][2][3][4][5][6][7]. It draws inspiration from organisms making it ideal for applications that require adaptability, flexibility, and precision like living organisms[8]. These soft, flexible robotics are extremely useful in biological engineering because they may function as artificial muscles[9], medical devices, and less invasive surgical tools[10] .The addition of bio hybrid actuators enhances their performance by integrating natural adaptation with artificial responsiveness[11].

An important challenge to address in developing these advanced actuators is to establish a precise, applying light as an actuation stimulus is a non-invasive control mechanism and one of the most promising methods for biohybrid actuators[12].The light is controllable, clean and abundant energy source, making it magnificent choice for wireless and remote-controlled operations. The light-sensitive materials tackle photothermal or photomechanical effects to induce motion, enabling precise control over the actuators[13][14]. Among these nanomaterials, plasmonic nanostructures have emerged as highly effective due to their unique optical properties [15][16]. By coupling plasmonic nanomaterials into biohybrid actuators it represents a synergistic convergence of material sciences, photonics and biology.

2. Plasmonic Materials and Light-Responsive Actuation

Gold and silver nanoparticles are examples of plasmonic materials that exhibit Surface Plasmon Resonance (SPR) and Localised Surface Plasmon Resonance (LSPR), where incident light at a specific wavelength excites collective oscillations of their free electrons, enabling strong light absorption and efficient heat production at specific wavelengths [17][18][19].

Such properties, displayed by the plasmonic materials, allow them to convert light energy into confined heat. The heats that are produced can cause soft robotic systems to deform or activate. These features make them suitable for a wide range of biomedical uses, including as targeted medication administration, tissue stimulation, imaging, and sensing[18], photothermal therapy, biosensing[20], and responsive implants[16]. One of the main benefits in the field of biomedicine is that the LSPR peak is highly tunable. Thus, researchers are capable of accurately designing the particle size, shape, and material so that the absorption wavelength is shifted, thereby securing no or little biological damage. In biohybrid actuators, the pairing of plasmonic materials with biological tissues or synthetic constructs could augment the performance, e.g. in optogenetic methods, light-sensitive proteins are used to activate the cellular responses with a consequent fine biological control of movement[21][22]. When the plasmonic nanoparticles are coupled with the biological components, the sensitivity is enhanced even more [23][24], as well as the speed and adaptability.

2.1 Surface Plasmon Resonance (SPR)

Surface Plasmon Resonance is an optical event that happens at the junction between a metal and a dielectric when light interacts with the metal's free electrons, producing surface plasmons, resulting in collective oscillations. This resonance effect is a commonly used method in sensing applications because it is sensitive to alterations in the refractive index close to the metal surface.

2.1.1 Principle of SPR

Under certain conditions, the incident light couples with the combined motion of free electrons (surface plasmons), which produce an electric field at the metal's surface (Gold/Silver) and solution boundary at 300 nm, resulting in a resonance[25]. According to the angle of incidence and the light's wavelength, this coupling takes place when the speed of the incident light and the surface plasmons are equal. Though small fluctuations affect the resonance state, SPR is extremely sensitive to changes in the refractive index of the dielectric material next to the metal surface.

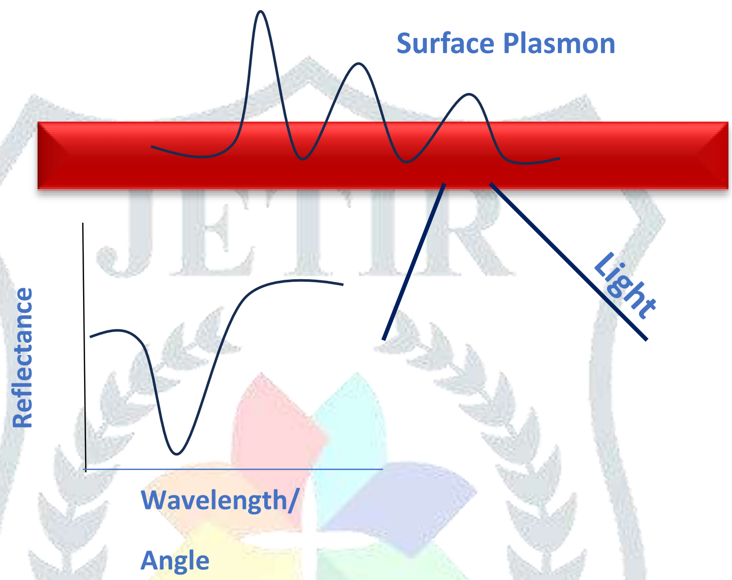


Fig.1 Schematic representation of surface Plasmon resonance (SPR).

The evanescent wave produced when light is reflected off a thin metal film—typically gold or silver—under the total internal reflection conditions depicted in Fig. 1 provides the basis for the SPR concept [25]. The surface plasmons are excited by this wave as it briefly enters the dielectric medium. The resonance is measured by seeing a notable decrease in reflected light intensity at the resonance angle. SPR can be used as an extremely sensitive detection technique since the change in the dielectric refractive index modifies the resonance angle. The SPR is a technology that is mainly used in bio sensing and similar areas where it can detect real-time molecular interactions without labelling. The refractive index changes on the metal surface are detected by SPR and this allows the study of biomolecular binding, for instance, protein-ligand interactions, with an extremely high degree of accuracy. Besides, this phenomenon is widely applied in material science, chemistry, and environmental monitoring as its high sensitivity to surface conditions reveals powerful analytical capabilities.

2.2. Localized Surface Plasmon Resonance (LSPR): It is a process that results from a metallic nanoparticle's conduction electrons coherently vibrating in resonance with incident light. The resonance is confined to the nanoparticle's surface and causes the electric and magnetic fields directly above the surface to amplify.

2.2.1 Principle of LSPR

Although they have many conduction electrons per unit volume, metals like silver (Ag) and gold (Au) have remarkably high electrical conductivity[26].Whenever light from outside the environment interacts with these conduction electrons, it generates the electric field. The conduction electrons of the metal are, therefore, displaced in a way that they form a surface dipole relative to the positively charged particles inside the nanoparticle. This displacement is, hence, opposed by the attraction of the positive core of the nanoparticle. The light of the same frequency as the oscillation of these electrons will cause resonance to happen which is a phenomenon called Localized Surface Plasmon Resonance (LSPR) as depicted in Fig. 1 [27]. This resonance results in a significant absorption and scattering of light at certain wavelengths.

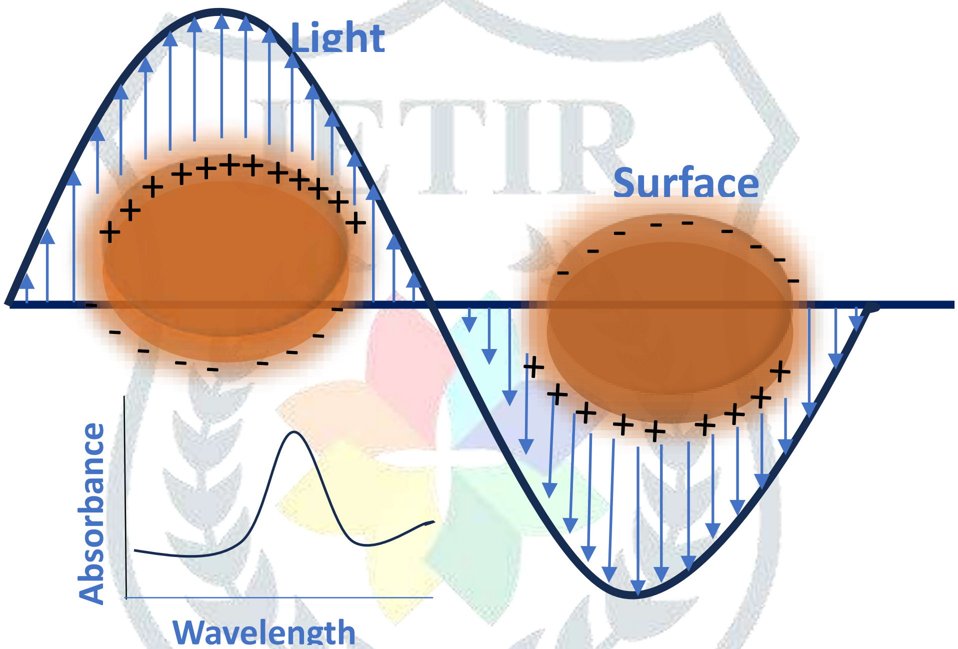


Fig.2 Schematic representation of localized surface Plasmon resonance (LSPR) in spherical metallic nanoparticles.

LSPR occurs only at the individual nanoparticles' surfaces but Surface Plasmon Resonance (SPR), requires either thin films or continuous metal surfaces. The resonance is limited to areas very close to the nanoparticle, generally within tens of nanometers, which leads to the production of very high electromagnetic fields in those localized areas. The resonance frequency or wavelength of the LSPR is affected by several factors, such as the material of the nanoparticles, their shape, size, surrounding medium and the distance between the particles. Ultra-plasmonic metals like Gold and Silver are very good candidates for producing powerful LSPR because they have a great number of free electrons in them. A single LSPR peak is typical for smaller nanoparticles while anisotropic shapes, for instance, nanorods or cubes, can have numerous peaks because of their different oscillation modes. The resonance frequency shifts when the environment's refractive index changes, and the nanoparticles that are very close together can even interact so strongly that their plasmonic effects merge into one, thus changing the resonance wavelength as well.

When the system is at its resonant frequency, the oscillating electrons produce a strong electromagnetic field that is localized and near the nanoparticle's surface. This field enhancement is of utmost importance for instances such as sensing, where even minor alterations in the local environment can be noticed. During LSPR, the incident light's energy gets divided up into either scattering, which is light redirected and used in imaging applications, or absorption, wherein light energy is converted into heat, thereby, making possible the photo thermal treatments. The ratio of scattering to absorption is determined by the nanoparticles' size. LSPR's behavior can be mathematically modeled using Mie Theory for spherical objects which solves Maxwell's equations for light's interaction with small particles. The optical characteristics, i.e. scattering and absorption, are determined by the dielectric constant of the nanoparticles, the surrounding medium, and the particle size.

LSPR can be applied over a wide spectrum, including sensing, where it detects changes in the refractive index; photo thermal conversion, where it heats up for therapies or actuators; solar energy, where it promotes light absorption in plasmonic materials for better efficiency; and optical imaging, where its powerful scattering properties are exploited for diagnostics and imaging. This effect has turned out to be one of the main things in nanotechnology and promises to be very important for the progress of many areas in science and technology.

2.3 Effect of particle size, shape and material.

2.3.1 Nanoparticle size and aspect ratio

The efficacy of plasmonic nanoparticles in a variety of applications, most notably plasmonic biohybrid actuators, is affected by their size and aspect ratio, which are critical for controlling their optical, thermal, and mechanical features. The Localized Surface Plasmon Resonance (LSPR) effect, in which the incident light excites the conduction electrons, can be observed in nanoparticles, which are often made of noble metals like gold and silver. The size of the nanoparticles has a direct effect on the LSPR wavelength; the larger ones (>50 nm) tend to shift towards the infrared area while the smaller ones (10–50 nm) stay at shorter wavelengths.

In the case of anisotropic materials such as nanorods or nano disks, the importance of the aspect ratio, which is the length-to-width ratio of the particle, is amplified very much. The larger the aspect ratio shifts the LSPR peak further into the infrared range (redshifts) enabling tuning of the optical responses for particular applications, one of which is near-infrared light activated actuation. When the particles are small and have good aspect ratios, they will be stable and will also suffer from lower scattering losses, which will cumulatively increase the efficiency of both the actuation and energy conversion processes. So, the ability to control size and aspect ratio very precisely is thus required in order to adapt the properties of plasmonic nanoparticles to meet the specifications of the different applications already mentioned, such as in biomedical devices, environmental sensors, and wireless actuation systems.

2.3.2 Morphology of Nanoparticle

Plasmonic nanoparticles' optical, electrical, and catalytic characteristics are largely determined by their morphology, which includes their size, shape, and surface structure. Plasmonic nanoparticles are frequently shaped as spheres, rods, cubes, triangles, stars, and shells, and each one has its own special localized surface plasmon resonance (LSPR) properties. For example, anisotropic geometries like nanorods and nano stars have several peaks because of their longitudinal and transverse plasmon modes, but spherical nanoparticles usually display a single LSPR peak. The optical properties can be altered to specific wavelengths in the visible and near-infrared spectrum thanks to the morphological transformations.

The plasmonic behavior and, in turn, the encircling of the electromagnetic field in the so-called "hot spots" are mainly determined by the surface roughness and material structure. Whenever using methods like SERS and photothermal therapy, these factors are essential. The nanoparticles' morphology is an important factor that is responsible for their stability, biocompatibility, and reactivity, which consequently makes it one of the main factors controlling the scale up of the material for specific applications. The operator can precisely manage the product's morphology via innovative synthesis strategies like seed-mediated growth and template-assisted techniques. The outcome is the generation of such plasmonic nanoparticles that are very suitable for the new applications, such as biomedicine, environmental monitoring, and energy harvesting, just to mention a few.

2.3.3 Material of Nanoparticles

The plasmonic characteristics of plasmonic nanoparticles, such as LSPR is the harmonized oscillation of free electrons brought on by light, are largely determined by their composition. Because of their exceptional capacity to maintain strong plasmonic resonance across a broad range of wavelengths, particularly in the visible and near-infrared regions, noble metals such as silver, gold, and copper—are regularly used for plasmonic particles. Due to the long-term stability and biocompatibility, the gold nanoparticles are mostly used in biological applications, such as imaging and medication delivery. Silver, on the other hand, is stronger when it comes to plasmonic responses and energy transmission but may be unstable and pose biological toxicity risks.

Recently, due to their different characteristics, titanium, aluminum, and even some semiconductors besides metals have been considered for possible replacement of silver and gold in the production of nanoparticles. Additionally, because of their superior optical traits, conductivity, and ability to adapt, hybrid materials—which combine metal and another nanomaterial—are becoming increasingly attractive. The efficient use of nanoparticles in sensors, biohybrid actuators, and environmental monitoring applications depends significantly on their reactivity, stability, and biological compatibility, all of which are affected by particle selection.

2.3.4 Plasmonic Materials and Their Properties:

Plasmonic materials, primarily gold and silver, possess the rare quality to maintain surface plasmon, which are synchronized oscillations of the free electrons present at the boundary between a metal and an insulator. When light hits the surface of the metal, the free electrons get excited and start to move together, thus plasmon resonance is produced. As a result, there is a strong electromagnetic field confinement that allows the control of light at dimensions even smaller than its wavelength.

It would be overstatement to claim that these materials have amazing properties. Their broad light-matter interaction properties have led to their widespread application in nanophotonics and other fields like sensing, imaging, and energy harvesting[28]. Furthermore, their capacity to enable LSPRs in nanoparticles positioned at the nanoscale opens up new possibilities in PTT, SERS, and biosensing. Furthermore, plasmonic nanostructures are essential for the development of sophisticated light-trapping devices, photonic circuits, and optical metamaterials, all of which contribute significantly to the continuous advancements in optics and photonics.

2.3.5 Negative Permittivity: Negative permittivity signifies an intriguing and unconventional scenario wherein the permittivity (ϵ) of a substrate becomes negative. Permittivity is a basic attribute that reflects how a substance may polarize under an electric field, thus interacting with electromagnetic waves. For the most part, everyday substances have positive permittivity, which means they usually polarize in the same direction as the electric field. This property makes them to be very predictable in their reactions to the electromagnetic influences coming from outside. But, in the case of some engineered or naturally occurring materials, especially when particular frequencies are involved, there occurs a drastic change in the behavior that leads to negative permittivity. The appearance of negative permittivity is in turn the cause of a series of remarkable and strange electromagnetic properties. One such major phenomenon linked with this condition is surface plasmon resonance (SPR), a phenomenon that boosts the interaction between light and the electrons residing at the surface of a conductor. The succeeding stages of SPR; the permittivity of the metal, which usually lies within the range of negative values at optical frequencies, must be exactly matched with that of the dielectric material surrounding it. Gold and silver are the most common metals for this application, as they have a negative permittivity profile. Thus, the effect of negative permittivity is so compelling that it can even lead to the occurrence of marvelous events like SPR, which in the end is associated with the modern applications including, among others, advanced sensing technologies, where the most sensitive detection techniques are created, and the development of new materials with unusual electromagnetic properties, thus, opening up new areas of research in the field.

2.3.6 High Field Enhancement: At resonance conditions, the plasmonic materials can considerably amplify the electromagnetic fields at their surfaces that makes them to be used in the sensing and surface-enhanced spectroscopy.

2.3.7 Material-Dependent Losses: Due to their specific permittivity noble metals like gold and silver are used as conventional plasmonic materials. However, their ohmic losses, which are inherent, could limit the performance of the devices. The transition metal nitrides (e.g. titanium nitride) have been proposed as the alternative materials that eventually will lead to the thermal stability, niceness, and easy fabrication as they are the ones who are being investigated as a result of this limitation.

2.3.8. Fabrication Techniques for Plasmonic Nanomaterials

The production of plasmonic nanomaterials involves the utilization of techniques that enhance the plasmonic characteristics of the nanoparticles through the precise control of their size, shape, composition, and distribution[29]. The different methods used for creating plasmonic nanomaterials are presented in the diagram below as Fig. 3.

I) **Chemical synthesis**: The colloidal nanoparticles are synthesized by reduction method, allowing very precise control over the nanoparticles' morphology, like spheres, rods, and cubes. The chemical techniques enable the control of the shape, size and optical properties of plasmonic nanoparticles. The chemical phase synthesis is the most common and versatile technique for the synthesis of nanoparticles by using noble metals such as gold and silver. In particular, the polyol reduction method has emerged as a dependable technique for producing shape-controlled nanoparticles, in this method, ethylene glycol serves as both reducing agent and solvent, reducing the metal precursors into atoms at high temperatures. A capping agent such as poly(vinyl pyrrolidone), is used to control the particle growth by selectively attaching to the specific crystal facets and to influence the morphology of the end product[30].

II) **Top-down approaches:** The production of patterned plasmonic devices at the nanoscale can be realized with the help of top-down method such as lithography (for instance, electron-beam lithography or nanosphere lithography) which are very precise and accurate in their output[31][32].

III) **In situ method:** The methods that get silver or gold nanoparticles on flexible substrates through fluoride-assisted reduction allow for the direct synthesis on the desired platform and at the same time the combining of fabrication and integration processes[33][34][35][36].

IV) **Physical vapor deposition techniques**: By employing methods such as sputtering and thermal evaporation, the deposition of plasmonic materials, for example, gold and silver, is done in thin films. The subsequent layers can be further processed for producing various nanostructures. Due to the versatility of these techniques, researchers are able to design different kinds of plasmonic nanomaterials suitable for advanced applications in optoelectronics, photothermal therapy, detection, and catalysis[37][38][39].

V) **Emerging techniques:** The methods such as template-assisted fabrication and self-assembly are among the new techniques that employ molecular templates or take advantage of the natural tendency of nanoparticles to form well-ordered arrays[40][41][42].

Fig. 3 Different methods for fabricating plasmonic nanomaterials.

3. Actuators

Actuators are devices that transform energy into mechanical motion and play an important part in many systems, including robotics, industrial machinery, and home automation[43]. They receive electrical, hydraulic, pneumatic, or thermal energy and generate linear or rotational motion to execute specialized tasks. Electric motors, pneumatic cylinders, hydraulic pistons, and piezoelectric devices are common actuator types, each having its specific application determined by power, velocity, and accuracy. Actuators, in turn, are always present and active in such fields as robotics, automotive, and medical technology, where their ability to perform and control movements automatically makes them indispensable for modern engineering and tech solutions.

Biohybrid Actuators: Combining Biology and Engineering

Biohybrid actuators effectively merge living tissues or cells with synthetic materials to harness the flexibility and adaptability of biological systems. They mimic the natural functions of muscles, thus paving the way for the production of soft robots of high performance[44] [45][46] . The recent advances in materials science, for example, the creation of 3D-printed biohybrid structures, have opened new avenues for their use in the medical field[47][48]. One of the upsides to the presence of such structures is that researchers have been able to create light-responsive actuators that are both remote-controlled and accurately operated by the incorporation of plasmonic nanoparticles into the biohybrids [49]. Not just that, the actuators are capable of imitating muscle movements and also react to external stimuli, thus making them ideal for soft robotics applications.

3.1 Biohybrid Actuators: Design and Fabrication

Biohybrid actuators are luxury technologies that make use of synthetic materials and biological elements, in the form of tissues, cells, or even biomolecules, to come up with devices that imitate nature's behaviors[50][51]. The main goal of these actuators is to rely on the properties of living organisms by using their electrical impulses to their whole contractile states[52]. They then allow very accurate and adaptable movement by directly controlling their response to different inputs, e.g., light, chemical gradients, or electrical signals. The applications of biohybrid actuators range among soft robotics, bioengineering, and medical devices[47]. The main attributes of biohybrid actuators i.e. their biocompatibility and the capability to imitate the natural way of motions, provide the potential for the making of realistic and sustainable systems to a great extent.

Typically, the construction of these actuators involves a careful combination of biocompatible materials, synthetic scaffolds [53] , and biological elements capable of response, such as tissues or muscle cells [54]. Sophisticated production methods like soft lithography, 3D bioprinting [55], and microfabrication yield very accurate structures that also facilitate cell growth and alignment[56]. The biocompatibility, scaffold's mechanical traits, and the inclusion of stimuli-responsive elements for the purpose of controlled movement are critical criteria. These actuators open the door for making soft, flexible, and efficient systems that can imitate the functioning of actual muscles, which may then find applications in tissue engineering, biomedical devices, and robotics[54][7].

4. Biological Components and Integration

The integration of biological component and their functioning is a complicated field of research which brings together biological substances and systems along with engineering methods to produce hybrid machines and technologies[57]. The biological components, such as enzymes, cells, tissues, DNA, or other macromolecules, are selected and then incorporated into synthetic scaffolds to perform specific functions[58][59][60][61][62].The successful integration is achieved by ensuring that the biological and artificial parts are compatible with one another, with emphasis on factors such as biocompatibility, stability, and operation[63][64][65].

Artificial skin can perceive and even mimic natural human touch, which is among the many breakthroughs that the medical field is experiencing due to the application of biosensors and brain-machine connections[65][66]. Another significant field is tissue engineering, which uses living cells transplanted on top of biological scaffolds composed of synthetic or natural polymers to improve the lack of tissues or organs[67].Through their combination with electronic devices, bioelectronics designers are inventing biohybrid systems for applications such as microbial fuel cells or brain-machine interfaces, where biological components like neurons or biofilms are fused with the electronic ones[68].

Outside the health and wellness sector, biological integration finds application in the fields of biotechnology and environmental monitoring. For example, specific and sensitive detection of pollutants, pathogens, or toxins can be done using biosensors that employ enzymes or antibodies[69][70][71]. Synthetic biology, for example, allows for the production of future living organisms or systems that could yield biofuels, drugs, or other commercially significant compounds through the integration of genetic circuits into living cells[72] [73].

The field also stays focused on the ethical, social, and environmental sustainability impacts of such technologies along with the new biological and combined material worlds. This multidisciplinary approach is necessary to tackle globally energy, medicine, and environment issues.

5. Light-Responsive Actuators

Light-responsive actuators are promising materials that change drastically in shape or properties as a result of light exposure [74]. These materials are capable of taking light energy directly, and then turning it into mechanical motion or some other energy forms. The ability of such materials to respond in different ways to light in the major case makes them attractive for soft robotics, which needs movable parts that deliver the same functional changes in different settings, and medical devices that require very accurate control. Photo isomerization is one among others that the list of light-induced changes of state includes; it is the conversion of the molecules of a compound into a different structure by the light absorbed. The azobenzene molecules serve as a perfect example in the scenario, which is capable of existing in two molecular configurations upon illumination with specific wavelengths of light[75]. Besides the inherent changes in size and the feature of the material to perform movements that are just right for the purpose, this process has been the base for applications to come in the near future. Among the remarkable properties of some materials that absorb light and later transform it into heat are photothermal events[76]. The transformation of the material dimensions (either by expanding or contracting) is one of the possible mechanical responses to the process. Among the materials that utilize this principle of operation are the special polymers and nanomaterials (e.g., gold nanoparticles), which have the ability to respond to light stimuli very quickly and effectively. This is a very important factor in applications that need such materials to be able to move or be shaped in a certain way, thus the change of the environments would not affect the materials' ability to carry out their task. Photo catalysis was displayed in various materials where the process of bonding leading to growth took place as new bonds were forming due to reaction activation by light.

6. Coupling Plasmonic Nanomaterials with Biohybrids

Nanomaterials possesses the most desired optical properties and the biohybrids provides living organisms and biomolecules with their intricate biological functionalities thus forming a vibrant and innovative inter-disciplinary research area which is the combination of plasmonic nanomaterials and biohybrids[77]. This interesting combination of optics and biology opens up many possibilities for applications in different areas like bioengineering, bio sensing, therapeutic delivery, and diagnostics, where every application is considered as a harbor of powerful potential for revolutionary advancements.

The most active and costly metals—gold, silver, or copper—are the primary constituents of plasmonic nanomaterials, which are tiny metal particles[78][79]. One of their most interesting features is that they exhibit a type of light wave resonance at the surface (SPR) when exposed to light. When the nanoparticles are exposed to radiation, localized surface plasmons occur, which causes extremely powerful electromagnetic fields to surround their surfaces. Due to these features, plasmonic materials are used in green chemical processing, advanced microscopy, and ultra-sensitive sensors. On the other hand, bio hybrids, which are composed of biological components like enzymes, proteins, DNA, bacteria, or tissues combined with polymers and metals, exhibit the highest degree of complexity in the combination of living and non-living parts. The primary functions of the biological elements are the bio compatibility and rigidity of living cells and tissues, whereas synthetic materials offer numerous benefits of high mechanical strength, ease of manufacturing, and property customization. Therefore, a very creative and adaptable platform is developed for the numerous applications listed above.

There are several ways to start the dynamics of plasmonic nanomaterials' associations with biological systems. One important strategy is optical coupling, in which the surrounding plasmonic nanoparticles act as enhancers of the electromagnetic field [80]. This enhancement can be so strong that it impacts biological elements like protein folding, enzyme activity, and cell signaling pathways, which in turn affects the entire process of biochemical reactions and interactions at the cell level. Additionally, scientists can precisely and selectively bind to the biological target of their choice by coating the plasmonic nanoparticles' surfaces with biocompatible molecules like peptides, antibodies, or nucleic acids [81]. This ability allows researchers to perform extremely precise interactions with different biological systems, thereby encouraging the development of targeted medicines and diagnostics. Furthermore, plasmonic nanomaterials are recognized for their exceptional sensitivity as biosensors, which is the case when they rely on their capacity to amplify light signals like Raman scattering and fluorescence, in addition to their role in improved biological interactions.By virtue of this property, plasmonic nanomaterials can identify minute amounts of markers or even cellular events in real time, making them useful tools for both basic biological research and clinical diagnostics. There are so many possible uses for this technology, and it still has the capacity to drastically alter how we view and engage with diverse biological systems.

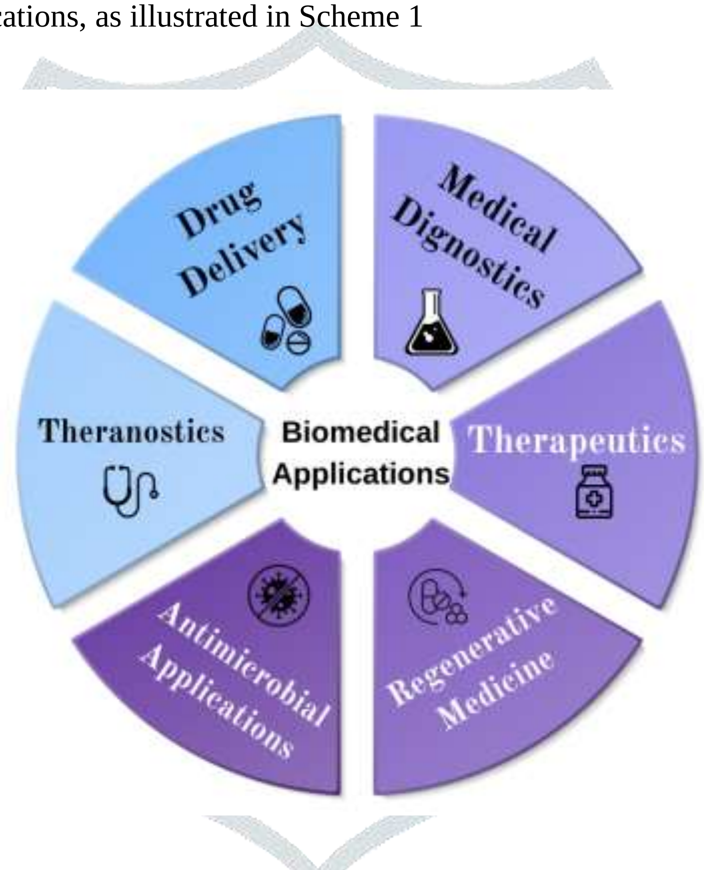
7. Applications of light sensitive biohybrid actuator

Utilizing the properties of plasmonic nanoparticles, ground-breaking actuators known as light-sensitive biohybrid (plasmonic) actuators provide dependable, light-activated movement in biological or biohybrid systems. Gold or silver are frequently employed as the plasmonic nanoparticles in these actuators. In addition to absorbing light at particular wavelengths, these particles also transform it into mechanical energy or localized heat. They can be used in many different applications because of their distinctive qualities, particularly in industries that need non-invasive, remote-controlled actuation.

However, in the field of robotics, plasmonic actuators enable the creation of soft robots that are extremely precise while doing delicate jobs, such as stocking fragile objects or going into confined spaces. These actuators are also used in the medical industry for drug delivery systems, which employ light to regulate the flow of pharmaceuticals at specific patient locations, reducing adverse effects and enhancing treatment results[82][83]. They are also employed in the area of tissue engineering to grow new tissues and trigger cells via controlled motion or mechanical stimulation. Furthermore, light-operated switches and actuators based on plasmonic actuators have enabled extremely fast and effective operation in optoelectronics and microscale systems. Bio-mimetic systems, artificial muscles, and advanced diagnostic tools are made possible by their integration into biohybrid systems, which connect biological processes with engineering solutions[12][84].

7.1 Biomedical Applications:

Plasmonic materials derived from silver, gold etc. can be functionalized with various biomolecules, enabling their use in multiple biomedical applications, as illustrated in Scheme 1



Scheme 1: Representation of Biomedical application of Plasmonic Biohybrid.

7.1.1 Drug Delivery

Plasmonic biohybrid actuators provide promising biomedical applications, especially in drug delivery and tissue engineering. These actuators that are used in drug delivery, use plasmonic nanoparticles, like gold or silver, to react to particular light wavelengths by producing mechanical forces or localized heat. This characteristic reduces systemic adverse effects and enhances treatment results by enabling the precise, remote-controlled release of therapeutic medicines at specific places. For instance, plasmonic actuators can induce medication release within tumor microenvironments when irradiated by near-infrared light, which extensively penetrates tissues without seriously harming cells nearby.

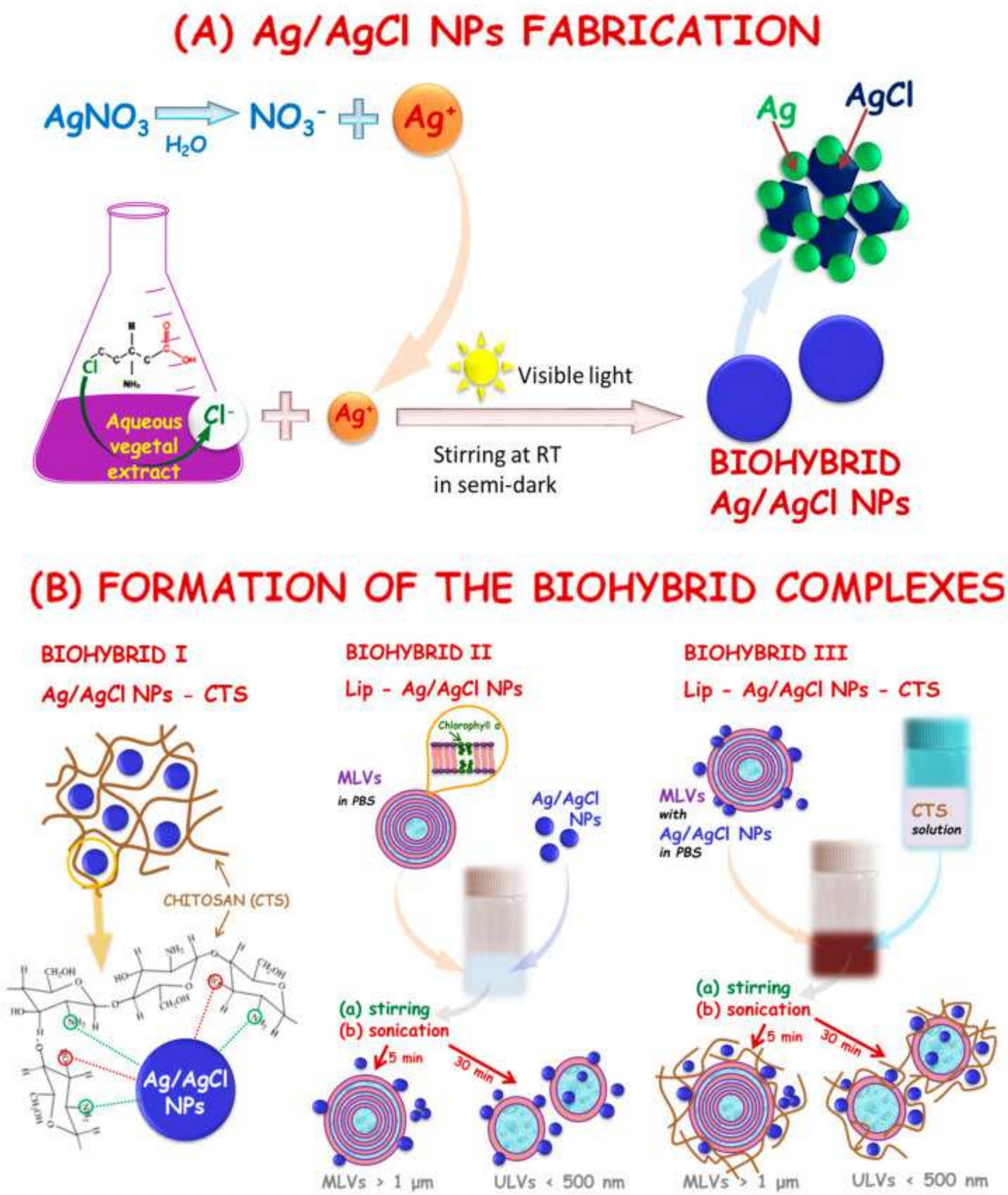


Fig. 4 Schematic representation of the biohybrid complex (Ag/AgClNPs–CTS) with the proposed interaction mechanism between chitosan and silver/silver chloride nanoparticles. **Figure reproduced from:** Reproduced from Gorshkova, Y.; Barbinta-Patrascu, M.-E.; Bokuchava, G.; *et al.* "Biological Performances of Plasmonic Biohybrids Based on Phyto-Silver/Silver Chloride Nanoparticles," *Nanomaterials* **2021**, **11**(7), 1811. https://doi.org/10.3390/nano11071811. Licensed under **CC BY 4.0**

Silver/silver chloride nanoparticles (Ag/AgClNPs) were synthesized utilizing nettle and grape extracts in a Green Chemistry technique to produce plasmonic biohybrids with biomimetic membranes and chitosan (Ag/AgClNPs–CTS) as shown is Fig.4. These biohybrids showed 71-75% antioxidant activity, considerable antibacterial properties (*E. coli* IGZ = 45 mm, *S. aureus* IGZ = 30-35 mm), and high anticancer activity against HT-29 and HepG2 cells (therapeutic indices of 1.30 and 1.77). Characterization indicated that AgNPs and hybrid

Ag/AgClNPs may be integrated without affecting membrane integrity. These multifunctional, hemocompatible silver-based biohybrids have potential for treating colorectal and liver cancer[85].

Janus gold-iron oxide nanoparticles are extremely powerful therapeutic agents for cancer nano therapy due to their dual magnetic and plasmonic characteristics. They serve as effective nano heaters in magneto-thermal hyperthermia (MHT) and photo thermal treatment (PTT). MHT has been found to be efficient at nanoparticle dosages that are high but it does possess some drawbacks due to the absorption by the cells, nevertheless, PTT is gaining more traction at even the lower levels. The combination of MHT and PTT results in a higher quality death of cancer cells, which is less than 5% of cancer cell viability. The magnetic targeting that is used together with the external field enhances considerably the nanoparticle internalization leading to a higher efficiency in vitro for the photothermal treatment. The animals' experiments show that the magnetic guidance leads to improvement of the concentration of the nanoparticles at the tumor sites, which makes it possible to perform PTT with laser power of 0.8 W/cm², 680 nm, that total suppresses the tumor growth. The results of this work present Janus nanoparticles as a possible solution to the problems of nanoparticle delivery and as a way to improve cancer treatment in clinics[86]. The intense electric fields that are always present on the surfaces of the noble metal nanoparticles are responsible for the fact that these nanoparticles have a very high absorption and scattering of the electromagnetic radiation. The extraordinary optical characteristics make it possible to create with the help of these tiny materials the new agents that will be used in the treatment of cancer by rightly combining molecular imaging and photothermal therapy. It is a huge advantage for clinical applications to have the agents that work within (NIR) range (650–900 nm), where the absorption by the tissue is very low and the light can penetrate deeper. The excellent absorption and scattering in the near-infrared spectrum can be achieved by designing the gold nanorods with specific aspect ratios (length-to-width).

The use of gold nanorods as dual-purpose agents for photothermal cancer treatment and targeted imaging was assessed in vitro. Monoclonal antibodies targeting the epidermal growth factor receptor (EGFR), which is typically overexpressed on malignant epithelial cells, were used to attach gold nanorods. The antibody-conjugated nanorods were inserted into three cell lines: two malignant oral cancer lines (HOC 313 clone 8 and HSC 3) and one nonmalignant epithelial line (HaCat). The functionalized nanorods specifically bound to the malignant cells with a higher degree of specificity than to nonmalignant cells because cancer cells have higher levels of EGFR. The very light scattering capabilities of gold nanorods, particularly in the red region, allowed for the unambiguous spotting of malignant cells using dark-field microscopy. To add on, during the continual exposure to 800 nm laser light, the malignant cells almost needed half of the laser energy for thermal ablation in comparison to nonmalignant cells. The results of this study point at the possibility of using gold nanorods as powerful devices not only for imaging but also for killing cancer cells in a selective manner[87].

7.1.2 Medical Diagnostics

Plasmonic biohybrids are used in diagnostics and bio sensing because of their enhanced optical properties, such as surface-enhanced Raman scattering (SERS) and localized surface plasmon resonance (LSPR).

Plasmonic biohybrids can detect biomarkers (e.g., proteins, nucleic acids) at extremely low concentrations, enabling early diagnosis of diseases like cancer, Alzheimer's, and infectious diseases. Gold nanoparticles (AuNPs) functionalized with antibodies can detect cancer biomarkers like prostate-specific antigen (PSA) with high sensitivity[88]. Plasmonic biohybrids are integrated into portable devices for rapid and accurate diagnosis in resource-limited settings. Plasmonic nanoparticles combined with microfluidic chips for detecting pathogens like SARS-CoV-2[89][90].The microfluidic channels precisely control small-volume fluid samples, while plasmonic nanoparticles generate or enhance optical and electrochemical signals when a pathogen is detected.

Funari and et al. developed an opto-microfluidic sensing platform of gold nanospikes fabricated by electrodeposition based on the principle of LSPR, which enables identification of both presence and quantity of antibodies specific to SARS-CoV-2 spike protein present in 1L of human plasma diluted in 1mL of buffer solution in less than 30 minutes. The peak shift in the LSPR wavelength of gold nanospikes, due to a local change in refractive index induced by antigen-antibody interaction, could be associated with the target antibody concentration. This label-free microfluidic platform with a limit of detection of 0.08ng/mL falls within clinically relevant concentrations. They showed that opto-microfluidics technology could enhance serological assays and offer faster, cheaper, and easier quantitative SARS-CoV-2 detection at the point of care[91].

The new *Mycobacterium tuberculosis* (Mtb) diagnostic methods have increased the chances of survival in patients, but still the early detection of the disease is hampered by very expensive instruments; requirement of highly skilled professionals, and low specificity in some laboratory methods. A new biosensor that is low-cost, portable, and user-friendly has been invented for the detection of TB in its early stages. Author Peláez et al. have come up with a novel SPR-based direct immunoassay that does not involve labels to detect and quantify dying and dead cells in treated sputum using monoclonal antibodies attached to a plasmonic sensor. The technique has a detection limit of 0.63 ng mL^{-1} and 2.12 ng mL^{-1} for quantification, which means direct biomarker detection can be carried out without amplification. The analysis of treated sputum discloses a very distinct difference in HspX levels between TB patients (116–175 ng mL^{-1}) and healthy (below the assay’s LOQ)[92]

7.1.3 Therapeutics

Plasmonic biohybrids are used in targeted drug delivery, photothermal therapy (PTT), and photodynamic therapy (PDT).

Targeted Drug Delivery: Plasmonic nanoparticles can be conjugated with drugs and targeting ligands (e.g., antibodies, peptides) to deliver therapeutics specifically to diseased cells. Gold nanorods functionalized with anti-HER2 antibodies for targeted delivery of doxorubicin to breast cancer cells[93].

Photothermal Therapy (PTT): Plasmonic nanoparticles absorb near-infrared (NIR) light and convert it into heat, selectively killing cancer cells. Gold nanoshells used for PTT in glioblastoma treatment[94][95].

Dual plasmonic nanomaterials—gold nanorods and PEG-functionalized MoS_2 nanosheets—were electrostatically bonded with indocyanine green (ICG) to enable combined PDT/PTT under low-power NIR irradiation (0.2 W/cm^2). This hybrid successfully reduced ICG photobleaching. Moreover, a core–shell nanohybrid was designed with AuNRs loaded with ICG as the core, coated with mesoporous silica, and then wrapped with rGO-PEG carrying[96]. Following gold nanoparticles, silver nanoparticles also exhibit tunable surface plasmon resonance across the biologically transparent window (650–1200 nm) with strong light trapping and scattering abilities. Folate-targeted, quercetin-loaded AgNPs (QRC-FA-AgNPs) demonstrated a robust plasmonic response above 800 nm. Under 808 nm NIR irradiation (1.5 W/cm^2, 5 min), quercetin quenching enhanced hyperthermia, promoted targeted endocytosis, and increased breast-cancer cell sensitivity to heat. Similarly, chitosan-coated silver nanotriangles (Chit-AgNTs) showed strong PTT efficacy against NCI-H460 lung cancer cells. Compared with PEG-AuNRs, these AgNTs achieved a higher rate of cancer-cell destruction under identical Ti:sapphire laser irradiation (800 nm), confirming their superior photothermal performance[97].

7.1.3 Medical Imaging

Plasmonic biohybrids enhance imaging modalities such as fluorescence imaging, photoacoustic imaging, and dark-field microscopy.

Photoacoustic Imaging: Plasmonic nanoparticles improve contrast and resolution in imaging, enabling real-time visualization of tumors and blood vessels. Gold nanorods used for photoacoustic imaging of breast cancer[98][99][100]. Strong NIR absorption and scattering is shown by gold nanorods with suitable aspect ratios. Researchers demonstrated their dual role as contrast agents and photothermal therapeutic agents in vitro. Gold nanorods were generated, coupled with anti-EGFR monoclonal antibodies, and injected into cultures of nonmalignant epithelial cells (HaCat) and malignant oral epithelial cell lines (HOC 313 clone 8 and HSC 3). Since there is EGFR accumulation on malignant cells, the antibody-conjugated nanorods particularly bind to these cells with substantially greater affinity. The cancerous cells show strong red scattering from the attached nanorods under dark-field microscopy, making diagnosis and visualisation easy. Malignant cells need about half as much laser energy for photothermal death when exposed to an 800 nm laser as nonmalignant cells[87]. Molecular optical imaging offers real-time, noninvasive identification of biomarkers with subcellular resolution. Since gold nanoparticles provide powerful signals when bound to particular targets, researchers have employed them as optical probes. In order to maximize binding efficiency, a unique conjugation technique is presented in this work to regulate the orientation of antibodies on gold nanoparticles. A heterobifunctional linker—hydrazide-PEG-dithiol—is applied to attach the Fc (nonbinding) region of the antibody directly to the nanoparticle surface, maintaining the antigen-binding sites. By enabling the display of several glycosylated antibodies on a single nanoparticle, this method also facilitates multiplexing. Using this technology, multifunctional nanoparticles can be created to integrate both targeting and delivery components, addressing the difficulty of imaging intracellular biomarkers. It takes about six hours to finish the entire preparation procedure[101].

Fluorescence Imaging: Plasmonic nanoparticles enhance the fluorescence of dyes or quantum dots, improving sensitivity in cellular and molecular imaging. Silver nanoparticles used to enhance fluorescence imaging of cancer cells[102]. $Ag@SiO_2@SiO_2$-RuBpy is a shell fluorescent nanoparticle that exhibits a ~3-fold enhancement in photoluminescence when the RuBpy-infused outer silica shell is placed ~10 nm from the silver core.

These MEF-capable nanoparticles have several benefits: the silica shell reduces self-quenching, enabling higher RuBpy loading; the interaction between RuBpy and the silver core enhances excitation power and fluorescence intensity; and it shields the dye from photodegradation while offering an abundance of hydroxyl groups for bioconjugation.

Using nanoparticles, a quick and sensitive PSA detection technique combining metal-enhanced fluorescence and magnetic separation was devised. Immunomagnetic nanospheres collected PSA, whereas immunofluorescent nanoparticles permitted its detection. With a detection limit of 27 pg/mL, the device produced a robust linear response over 0.1–100 ng/mL PSA[103].

7.1.4 Theranostics

Plasmonic biohybrids combine diagnostics and therapy into a single platform, enabling real-time monitoring and treatment.

Cancer Theranostics: Plasmonic nanoparticles can play dual role of simultaneously taking image tumors and deliver therapeutic agents[104][105][106]. Gold nanoparticles loaded with doxorubicin and imaging agents for theranostics in ovarian cancer[107].Multimodal therapy may be more effective than regular chemotherapy. Based on mesoporous silica-coated gold nanorods, group of researchers has created a dual-responsive nanohybrid for combination tumour treatment. The hyaluronic acid coating allows for both CD44-targeted administration and improved biocompatibility when DOX and the photosensitizer IR820 are co-loaded into the silica pores. When GSH and hyaluronidase are present in 4T1 cells, nanohybrids can break down quickly, guaranteeing adequate intracellular release of medications and photosensitisers. Nanohybrids produce ROS and intense photothermal heating in response to 808 nm NIR irradiation, resulting in a synergistic photodynamic, photothermal, and chemotherapeutic impact. The current technology offers a viable approach for multimodal cancer therapy and demonstrates great antitumor effectiveness both in vitro and in vivo[108].

7.1.6 Antimicrobial Applications

Plasmonic biohybrids are used to combat antibiotic-resistant bacteria and other pathogens.

Antibacterial Therapy: Plasmonic nanoparticles generate heat or ROS under light irradiation, killing bacteria. Silver nanoparticles combined with antibiotics for enhanced antibacterial activity[109][110].

7.1.7 Regenerative Medicine

Regenerative medicine is focused on repairing or replacing damaged tissues. Plasmonic biohybrids are used to stimulate cell growth and tissue regeneration[111].

Tissue Engineering

Plasmonic actuators in tissue engineering offer dynamic mechanical stimulation to encourage tissue development, cell division, and proliferation. These actuators imitate natural physiological conditions by using light as a non-invasive trigger to produce localized stresses or motions in bioengineered scaffolds. This skill is especially helpful for the regeneration of complex tissues, such cardiac muscle or cartilage, where functional recovery depends heavily on mechanical inputs. Their incorporation with biological elements also improves biocompatibility and functioning, providing a flexible platform for the advancement of regenerative therapies and personalized medicine.

Gold nanoparticle (AuNP)-hybrid scaffolds are created by incorporating gold nanoparticles into different scaffold materials to improve their mechanical, electrical, and biological characteristics for use in tissue engineering applications[112]. AuNPs may be integrated into scaffolds utilizing a variety of methods, including generating the nanoparticles in situ inside the scaffold material, depositing them onto pre-formed structures, and embedding them in hydrogels and nanofibers. These scaffolds exhibit considerable gains in mechanical strength, electrical conductivity, and cell adhesion, all of which are required to create environments that closely resemble genuine tissues. The inclusion of AuNPs allows the scaffolds to offer nanoscale anchoring sites, greater mechanical integrity, and increased electrical conductivity, making them ideal for regenerating electrogenic tissues such as cardiac and neural systems.

AuNP-hybrid scaffolds also stimulate stem cell proliferation, differentiation, and maturation, all of which are necessary for the fabrication of functional tissues. Scaffolds implanted with AuNPs, for example, have been demonstrated to promote mesenchymal stem cell development into cardiac and brain cells while also improving the organization and performance of created tissues. The scaffolds' capacity to transfer electrical impulses and induce synchronized cell contractions increases their usefulness in regenerative medicine. These qualities make AuNP-hybrid scaffolds useful tools in tissue engineering, addressing issues such as scaffold stability, mechanical flexibility, and effective cellular contact. As a result, they have considerable potential to further regenerative treatments and therapeutic applications.

8. Conclusions

This article highlights the potential of plasmonic materials in biohybrid actuators for soft robotics. By combining biological adaptability with engineered responsiveness, these systems offer groundbreaking solutions in biomedical, environmental, and industrial applications. Future research will address challenges related to scalability, biocompatibility, and energy efficiency, paving the way for the next generation of soft robotic technologies.

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