

Review Article

Biomaterials in Medicine: Current Trends and Future Directions

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Abstract

Contemporary medicine relies significantly on biomaterials as essential elements across various applications. From polymers and ceramics to metals and hydrogels, these materials enable innovations in implants, drug delivery systems, and tissue engineering, ultimately enhancing patient care and treatment outcomes. In this review, we explore current trends in biomaterials and their applications, emphasizing recent innovations, particularly in biocompatibility, biodegradability, and functionality. We also discuss emerging technologies such as 3D printing, smart biomaterials and nanotechnology, which are transforming the field of biomaterials. Furthermore, we identify challenges and opportunities in biomaterials research, highlighting potential future directions. The integration of biomaterials with cutting-edge technologies has opened new avenues for personalized medicine, regenerative medicine, and targeted therapies. This review seeks to bridge the gap between biomaterials research and clinical applications, providing insights into the latest developments and future prospects. By exploring the current landscape of biomaterials, we aim to inspire further research and innovation in this rapidly evolving field. Ultimately, this review will contribute to the advancement of biomaterials and their applications, improving patient outcomes and shaping the future of medicine.

Keywords

Biomaterial, Drug, Tissue, Biocompatibility, Biodegradable, Nanotechnology, Medicine, Patient

1. Introduction

Regenerative medicine continues to grow as a revolutionary field with the potential to restore functionality to damaged organs and tissues. Using biomaterials is at the center of this discipline. For medical purposes, biomaterial substances have been engineered to interact with biological systems. Biomaterials are important in supporting regeneration of tissues, improving healing processes, and delivering therapeutic medicine, and emphasizing on the latest advancements and applications, as well as future directions [1]. Biomaterials fall

into different categories depending on their origin, function, and composition. They can also be drawn from natural sources like proteins, polysaccharides, and biomolecules or synthesized artificially, for example, metals, polymers, or ceramics. Thus, choosing a particular biomaterial is crucial since it significantly influences biodegradability, biocompatibility, functionality, and mechanical properties [2].

The essential role of biomaterials in the human body stems from their strong biocompatibility, which enables them to be

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used without provoking resistance. Biomaterials are available in different forms. They can be naturally found as polysaccharides and dextran or can be synthesized such as polypropylene or polyurethanes [3]. Mostly biomaterials are polymers, but they can also be metals such as titanium which has numerous applications, especially in prostheses functions. Regardless of their form, all biomaterials are capable of interacting with living tissues passively or actively which allowing them to be prime candidates for advancing medical services. [4]. Nowadays, researchers have increased their activities around biomaterials as evidenced by the significant advancements made in biotechnology, chemistry, medicine, and biology. This motivation comes along with the ability of biomaterials to be flexible in adapting to desirable products.

Biomaterials serve as foundational elements in tissue engineering, providing scaffolds for cell growth and tissue regeneration (Figure 1, tissue engineering process) [5], which is crucial for healing injuries and addressing degenerative diseases.

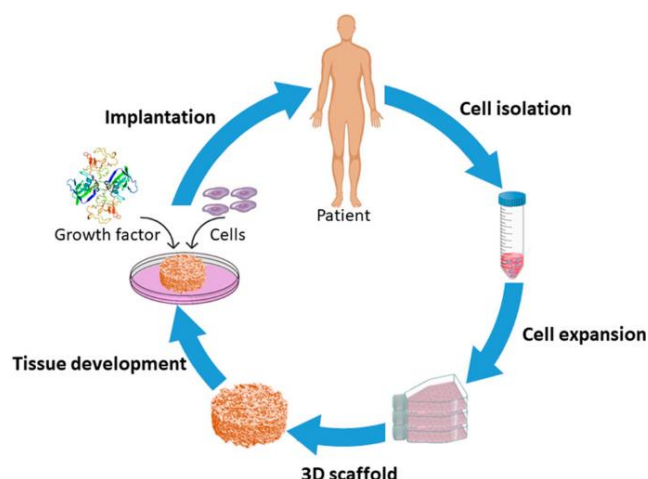


Figure 1. Schematic diagram illustrating the stages involved in culturing cells on a scaffold for tissue engineering applications [Farag et al. 2023].

These devices are developed from materials such as metals, ceramics, an array of composites, and polymers. The use of biomaterials has been on the rise due to improvements in surgical skills and knowledge about how they interact with the body. In addition, the biocompatibility of these materials is an issue that influences the effectiveness of the application of these materials.

Every year, thousands of people globally experience an improvement in the quality of their lives resulting from implanting devices in their bodies [6]. Some of the implants can be artificial hips, pacemakers, knee and finger joints, heart valves, and arteries. Biomaterials also enable advanced drug delivery systems that optimize medication efficacy while minimizing side effects. Particularly, biomaterials have improved the efficacy and delivery of various pharmaceutical

compounds like drugs, peptides, antibodies, and enzymes [7]. The physicochemical biomaterial properties, and their designed or intended administration route can be tailored systematically to maximize therapeutic benefits. Biomaterials also enhance injectable and oral drug delivery as common drug administration modes, while identifying new avenues for delivering drugs like ocular, pulmonary, transdermal, and nasal routes [8].

As showing in Figure 2, specialized biomaterials in wound healing promote faster recovery and reduce infection risks. Additionally, they play a critical role in diagnostics, improving the sensitivity and specificity of tests. Innovations in personalized medicine are also driven by biomaterials, allowing for customized treatments that enhance patient outcomes.

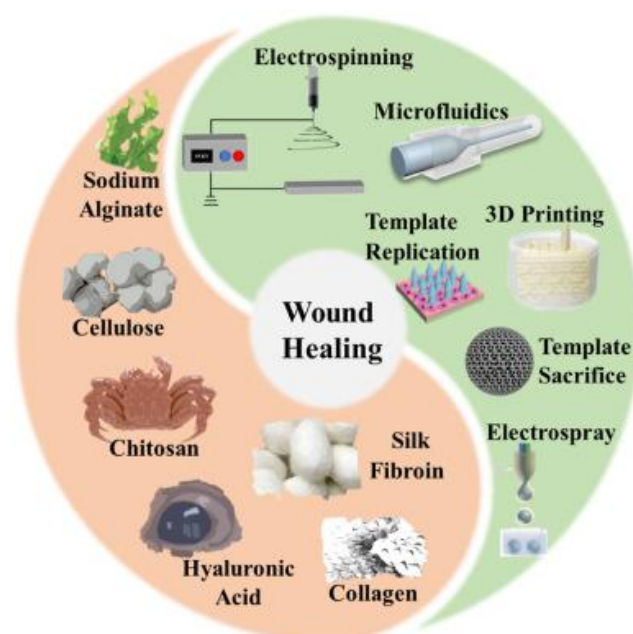


Figure 2. Specialized Biomaterials in Wound Healing for Faster Recovery.

2. Current Trends in Biomaterials

Biocompatibility and Bioactivity

A lot of attention in biomaterials research has been concentrated on biocompatibility. According to Huzum et al., biocompatibility is a key factor of consideration in regard to biomaterials and is defined as the ability of the biomaterial to function as intended in medical therapy without causing undesirable effects on patients [9]. The biocompatibility concept has advanced to include bio-functionality, biostability, and bio-inertia. New biomaterials should possess high biocompatibility as this ensures that they are highly effective as implants. At the height of research on biocompatibility, a spectrum of various in vitro and in vivo tests that investigate cytocompatibility, carcinogenicity, genotoxicity, hemocompati-

bility, irritation, and acute and chronic toxicity are recommended. Another trend has been in the bioactive glass scaffolds that are developed targeting bone tissue regeneration and the treatment of osteomyelitis and cancer [10]. Therefore, there is a growing interest in more research on the biocompatibility and bioactivity of biomaterials due to their potential to impact the medical field positively.

Biodegradable Materials

Due to their remarkable properties, there has been an increasing interest in biodegradable polymers because of their suitability in the scientific field such as material and tissue engineering. The number of diagnosed ailments and conditions has increased at an alarming rate leading to an increased interest in biodegradable polymers as they hold a significant potential in application [11]. In addition, there has been an increase in the use of biodegradables in the field of biomedicine. This is because of the improvement and utilization of old and new techniques that facilitate the production of biodegradable materials that possess the desired properties like controlled rate and time of degradation, mechanical strength, and antimicrobial and antimicrobial factors. Moreover, the ability of these materials to assume the desired shape via appropriate design has contributed to the increasing interest in research and the use of biodegradable materials [12]. These properties are preferred when there is a need to develop new structures that contribute to restoring the optimal functionality of human systems.

Multifunctional Biomaterials

Tissues in the human body can self-regenerate. This function can be altered when the body suffers an injury, gets a disease attack, or starts to age. Examples include the skin, liver, and gut lining. Particularly, the liver can remarkably regenerate following a partial removal or damage; other tissues include the gastrointestinal tract and bone marrow [13]. Non-injured tissues regenerate over time as available and new cells replace expended cells. In such cases, biomaterials are required to guide tissues to regain their normal biological functions and structure [14]. Biomaterials act as a structural frame that favors the attachment of host cells during the regeneration process and supports stem cell migration and differentiation into their proper tissue-specific type of cells. As a result, this is evidence that biomaterials are used for multiple purposes such as tissue engineering and drug delivery. Biomaterials are preferred because of their adaptability to various variations like pH, light, or temperature [15]. These properties and capabilities prompt the use of biomaterials in various applications like treating complex diseases and tissue engineering rendering them multifunctional.

3. Emerging Technologies in Biomaterials

Advancements in biomaterial technology present new opportunities following scientific success in tissue engineering. The success has seen the development of tissue engineering products in the medical field. Biomaterials are preferred be-

cause they are easily crafted to the desired shape similar to the natural extracellular matrix, which makes them a preference due to their ability to mimic 3D stimuli needed to support adequate tissue functionality in both vivo and vitro tests [16]. Moreover, scientific innovations have also led to the development of biodesign of nano biomaterials that are important in cell functioning control. Smart biomaterials continue to gain more recognition due to their significance in the development of biomaterials that recognize stimuli and perform specialized tasks in modern medicine [17]. These technological innovations have played a significant part in the advancement of modern medicine and in changing people's lives.

3.1. 3D Printing



Figure 3. Using 3D printing technologies to create three-dimensional complex structures [Minds et al. 2017].

The 3D printing technology has restructured biomaterial processing leading to the development of complex structures characterized by high precision and resolution (an example of 3D printed heart Figure 2 [18]). Technology has facilitated the production of various biomaterials like ceramics, polymers, composites, and metals [19]. In addition, 3D printing technology has supported the production of 3D structures in a manner that is easy to control composition and reduce wastage. By relying on tissue engineering and regenerative medicine, the application of 3D printing technology has the potential to produce patient-specific implants and scaffolds hence supporting personalized medicine [20]. Recent 3D printing technology has led to the development of dental molds, scaffolds for tissue regeneration, prosthetic parts, surgical models, craniofacial implants, and new drugs. With the help of computed tomography (CT) and magnetic resonance imaging (MRI), 3D physical models are developed layer by layer without the need for any tools, fixtures, or dies but relying on the produced patient pictures [21]. Moreover, the technology has facilitated the incorporation of more materials with different properties hence leading to the im-

provement of biomaterials mechanically and in terms of biocompatibility.

3.2. Nanotechnology

Nanotechnology has become an integral part of modern medicine through the development of nano biomaterials that are in high demand in biomaterials engineering, especially in the disciplines of drug delivery, bone replacement, cardiovascular treatment, and tissue regeneration [22]. Generally, polymers, advanced composites, ceramics, and hybrids have gained popularity due to their desired properties like mechanical durability and biocompatibility. However, research is in high gear in investigating different ways of improving the properties of biomaterials in attempts to minimize toxicity while incorporating smart features that facilitate the creation of a new generation of biomaterials with exceptional properties. Through nanotechnology, it has become possible to develop a variety of new biomaterials whose properties are borrowed from synergistic effects originating from the matrix and nanomaterials [23]. The nanotechnology has become crucial in developing advanced biomaterials that are non-toxic, biocompatible, and mechanically fit. Moreover, the technology has made it easy to fabricate biocomposites and biomaterials which is an improvement from the traditional methods that used animal tissues. The use of nanoparticles has become crucial in targeted drug delivery and this improves therapeutic effectiveness by minimizing side effects [24]. Nanoparticles in biomaterials are also used in coloured cornea replacement, as bone cement, and in wound healing depicting their significance in medicine.

3.3. Smart Biomaterials

Since the concept of tissue engineering picked momentum, smart biomaterials have increasingly been advancing in research and application. Their role in novel tissue morphogenesis supported by biomaterials cannot be overlooked as they facilitate interactions with human cells [25]. The application of smart biomaterials has positioned its development as a promising innovation that can restructure how injuries and diseases are treated. They draw their strength from their ability to respond to the surrounding environment hence facilitating their controlled interaction with biological systems. In addition, smart biomaterials occur in two variances; those that can respond to chemical stimuli and others that can respond to physical stimuli [26].

Smart biomaterials respond to external stimuli like light, temperature, or pH making them flexible and versatile for different applications. Particularly, hydrogels that shrink or swell as they react or respond to environmental changes can be used for releasing controlled drug. These materials are effective for facilitating regenerative therapies, and allow tailored reactions and responses to the biological setting or environment. The biomaterials field has benefitted significantly from nanotechnology by enabling the development of nanoscale materials, which possess outstanding and unique properties [27]. Nanofibers, nanoparticles, and nanotubes can improve the biomaterials' mechanical strength and biological performance. As shown in Figure 3 below, adding silver nanoparticles into dressings can offer antimicrobial properties into dressings resulting in antimicrobial properties. At the same time, the electrospun nanofibers can mimic the natural ECM structure promoting growth and cell adhesion.

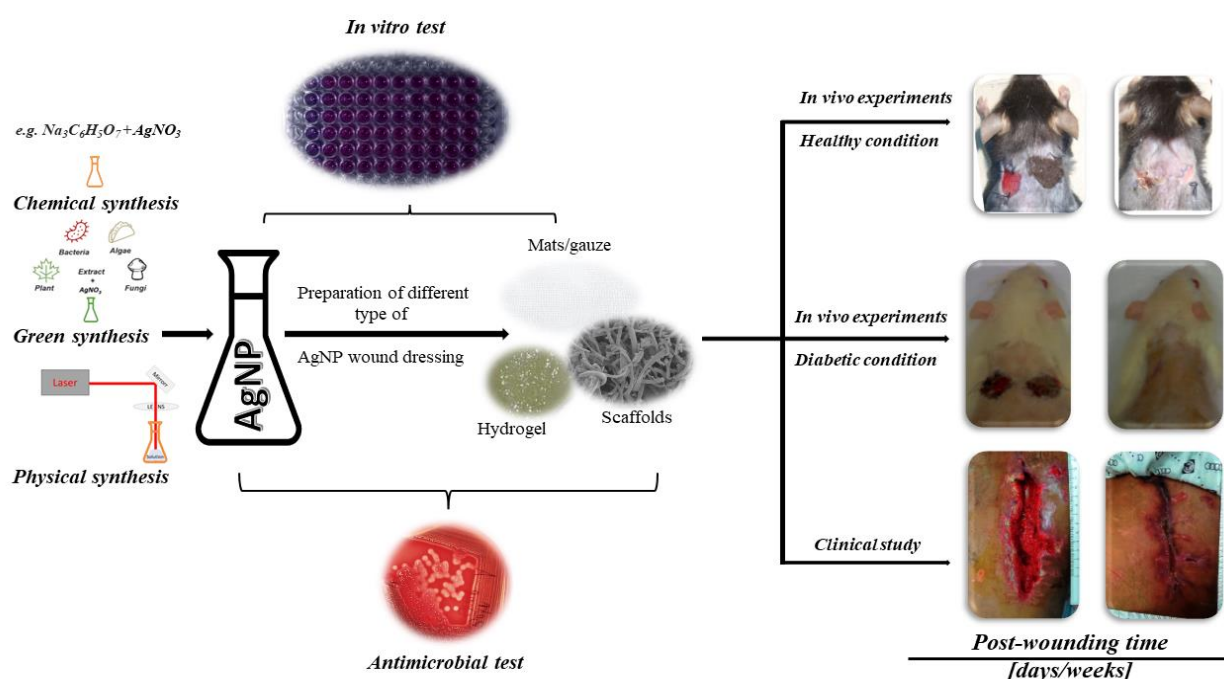


Figure 4. Wound Dressing with Silver Nanoparticles.

Chemical-responsive biomaterials play a crucial role in revolutionizing medicine since they respond to controlled environments like pH, ions, and enzymes. Following this property, they can be designed to respond to stimuli by releasing drugs, a role that is reliable in treating tumors and cancer through drug delivery since pH is usually lower in the affected organs than in healthy tissues. In other words, smart biomaterials are used in drug delivery owing to their ability to respond to changes making them a perfect option for treating complex diseases like cancer and tumors [28]. Moreover, smart biomaterials have the potential to detect biomolecules like cholesterol and biomolecules through biosensors. They are also used to create implants that can respond to body changes like temperature. The evolution of smart biomaterials has yielded huge potential and has revolutionized injuries and disease treatment.

4. Analysis of Emerging Technologies in Biomaterials

Integrating functionalized biomaterials with emerging technologies like nanotechnology, 3D printing, biomaterials and microfluidics, among others, present a range of benefits for developing complex tissue designs with extensive applications in tissue or cell engineering, vitro tissue, and regenerative medicine [29]. Particularly, by examining 3D printing extensively, it is evident that the success of implants, for example, depend on the biomaterial type used for fabrication. For example, an implant material should be inert, biocompatible, can be moulded, and mechanically durable. Managing to develop implants specific to patients before incorporating it within the cells, bioactive drugs, and proteins have shown the revolutionary nature of 3D printing as an emerging technology.

Given the chemical nature of substances, biomaterials necessary for 3D printing falls into specific categories like polymers, composites, and allows. At the same time, these 3D printing biomaterials should be printable with tunable rates of degradation, while also being able to mimic living tissues [30]. Biomaterials with mechanism to facilitate 3D printing depends on the product application. Particularly, biomaterials used for dental or orthopaedic applications should demonstrate high level of mechanical stiffness and prolonged rates of biodegradation. Contrastingly, for visceral or dermal applications, the biomaterials used should be highly flexible, and with faster rate of degradation.

Working with biomaterials involves carefully analysing and manipulating living tissues and artificial materials for replacement or repair, and biological system improvement. Thus, nanotechnology facilitate creation of tools, which work at nano level. Nanoscale materials like nanowires, nanoparticles, and carbon nanotubes have specific and unique nanoscale properties that include more surface area, and enhanced interactions, especially with biological systems [31].

As shown in Figure 4, combining biomaterials with nanomaterials result in the development of synergistic effects that result in enhanced functionality and improved properties for medical applications. Diverse applications include drug delivery, tissue regeneration, biomedical devices, biosensors, and antimicrobics and anticancer applications.

Smart biomaterials are crucial in medicine. Guiding stem cells to improve the regeneration levels of tissues depends on smart biomaterials. There are numerous applications in reengineering; these applications facilitate release of cells and encapsulate, but in a controlled way, which result in the development of a smart drug system for delivery. At the same time, exhibiting a change in their chemical or physical properties in response to internal environmental change or external stimulus [32]. Smart biomaterials exhibit specific response mechanisms key to their application like pH-responsive, stimuli-responsive hydrogels, or temperature-sensitive.

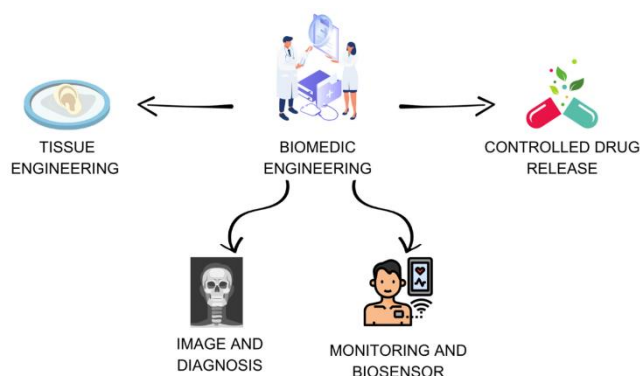


Figure 5. Biomedical Approach of Nanotechnology.

5. Future Directions

Biomaterials have revolutionized medicine to a great extent. Despite these improvements, there are existing challenges that are a hindrance to the utilization of biomaterial's full potential. In the future, more advancements will be made in the drug delivery system, drug transformation, and enhancing the diffusion properties of drugs. In addition, future developments will see the creation of polymers with specific roles like in vaccines. Such developments will help in preventing disease attacks and in eliminating some of the diseases. Future developments will also facilitate the enhancement of personalized medication through the creation of computer-aided orthopaedic materials. Computer-aided orthopaedic materials comprise custom implants and devices designed and tailored to the specific needs and anatomy of the patient. Some of these materials also fall under the 3D printing category where materials like stainless steel, titanium, and polymers apply in orthopaedics [33].

5.1. Integration of Artificial Intelligence

Artificial Intelligence (AI) and machine learning (ML) applications have penetrated different industries including the biomaterial field. According to Gokcekuyu et al., AI and ML have become integral in predictive modelling. Researchers train algorithms to predict the characteristics and behaviors of biomaterials by using extensive datasets. A good example is where AI through ML can be trained to predict biocompatibility and the rate of degradation of a biomaterial. AI reduces the time wasted and high costs associated with trial and error by predicting the selection of biomaterials appropriate for specific purposes [34]. The integration of AI in biomaterial technology is a promising venture that might accelerate the innovation and discovery of new designs and materials to meet specific needs.

5.2. Regenerative Medicine

Regenerative medicine is a field that has gained popularity due to its incorporation of biomaterial in replacing and restoring injured or damaged tissues. Moreover, regenerative medicine has laid a strong foundation for the advancement of stem cell research that is applied in treating diseases [35]. In the future, regenerative medicine will lead to breakthroughs in treating pathologies that have remained a mystery to humans. Further, regenerative medicine will play a crucial role in navigating hurdles in medicine that are experienced due to ethical practices and hence come up with solutions that do not violate humanity or go against healthcare ethics [36]. The future of regenerative medicine is bright and it holds undeniable potential for treating degenerative conditions such as cardiovascular diseases, diabetes, hypertension, osteoarthritis, and diabetes. These are chronic diseases that affect many people in the world and a breakthrough using regenerative medicine will be a win in the medicinal discipline.

5.3. Personalized Medicine

Personalized medicine is a concept that has been gaining popularity. The use of biomaterials will facilitate the development of tailor-made healthcare services that meet individual patients' preferences. Biomaterials contribute immensely toward precision medicine which bases its approach on a patient's lifestyle, genes, and environment [37]. The population is divided into scientific stratifications that are classified into subpopulations based on data in a bid to provide the right medication that matches their phenotype. Moreover, through the use of AI in biomaterials, it has become easy to predict behaviours, reactions, biocompatibility, and degradation rates of biomedicine, an approach that has supported personalized medicine [38]. As a result, patients can receive treatment that matches their body requirements hence reducing the chance of body resistance and rejection.

6. Conclusion

Biomaterials have been on the front line of stimulating medical innovations and improvements in patient care and treatment. The trend has been shifting towards achieving higher biocompatibility, developing biomaterials that are multifunctional, and attaining biodegradability. Moreover, the incorporation of technology like 3D printing, AI, ML, and nanotechnology is expected to revolutionize the biomedical field. In addition, technology will enable the attainment of personalized medicine, a concept that has been gaining momentum. Lastly, the biomaterial field is promising to enhance patient outcomes through the application of innovative and creative therapies.

Abbreviations

CT	Computed Tomography
MRI	Magnetic Resonance Imaging
AI	Artificial Intelligence
ML	Machine Learning

Author Contributions

Fahad Alshabona: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing

Ahmad Fallatah: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing

Ibraheem Redhwi: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Resources, Software, Validation, Writing – original draft, Writing – review & editing

Conflicts of Interest

The authors declare no conflicts of interest.

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Biography



Ibraheem Redhwi is a senior researcher at King Abdullaziz City for Science and Technology (KACST), Advanced Material Institution. He completed his PhD in Nanomanufacturing from Iowa State University in 2021, and his Master of Engineering in Robotics from the Vanderbilt University in 2015. Over the last 14 years, Dr. Ibraheem has been working in many research projects that contribute to several mechanical engineering fields with KACST, Vanderbilt, and Iowa State University. In addition, he participated in many collaborations in the United States and Saudi Arabia. His experimental work contributes also and some mechanical engineering fields in addition to other fields like electrical engineering, education, and management.



Fahad Alshabouna earned his undergraduate degree in chemical engineering from King Saud University (KSU), where he also completed a master's in polymer engineering. Acknowledging his capabilities, he pursued further studies at Imperial College London, obtaining his PhD in the bioengineering department. His doctoral research centered on creating thread-based wearable and implantable sensors for healthcare applications. Currently, at King Abdullaziz City for Science and Technology (KACST), Fahad is involved in various research projects, including water treatment and desalination, the development of innovative polymeric materials, and 3D printing technology, with a primary emphasis on creating healthcare devices.



Ahmad Fallatah is a senior researcher at the Future Mobility Institute of King Abdullaziz City for Science and Technology (KACST). He earned his Master's Degree in Mechanical Engineering from University of Dayton in 2015, then he completed his Ph.D. in Mechanical Engineering from Iowa State University with a focus in Material Science, Biosensor, and Photoelectrochemical measurement in 2022. He has made significant contributions to research in Biosensing using metal oxide nanomaterials to detect several analytes: glucose, cholesterol, lactic acid, and pesticides. As well as his contribution to photoelectrochemical water splitting to produce hydrogen gas from water with the help of solar energy using the metal oxide nanomaterials.

Research Field

Ibraheem Redhwi: Robotics Systems, Mechatronics devices, Nanomanufacturing, Material Science, Additive Manufacturing, Composite Materials, Mechanical Components Design, Finite Element Analysis

Fahad Alshabouna: Water Desalination, Water Treatment, Membrane Fabrication, 3D printing, Implantable, Wearables, Nanocomposite materials, Conducting Polymers

Ahmad Fallatah: Material Synthesis, Nanomaterials, Electrodeposition, Biosensor, water splitting, Renewable Energy, Hydrogen Production, Food Safety, Photocatalysis