

# Classification Of Biomaterials and Their Applications

Noor M. S. Mahdi\*<sup>1</sup>, Ayad K. Hassan<sup>1</sup>, Fatima J. Al-Hasani<sup>1</sup>, Waleed Ameen. Mahmoud Al-Jawher<sup>2</sup>

<sup>1</sup> College of Material of Engineering, University of Technology, Baghdad, Iraq.

<sup>2</sup> College of Engineering, Uruk University, Baghdad, Iraq

[noor22199090@gmail.com](mailto:noor22199090@gmail.com)

**Abstract** Biomaterials, designed to interact with living systems, play a vital role in various medical applications. Classifying these materials effectively is crucial for understanding their properties and ensuring optimal use. Biomaterials are classified based on their chemical composition, structure, and properties relevant for biological applications. In this paper five types of Biomaterials classification methods are given namely. Chemical, Functional, Source of biomaterials, Structural and Smart levels classification. Each of these five-biomaterial classification method offers unique advantages and disadvantages. Chemical Classification is simple and well-established method, easy to understand and interpret and provides a basic framework for material identification. Functional Classification is directly related to the application of the biomaterial, provides insight into the desired material properties and useful for identifying materials for specific therapeutic needs. Source-Based Classification is straightforward method based on material origin and can be useful for initial categorization and understanding general material properties (e.g., natural materials often biocompatible). Structural Classification provides information about material properties like strength, degradation, and permeability and can be relevant for understanding biocompatibility and material performance. Smart Level Classification captures the advanced functionalities of next-generation biomaterials, provides insights into targeted drug delivery or controlled cell interactions and useful for identifying materials for specific therapeutic applications. The most suitable method depends on the specific context and information needs.



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## 1. INTRODUCTION

Biomaterials represent the materials that can be interaction with biological system to achieve specific function. Biomaterials classification is crucial due to the diverse applications of biomaterials in medical devices and implants, ranging from orthopedic devices to drug delivery systems [1] [2]. The classification of biomaterials into categories such as bio-ceramic, polymeric, and metallic is essential for selecting materials that are biocompatible, bio-inert, and suitable for specific medical uses [1][3]. Understanding the physicochemical properties of biomaterials, such as their ability to induce cellular reactions like multinucleated giant cells (MNGCs), aids in assessing their integration within host tissues and their suitability for bone and soft tissue implantations [4]. Moreover, advancements in biomaterials design aim to minimize adverse biological responses and enhance tissue regeneration by creating materials that interact specifically with biological elements and systems [2]. Therefore, biomaterials classification plays a vital role in ensuring the safety, efficacy, and success of medical interventions involving biomaterials.

In 2021, Carolina Montoya, redefinition of the term “Smart Biomaterial” and discusses recent advances in and applications

of smart biomaterials for hard tissue restoration and regeneration. To clarify the use of the term “smart biomaterials”, we propose four degrees of smartness according to the level of interaction of the biomaterials with the bio-environment and the biological/cellular responses they elicit, defining these materials as inert, active, responsive, and autonomous. The paper's final conclusion underscores the transformative potential of smart biomaterials in shaping the future of healthcare. By redefining the concept of smartness in biomaterials and exploring novel applications in tissue engineering, researchers are paving the way for innovative treatments that have the power to revolutionize patient care and improve clinical outcomes. [5]

In 2022, Arjunan, Arun Baroutaji, Ahmad Praveen, Ayyappan S Robinson, John Wang, Chang, introduces the need for classifying biomaterials based on their functionalities to aid in safety, performance, and application selection, accommodating both traditional and emerging biomaterials. It highlights the challenges in biomaterial selection due to current classification methods based on composition, emphasizing the importance of a functional classification framework for meaningful categorization. The paper emphasizes the importance of a functional classification framework for biomaterials to address challenges in selection, evaluation, and use. Also the

classification of biomaterials based on their biocompatibility classes and performance requirements is essential to ensure their safety and effectiveness in clinical use. Overall, the paper underscores the need for refined classification systems and practical reforms focused on biomaterial functionalities to enhance their clinical utility and regulatory compliance.[6]

This paper showing the methods of classification biomaterials and literature review about works done in this field. This paper dependent on different literature review that explain different method to classify biomaterials. This work has collected several branches of classification methods for biological materials and outlined the basic points of each classification. Smart biomaterials were also clarified, how they are classified, their importance, and the most important previous literature on these materials. The applications of smart biomaterials and their importance in this field were explained. Finally, future studies were proposed regarding applications for smart biomaterials.

The main aims of this paper are:

- i. Showing methods of classification of biomaterials
- ii. Explain what smart biomaterials is?

## 2. METHODS OF CLASSIFYING BIOMATERIALS

The classification of biomaterials is essential for understanding their properties, applications, and potential limitations. The main classification systems for biomaterials: Chemical Classification, Functional Classification, Source Classification, Structural Classification, and the newest way to classified according to level of smartness. In addition to the four main classification systems described above, there are also several other classification systems that can be used to categorize biomaterials. These include classification based on processing methods, application areas, and regulatory requirements. The field of biomaterials is constantly evolving, and new materials with novel properties are being developed all the time. As a result, the classification systems for biomaterials are also likely to continue to evolve in the future.

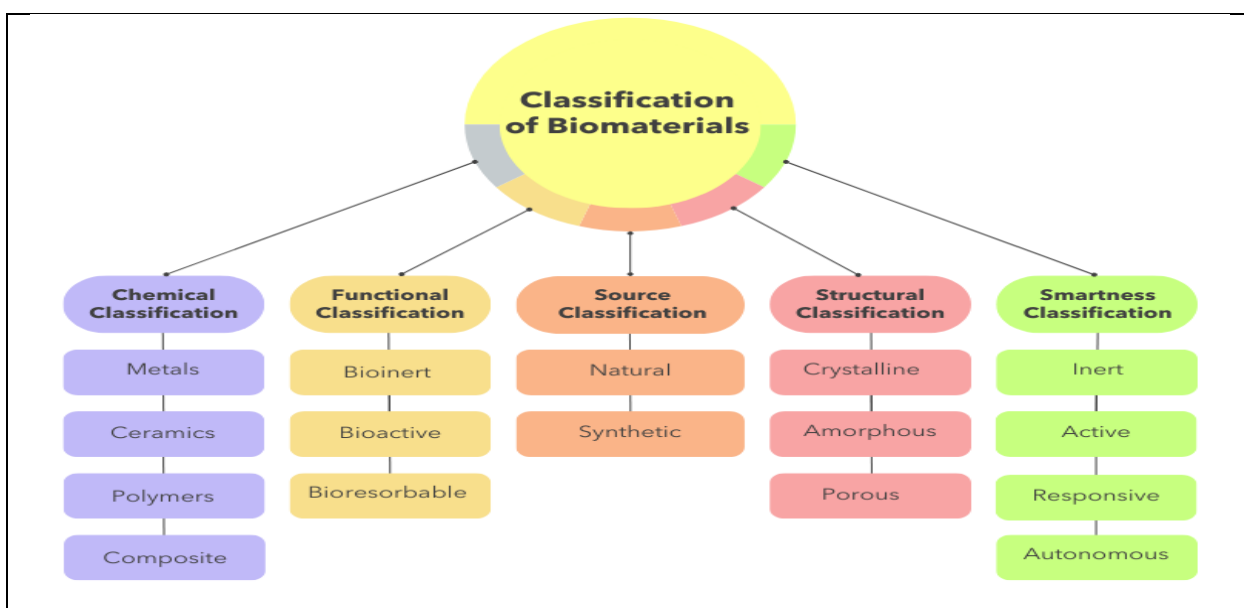


Figure 1: classification methods

### 2.1 chemical classification

Biomaterials are classified based on their chemical composition into different classes such as metal, ceramic, polymer, and composite materials [1][7]. Metals are primarily chosen for their mechanical load-bearing properties, while biopolymers are valued for their flexibility and biocompatibility, making them excellent options for biosensor development. Ceramics, polymers, and metallic biomaterials are extensively used in medical devices and implants, with each having its own set of advantages and disadvantages, such as

biocompatibility and mechanical properties [1]. The evolving functionalities of biomaterials are crucial in their classification, as they are expected to be multifunctional, customizable, and biologically active, posing challenges in selection, evaluation, and regulation.

#### Metals:

Metal is used as biomaterial due to its mechanical qualities and biocompatibility. Examples of such metals include liquid metals, titanium alloys, cobalt-chromium alloys, and stainless

steel. These materials possess properties such as high strength, ductility, and corrosion resistance, making them suitable for long-term implanted medical devices. Liquid metals have unique properties like high thermal and electrical conductivity, flexibility, and flowability, which makes them suitable for various biomedical applications, including drug administration, biosensors, tumor therapy, and bio-imaging. [8].

**Ceramics:**

Ceramic biomaterials are appropriate for use in biomedical applications due to their mechanical characteristics, biological functioning, and biocompatibility [9]. Applications in dentistry, regenerative medicine, orthopedics, and joint replacements, including implants for the hip, knee, and shoulder, as well as dental implants, are central to these fields [10]. Osteogenic ability and bioresorbability are the primary attributes that should be prioritized and developed for the regeneration of bone tissue [10] [11]. Bioactive ceramics can also be used in implants to improve tissue integration and biological reactions, which emphasizes how crucial it is to choose materials with the right physical, chemical, and biological characteristics for efficient body absorption.

**Polymers:**

Polymeric biomaterials play a crucial role in various biomedical applications due to their tunable physicochemical

characteristics, controlled degradation, and good biocompatibility. These materials are versatile building blocks that can be used in composite materials to enhance tissue repair and organ functionality in medical implants and equipment [12][13]. The development of smart polymers, including shape-changing and shape-memory polymers, has garnered significant interest in biomedicine, especially for minimally invasive surgeries and antimicrobial technologies[13]. Multifunctional polymeric nanomaterials can also be used for drug delivery and tissue engineering. Overall, Polymeric materials are highly scalable in various biological fields such as implantable bioelectronics devices, bio-printing, and soft robotics. [14].

**Composite Biomaterials**

Composite biomaterials are essential to medical applications, because it's proved combination of properties that individual materials may lack. The composite material consists of matrices reinforced with particles to achieve strength and functionality. [15] [16]. Furthermore, composite materials improved fabrication scaffold with high resistance to degradation and long-term 3D-structure. this is achieved by the development of versatile and mechanically tunable composite biomaterials, that combine natural and synthetic components [17].

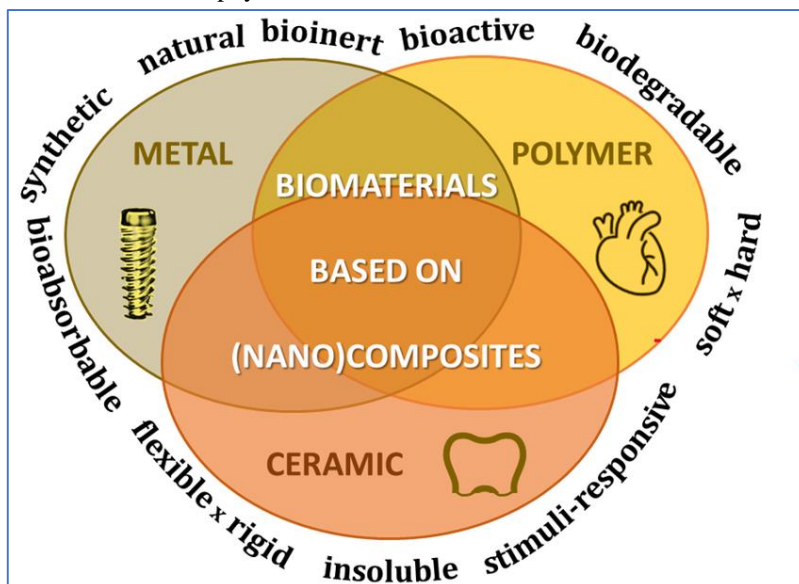


Figure 2: classification biomaterials according to type of materials

**2.2 Functional Classification**

Biomaterials can be classified according to tissue response into bio-inert and bioactive materials, which is very important because it determines how the implant interacts with surrounding tissue [18]. Bio-inert materials such as stainless steel and titanium show minimal interaction with tissues. Bio-

inert relies on mechanical integration and the generation of fibrous capsules around the implant [18]. Bioactive materials like hydroxyapatite actively interact with bone tissue. It makes surface modifications to enhance the formation of a bone-like layer called carbonate apatite, on their surface [18]. These materials actively bond with bone, enhancing their

biocompatibility and biological response, which is essential for successful tissue repair and integration of implants [19].

**Bio-inert Materials:**

Bio-inert materials do not provoke an immune response, which makes them essential for implants intended for long-term placement inside the body [20]. Assessing biocompatibility requires understanding how the immune system responds to biomaterials [21]. The effectiveness and longevity of medical implants depend largely on the body's immune response, which can have both pro- and anti-inflammatory effects [22]. Additionally, biomaterials interact with the body's immune system, so it is important to consider physicochemical aspects such as size, shape, charge, and biodegradability to modify immune responses and achieve positive treatment outcomes, especially in the case of ocular diseases [23].

**Bioactive Materials:**

When it comes to enhancing tissue growth and adhesion to bone or other tissues, bioactive materials like (hydroxyapatite, bioactive glass, and soft biomaterials) are essential. Advantages of these materials include specific immune responses, regulated release of bioactive compounds, and responsiveness to pH and temperature variations in the environment [24]. For example, research has demonstrated that bioactive glasses can hasten skin regeneration, promote angiogenesis, and help build a calcium-phosphate-like layer on hard tissues, which in turn promotes bone mending [25]. Furthermore, bioactive particles have been included in zinc-based composites to customize the rate of zinc corrosion, showing improved strength and good dispersion of second-phase particles [26]. Furthermore, research on restorative materials with bioactive properties for dentin coverage has

shown promising bioactivity potential in various in vitro studies, highlighting the current trends in bioactive materials development [27].

**Bioresorbable Materials:**

Biodegradable electronics, orthopedics, dentistry, and drug delivery systems are just a few of the several industries that use bioresorbable materials, which the body gradually breaks down. [28][28] [29]. These materials provide a considerable benefit in drug administration and temporary implant applications since they may degrade and be absorbed by the body over time. Polymers, ceramics, metals, and intelligent micro-nano materials are among this class of materials[30][31].

A range of bioresorbable materials has been studied for their biocompatibility and degradability in the search for ways to improve medical interventions and minimize their side effects. Some of these include iron, magnesium alloys, zinc alloys, gelatin, chitosan, and calcium phosphate. [32][29]. Development of bioresorbable materials and their fabrication technologies like 3D and 4D printing could benefit the area of temporary implants as well as drug delivery systems, which can facilitate the introduction of new medical treatments and body-implants that would dissolve or disappear from the system, over time.[31].

The functionality and long-term impact on the body of an implant application determines the choice of biomaterial to be used. It is often best to use bioinert materials where there is a need for stability over a long period compared with alternative materials that have advantages when it comes to supporting bone formation and tissue regeneration like bioactive or bioresorbable ones.[33]

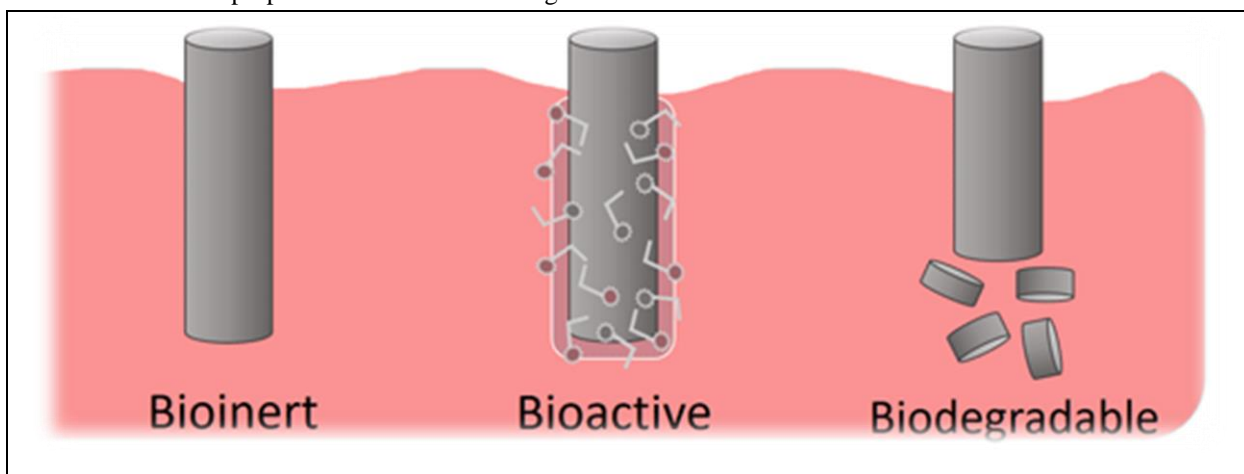


Figure 3: classification biomaterials according to tissue response

**2.3 source of biomaterials**

Biomaterials can be divided into categories based on their origins, i.e. natural or synthetic. There are a lot of investigations

that emphasize the importance of classification systems in diverse areas like domain adaptation in motor imagery EEG-based brain-computer interfaces. [37] brain source functional connectivity study [36] environmental protection [35], and digital security [34][37].

This research employs domain adaption techniques, hierarchical classification systems and machine learning algorithms to efficiently classify sources. Highlights of different strategies employed for categorization with examples in a variety of Application domains, Deep learning method used for tiredness detection in EEG & K-nearest neighbor algorithm based on environmental source apportionment. Using these techniques, scientists can differentiate between lab-generated biomaterials and naturally derived ones from living organisms like plants or animals. Here, a large study provides complete details which can be exploited in both understanding and application of features of biomaterials for various purposes. That is, natural biomaterials are live organism or their product-induced materials with well-defined medicinal and diagnostic applications[38][39]. Natural biomaterials and their applications have been used since the ancient civilization of Greeks and Romans Natural biomaterials and their applications have been used since the ancient civilization of Greeks and Romans [39]. Showing that these materials are indeed in the wild east of health care applications. In recent times, there has been a surge in the development of biomimetic natural biomaterials that mimic extracellular matrices and present appropriate biochemical and biophysical cues for tissue engineering as well as regenerative medicine applications. Showing that these materials are indeed in the wild east of health care applications. In recent times, there has been a surge in the development of biomimetic natural biomaterials that mimic extracellular matrices and present appropriate biochemical and biophysical cues for tissue engineering as well as regenerative medicine applications [40].

In addition, it has been reported a high efficacy of moist bioactive scaffolds for wound care significantly enhancing healing rates indicating the potential to investigate natural alternatives in chronic wounds therapy [41]With interesting perspectives as shown in the present review, these materials greatly enhance various biomedical applications including but not limited to self-powered electronics and tissue regeneration due to their unique benefits of biocompatibility/bioactivity, scalability/cost-effectiveness[39].

In fact, synthetic biomaterials are not naturally occurring materials[39]but their applications have become indispensable in many medical fields such as tissue engineering and drug delivery. To this same end, synthesis of mucus-inspired (SM) biomaterials has enhanced the therapeutic efficacy and controlled deposition of natural immune AMPs like LL37. Additionally, the creation of synthetic collagen biomaterials has addressed concerns regarding the purity and safety of natural collagen. This provides a viable alternative for tissue engineering purposes [42]. Synthetic biomaterials, designed to mimic natural structures and characteristics, have the potential to revolutionize the biomaterials industry. They can offer safer, more effective, and versatile solutions for various medical issues, including bone regeneration and wound healing [[43].Furthermore , the creation of synthetic collagen biomaterials has addressed concerns regarding the purity and safety of natural collagen. This provides a viable alternative for tissue engineering purposes [42]. Synthetic biomaterials, designed to mimic natural structures and characteristics, have the potential to revolutionize the biomaterials industry. They can offer safer, more effective, and versatile solutions for various medical issues, including bone regeneration and wound healing [43]

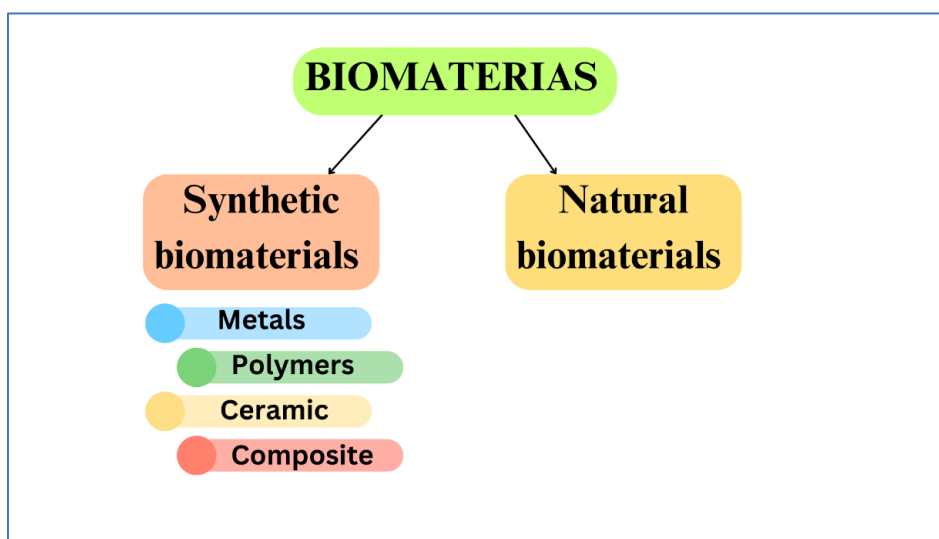


Figure 4: classification biomaterials according to their origin



## 2.4 Structural classification of biomaterials

When classifying biomaterials according to their atomic and molecular configuration, structural categorization is essential. Biomaterials can be divided into several types, such as amorphous materials, which include polymers and glasses, and crystalline materials, which include metals and ceramics and have highly organized structures. Porous materials also have spaces in their structure; examples of these are scaffolds used in tissue engineering and bone growth. Understanding the characteristics and behavior of biomaterials is crucial for their use in a variety of biomedical devices and therapies, and our classification system helps with that understanding [39].

Crystalline biomaterials have special qualities and functions because of their highly organized atom and molecular structure. Biomaterials with organized structures, like those based on silk fibroin and incorporating crystalline silk fibroin (CSF)[44], are essential for applications such as tissue regeneration, medication release, and cell encapsulation. Moreover, the relationship between liquid crystals (LCs) and biomaterials has been investigated, emphasizing the inherent LC behavior of biomaterials such as DNA and cellulose nanocrystals. Furthermore, studies on disordered crystals highlight the existence of linked disorder in crystalline materials, highlighting the possibility of manipulating and taking advantage of peculiar patterns within these states for functional responses that are not possible in traditional crystals[45]. Novel developments in materials science, biotechnology, and bioengineering are made possible by the comprehension and manipulation of the ordered groupings of crystalline biomaterials.

Amorphous biomaterials are different from crystalline structures in that they do not have a well-defined atomic and molecular organization. Weak non-covalent interactions from intrinsic disordered proteins (IDPs) cause the creation of membraneless organelles (MOs), highlighting the significance of disordered structures in cellular environments.

[46]. Furthermore, the study of correlated disordered media emphasizes the difficulty of producing materials without a regular component arrangement by examining the construction of structures with controlled spatial correlation. Form-changing materials inspired by nature exhibit programmed form changes at the microstructural level instead of the molecular scale, demonstrating the versatility of disordered materials in creating novel capabilities. These materials show biological systems[47]. These discoveries underscore the importance of amorphous biomaterials in a range of applications, from material manufacture to cellular physiology, where disorder is essential for enabling particular reactions to external stimuli and capabilities.

Porous materials are essential in many biomedical applications; examples of these materials are scaffolds used in tissue engineering and bone formation. Research has demonstrated that the integration of decellularized extracellular matrix (dECM) into scaffolds designed to replicate native bone tissue improves bone regrowth by imitating its molecular complexity[48]. These scaffolds can be designed with anisotropic channels to support the mineral deposition, differentiation, and proliferation of osteoblast cells—all essential for the regeneration of bone tissue[48]. Furthermore, the development of hybrid composite scaffolds with materials like poly-ε-caprolactone (PCL) and silica aerogel has demonstrated encouraging outcomes in terms of their mechanical, morphological, and physical qualities, qualifying them for use in bone tissue engineering applications[49]. Additionally, the development of polymeric porous scaffolds with various unit cell designs has been made possible by technological improvements in 3D printing. This allows for control over residual stresses and dimensional precision, which is crucial for the quality of the scaffold and its biomechanical performance in treating bone defects [50].

## 2.5 smart levels

Another method of categorizing biomaterials is based on their level of intelligence. In actuality, the most modern classification methods are represented by the way biomaterials are categorized. A novel classification scheme for smart biomaterials is presented in this review, which is predicated on the materials' level of interaction with the biological environment and the ensuing biological responses. The primary emphasis of conventional definitions of smart biomaterials has been their ability to react to external stimuli. Although this characteristic is still a defining feature of smart biomaterials, it is important to acknowledge the wider range of interactions that these materials can display with their biological environments. In order to tackle this issue, we put up a hierarchical classification scheme that groups intelligent biomaterials according to the extent of their interaction with the biological milieu and the consequent biological reactions. There are four levels of intelligence covered by this framework:

**Biomaterials that are inert:** These materials mainly function as structural supports and show little interaction with the surrounding tissue. Alumina, titanium, and stainless steel are a few examples.

The term "smart" in the context of biomaterials is usually used to describe materials that may self-adapt, self-sense, and self-repair by displaying dynamic behavior in response to environmental cues like pH, temperature, or stress [51] [52]. On the other hand, inert biomaterials are intended to live a largely passive life in the oral environment, focusing on biocompatibility, stability, and durability without causing any reactive interactions [51]. To create bio-inspired materials with controlled characteristics for applications like tissue



engineering and drug delivery, the field of biomaterials also investigates the combination of natural and synthetic polymers. This shows the potential for developing novel smart materials that address present limitations and offer advanced functionalities [53]. Therefore, inert biomaterials play a vital role in offering a solid and biocompatible base for a variety of biomedical applications, even though they do not have the dynamic responsiveness associated with smart materials. Biomaterials that are active: When certain biological cues or stimuli are encountered, active biomaterials either release or absorb chemicals. These substances can reduce inflammation or encourage the creation of new tissue. Resorbable polymers and calcium phosphate cements are two examples.

Second-level smart biomaterials are nimble and responsive to external cues, which enables them to carry out sensing, controlling, and actuating tasks [52]. Among these biomaterials are functional composites, which are materials that have been combined to improve their overall functionality. This allows the biomaterials to respond to alterations in temperature, pH, ionic strength, and other conditions to regulate medication release, cell interactions, and tissue regeneration.[24]. These biomaterials replicate biological systems by combining sensors, actuators, and control systems, and they provide functions like self-healing and synchronization with changes in the environment [52]. These active biomaterials are important for a variety of biological applications, such as drug delivery platforms and tissue engineering for the treatment of disease, because their design strives to give a dynamic reaction to the surrounding environment. [24][54]

Biomaterials that are responsive alter their structure or characteristics in reaction to external stimuli. These modifications may affect differentiation, proliferation, or adhesion of cells. Hydrogels and shape-memory polymers are two examples. In biomedical applications, responsive biomaterials demonstrate a high degree of intelligence by being sensitive to different stimuli and reacting appropriately [55]. These biomaterials have advanced responsiveness, able to react to multiple stimuli simultaneously, including temperature, light, magnetic fields, and pH level [55].

Furthermore, under some circumstances, smart materials in the biomedical domain might degrade under control to release advantageous ions, emphasizing their dynamic behavior and their advantages[51]. By increasing the standard for intelligence, the invention of dual-stimulus-responsive soft bimorph materials allows for intricately programmed 3D shape-morphing with wireless stimuli control. These materials offer flexibility and adaptability for uses in bioengineering, robotics, and microfluidics [56].

Overall, responsive biomaterials are valuable in the biomedical field because they can detect and react to different stimuli. Autonomous biomaterials can independently respond to complex biological signals by regulating or adapting themselves. These materials can imitate the dynamic properties of biological tissues. Although samples are not widely accessible at the moment, research and development in this area are ongoing.[5]

Autonomous biomaterials are a new concept that combines materials science and information technologies. They have various functions, including feedback systems, actuation, and sensing. The rise of intelligent items, such as self-governing biomaterials, has led to the need for an accurate classification system to effectively assess their levels of intelligence. Recent research has introduced a 12-level scale to measure smartness, ranging from traceable-only to fully autonomous and self-driven objects, to help classify and understand the autonomy and capability of smart systems [57] .

In addition, advances in autonomous experimentation, driven by artificial intelligence (AI) and active learning methods, have facilitated rapid exploration and optimization of complex material systems such as nanocomposites and metastable materials [58][59].

Autonomous biomaterials demonstrate innovative concepts with the potential to work independently and adaptively. This brings the usage of smart materials in scientific and technical applications one significant step closer. Autonomous biomaterials provide self-healing, sensing, actuation, communication, and other capabilities. These are critical for the development of medical technology and have a positive impact on tissue engineering and regenerative medicine. [59][60][61].

These materials have made significant strides in recent years and are crucial for tissue regeneration, minimally invasive operations, and the creation of structures that can directly connect with tissues—all of which will enhance people's health[60][59].

The incorporation of autonomous features into biomaterials not only enhances their mechanical and biological properties but also creates opportunities for innovative medical interventions such as automated drug delivery systems and robotic-assisted surgeries, demonstrating the potential of automation and technology in modern healthcare settings [61][62].

In general, self-governing biomaterials show great promise for future medical development, providing answers to existing constraints and propelling developments in regenerative medicine and other fields.

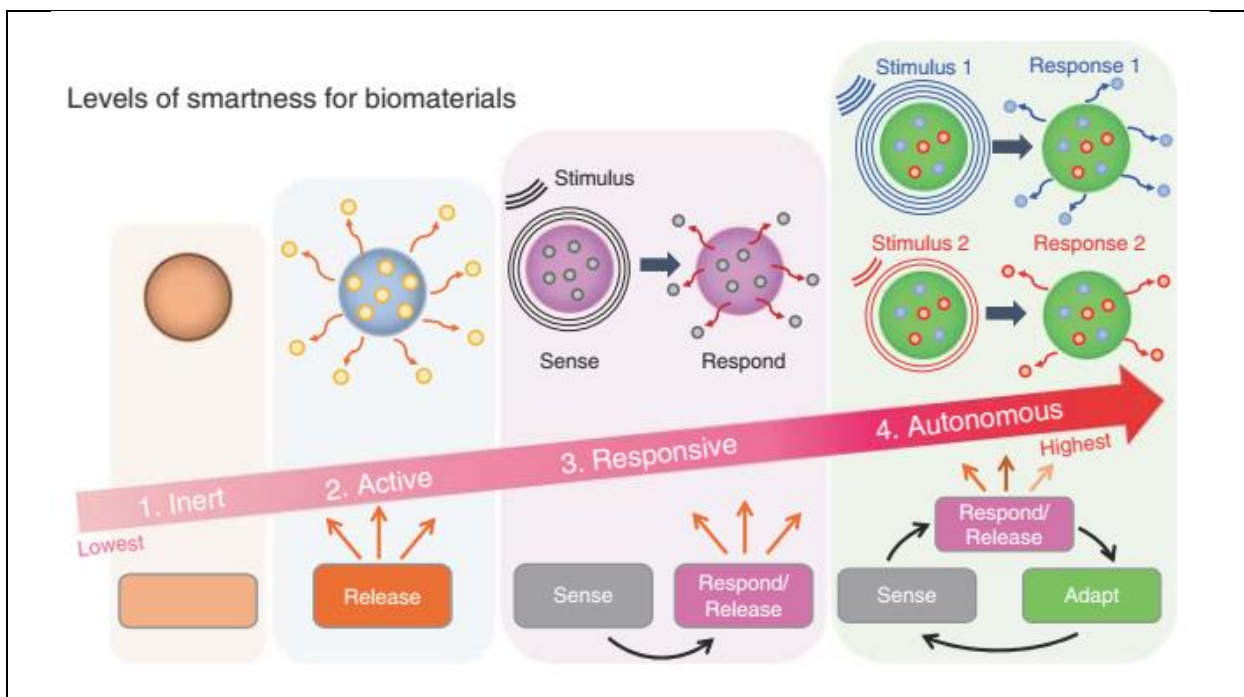


Figure 5: classification biomaterials according to increasing levels of smartness for biomaterials include inert, active, responsive, and autonomous.

Smart materials are materials that have behavior include responses to external stimuli such as self-sensing, self-healing, self-actuating, self-diagnostic and shape changing. Thus, smart materials can be seen as those which provide a means of achieving an active “smart” response in a product that would otherwise be lacking and have the potential to yield a multitude

of enhanced capabilities and functionalities. Examples of the capabilities of smart materials are as shown in Table I. Note that these categories are not necessarily mutually exclusive; for example, self-sensing may be combined with, or initiate, self-healing or self-diagnostics.[63]

Table1: Some capabilities of smart materials

Function	Comments
Shape changing	Material changes shape in response to an external stimulus
Self-actuating	Automated actuation in response to an external stimulus
Self-sensing	Allows automated detection and sometimes quantification of external stimuli
Self-diagnostic	Allows automated detection of defects. Closely allied to self-sensing
Self-healing	Automatic self-repair of damage

### 3. BIOMATERIAL CLASSIFICATION METHODS COMPARISON

In practice, biomaterial classification often involves a combination of these methods for a more comprehensive

understanding of the material. New classification schemes are emerging to categorize biomaterials based on their degradation profile, biocompatibility, or specific therapeutic applications.

Table 2: Classification Methods advantage and limitation.

Classification Method	Description	Advantages	Limitations	Examples
<b>Chemical</b>	Classifies biomaterials based on their chemical composition (e.g., polymers, metals, ceramics).	Simple and well-established method. Easy to understand and interpret.	Limited information about material properties and functionality. Doesn't consider material structure or design.	Classification of synthetic polymers (e.g., polyesters, nylons). Grouping metals (e.g., titanium, stainless steel).
<b>Functional</b>	Classifies biomaterials based on their intended function in the body (e.g., drug delivery, tissue engineering, implants).	Directly, related to the application of the biomaterial. Provides insight into the desired material properties.	Doesn't consider the material's underlying chemistry or structure. May have some overlap between categories.	Classifying biomaterials for bone repair (e.g., hydroxyapatite scaffolds). Grouping biomaterials for wound healing (e.g., collagen dressings).
<b>Source</b>	Classifies biomaterials based on their origin (e.g., natural, synthetic, or a combination).	Straightforward method based on material source. Can be useful for initial categorization.	Limited information about material properties or functionality. Doesn't consider the material's chemical structure or design.	Grouping natural biomaterials like collagen or silk. Classifying synthetic polymers like polyethylene or silicone.
<b>Structural</b>	Classifies biomaterials based on their internal arrangement of atoms and molecules (e.g., crystalline, amorphous, porous).	Provides information about material properties like strength and degradation. Can be relevant for understanding biocompatibility.	May require specialized techniques for structural analysis (e.g., X-ray diffraction). Structural features might not directly translate to functionality.	Classifying biomaterials with porous structures for tissue ingrowth. Grouping biomaterials with specific crystal structures for controlled drug release.
<b>Smart</b>	Classifies biomaterials that can respond to external stimuli (e.g., temperature, pH, light) or biological cues (e.g., enzymes, proteins).	Captures the advanced functionalities of next-generation biomaterials. Provides insights into targeted drug delivery or controlled cell interactions.	This is a rapidly evolving field with diverse materials. Classification criteria can be complex and depend on the specific stimuli-responsive behavior.	Grouping biomaterials that release drugs in response to a specific pH change. Classifying biomaterials that degrade in response to enzymatic activity.

#### 4. APPLICATION OF BIOMATERIALS

Applications for smart biomaterials are numerous and span a number of industries, including cancer theranostics and biomedicine. These materials have major benefits in biomedical technology, such as force measurement for tissue characterisation and cell analysis, because they can sense and react to external stimuli [64]. Smart biopolymer chitosan is unique in that it can form a variety of shapes, such as hydrogels and nanoparticles, which makes it perfect for use in drug delivery systems and the healing of wounds in the biomedical industry. Smart nanomaterials are essential in cancer therapy because they react to particular stimuli, such as pH or enzymes, allowing for focused medication administration and minimizing side effects, all of which improve cancer diagnostic

and treatment results [65][66]. Additionally, smart biomaterial scaffolds improve wound closure and treatment effectiveness in diabetic wound management by acting as responsive systems to the wound microenvironment [67]. These applications show the versatile nature and promise of smart biomaterials in the development of medical technology. In tissue engineering applications, smart biomaterials are essential because they can respond to external stimuli and carry out required tasks. These biomaterials, which include alginate and chitosan, change chemically or physically when exposed to different conditions, such as pH, temperature, or magnetic fields [68][53]. The use of stimuli-responsive biomaterials in 3D printing allows for the development of intelligent structures

with programmable features, taking tissue engineering products to new heights [69].

In 3D bioprinting, smart bioinks enable the precise release of components in response to stimuli, making it easier to create human bioprinted tissues that closely resemble in vivo characteristics [70]. Smart biomaterials have the potential to improve regenerative medicine since they can be used to improve tissue regeneration, drug delivery, and the creation of dynamic scaffolds for tissue rejuvenation[53].

Because they react to external stimuli such as magnetic fields, light, or electric fields, smart scaffold biomaterials are essential to tissue engineering because they provide targeted therapeutic delivery and stimulation-induced cellular responses for a variety of tissues[71][53][72]. Biocompatible polymers, both synthetic (PLGA, PCL) and natural (collagen, hyaluronic acid), are used in the construction of these scaffolds to build dynamic structures that imitate natural tissues and speed up the healing process[71][53]. Upconversion nanoparticles are one of the intelligent aspects that may be incorporated to ensure biocompatibility and efficacy in tissue regeneration. Real-time monitoring of tissue/scaffold interactions, cell adhesion, proliferation, and colonization[71]. Moreover, the incorporation of active peptides, including sequences generated from Transforming Growth Factor- $\beta$ 1, amplifies chondrogenic induction inside the scaffold, encouraging cartilage regeneration and repair[73]. These developments in smart scaffold biomaterials present viable answers for tissue engineering uses, such as the regeneration of muscle, cartilage, bone, and heart tissue [53][73][74].

Using smart biomaterials is a promising way to improve bone repair after damage. Innovative technologies that respond to both internal and external stimuli and provide a regulated microenvironment that promotes bone healing include smart hydrogels and bio-piezoelectric scaffolds [75][76]. These biomaterials can be engineered to display programmed and variable alterations, facilitating controlled bone regeneration in both space and time[76]. Furthermore, the creation of adaptable biomaterials that react to certain pathological microenvironments or external physical stimuli has demonstrated significant promise in bone therapy and regeneration, providing a means of treating bone abnormalities in conjunction with malignancies, infections, or other bone illnesses[77]. Through the incorporation of these cutting-edge materials into applications for bone tissue engineering, scientists hope to develop cutting-edge approaches that replicate the architecture of bone tissue and improve bioactivity for successful bone regeneration [78].

## 5. FUTURE STUDYING

The future of biomaterial classification using the five methods (chemical, functional, source, structural, and smart) is likely to see advancements in several areas:

### 5.1 Integration and Automation:

Combined Classification Systems:

We might see the development of integrated classification systems that combine information from all five methods to create a more comprehensive biomaterial profile. This could involve machine learning algorithms that analyze data from various sources (spectral analysis, microscopy images, material properties) and automatically assign classifications across different categories.

Standardized Databases:

Classification could become more automated with standardized databases containing detailed information about existing biomaterials categorized using all five methods. This would allow researchers to quickly identify materials with desired properties for specific applications.

### 5.2 Evolving Classification Schemes:

The future of biomaterial science may lead to the emergence of new classification schemes, reflecting the increasing complexity of materials. These classifications might be based on imperfection characteristics, such as the distribution of the material's breakdown in the body, as well as the material's compatibility with live tissue, known as biocompatibility. Additionally, classifications could be based on the specific diseases or conditions that the material is meant to address for therapeutic use. The classification of a substance may also become more dynamic, adapting to its biological environment. For example, a biomaterial initially categorized as "inert" (chemically inactive) may later be reclassified as "immunomodulatory" (influencing the immune system) based on its documented effects on the body.

### 5.3 Convergence with Other Fields:

Materials informatics involves the application of data science and machine learning to expedite the creation of new materials. By combining biomaterial classification data with materials informatics tools, researchers can design new biomaterials with specific tailored properties. As nanotechnology and bioprinting continue to advance, biomaterials with complex structures and functionalities will emerge. This will require modification of categorization techniques to account for the unique characteristics of these materials.

### 5.4 Focus on Functionality and Personalization:

"Function-Driven Design: There is a potential shift towards organizing biomaterials based on how they function within the body. This could involve creating classification systems that link specific treatment goals with material characteristics. Personalized medicine: Classification systems could be adjusted to consider individual patient needs. For example, a biomaterial intended for general bone repair could be further categorized based on its suitability for the bone density or healing capacity of a specific patient."

### 5.5 Classification of Biomaterials using Spectral Methods

Biomaterials are designed to interact with biological systems. Spectral methods are used to categorize their structure and chemical composition, offering powerful tools for analysis [79-87]. There are various spectrum methods employed in the analysis of biomaterials, providing information on different aspects of the material. Techniques such as mixed transformations, Fourier spectroscopy, Wavelet, and Multiwavelet help identify specific functional groups in the material's structure, allowing for the distinction of polymer types, natural materials, and composite biomaterials [88-104].

**Raman Spectroscopy:** Offers details on the molecular vibrational modes inside the substance. It can be applied to determine a material's crystallinity or to identify certain molecules [105-113].

**X-ray photoelectron spectroscopy (XPS):** Examines the surface of the biomaterial to determine the elemental makeup and electronic states of the atoms. Studying surface alterations or coatings on biomaterials can benefit from this [114-118].

Once spectral data is obtained, various chemometric techniques can be used for classification:

**Principal Component Analysis (PCA):** Minimizes the number of dimensions in the data while maintaining the majority of the pertinent details. This can aid in the visualization of clustering patterns that identify various types of biomaterials [119-121].

**K-Nearest Neighbors (KNN):** This approach clusters new, unidentified samples based on how much they resemble spectral data library biomaterials that have already been studied [122-123].

**Support Vector Machines (SVM):** SVM creates a hyperplane to split different classes of biomaterials in the high-dimensional spectral data space. This method works well for handling non-linear relationships between spectral features and material properties [124-133].

The future classification of biomaterials will largely rely on the application of new technologies, the integration of data from various sources, and the identification of practical applications of these materials to enhance patient care and personalized treatment. Biomaterials classification is a rapidly evolving field with diverse approaches. Utilizing chemo-metrics in combination with conventional spectrum analysis provides a strong foundation. Both machine learning and deep learning offer effective solutions for complex classification tasks. Understanding the advantages and disadvantages of each method will help researchers determine which approach will best utilize biomaterials to improve healthcare [134-142].

## 6. CONCLUSIONS

For various reasons, we utilize five different classification schemes for biomaterials:

1. **Providing a Comprehensive View:** Each classification method offers a unique perspective on the biomaterial. Using

multiple methods helps us gain a deeper understanding of the material's properties, intended uses, and potential applications.

2. **Catering to Diverse Needs:** Different classification techniques are relevant depending on the subject or the stage of development. Early on, a source-based classification (natural vs. synthetic) may be useful. Later, when functionality is the primary concern, understanding the chemical composition (e.g., polymers for drug administration) becomes essential.

**Optimize Material Selection:** Scientists and medical professionals can choose the optimal biomaterial for a specific application by utilizing various classification approaches. For example, when it comes to mending broken bones, it's important to know the source (natural bone transplant), the composition (porous for cell ingrowth), and the chemical composition (calcium phosphate for bone integration).

**Encourage Standardization and Communication:** By using these classification systems as a common language, producers, doctors, and researchers can communicate effectively about biomaterials. This promotes open communication and helps establish standards for the production and use of materials.

**Determine New Research Directions:** By employing various classification techniques to examine current biomaterials, scientists may be able to spot functional gaps or unrealized promise in particular material classes. This may result in the creation of novel biomaterials with enhanced characteristics.

Each of the five classes taken into consideration has specific limitations. The chemical class may not be sufficiently informative for advanced biomaterials because it provides little information about the structure and functionality of materials and ignores their qualities. Drug delivery materials, for example, can also be utilized in tissue engineering. The Functional classes do not take into account the underlying chemistry or structure of the material and may have some overlap within categories. The source of biomaterials classes may not be applicable to biomaterials obtained from a combination of sources, offers little information about particular features or functionalities, and disregards the chemical structure or design of the material. The structural properties of the structural classes could not correspond directly to functioning (for example, good cell ingrowth is not always ensured by a porous structure), and they might require specific techniques for structural examination (such as X-ray diffraction). Lastly, the categorization of Smart Levels is a quickly developing field with a variety of materials, making classification complex and requiring precise classification criteria based on the material's response to different stimuli. The best approach will vary depending on this investigation, the particular environment, and the information requirements. Here's a broad summary:

**First Classification:** Chemical or source-based classifications might serve as a foundation.

**Functional Needs:** Functional classification is essential for some applications.

Understanding Properties: To comprehend the behavior of materials, structural analysis is necessary.

Advanced Materials: For materials with intricate functionality, use smart level classification.

Lastly, for a biomaterial to be used as effectively as possible in a biological setting, it is essential to comprehend several

elements of it. The classification of biomaterials is an ever-evolving field that uses a variety of methods. A strong basis is provided by chemo-metrics in conjunction with traditional spectral analysis. For difficult categorization jobs, deep learning and machine learning provide effective methods. One can select the most effective strategy to unleash the potential of biomaterials for improving medical care by being aware of the advantages and disadvantages of each technique.

## REFERENCES

- [1] E. T. J. Chong, J. W. Ng, and P. C. Lee, "Classification and Medical Applications of Biomaterials—A Mini Review," *BIO Integr.*, vol. 4, no. 2, pp. 54–61, 2023, doi: 10.15212/bioi-2022-0009.
- [2] M. S. Valiathan and V. Kalliyana Krishnan, "Biomaterials: An Overview," *Natl. Med. J. India*, vol. 12, no. 6, pp. 270–274, 1999, doi: 10.1002/0471732877.emd022.
- [3] P. Parida, A. Behera, and S. Chandra Mishra, "Classification of Biomaterials used in Medicine," *Int. J. Adv. Appl. Sci.*, vol. 1, no. 3, pp. 31–35, 2012, doi: 10.11591/ijaas.v1i3.882.
- [4] S. Al-Maawi, J. L. Rutkowski, R. Sader, C. J. Kirkpatrick, and S. Ghanaati, "The biomaterial-induced cellular reaction allows a novel classification system regardless of the biomaterials origin," *J. Oral Implantol.*, vol. 46, no. 3, pp. 190–205, 2020, doi: 10.1563/aaid-joi-D-19-00201.
- [5] C. Montoya, Y. Du, A. L. Gianforcaro, S. Orrego, M. Yang, and P. I. Lelkes, "On the road to smart biomaterials for bone research: definitions, concepts, advances, and outlook," *Bone Res.*, vol. 9, no. 1, 2021, doi: 10.1038/s41413-020-00131-z.
- [6] C. W. Arun Arjunan, and Ahmad Baroutaji, Ayyappan S Praveen, John Robinson, "Classification of Biomaterial Functionality Arun." 2020.
- [7] Arjunan, A. Baroutaji, A. S. Praveen, J. Robinson, and C. Wang, "Classification of biomaterial functionality," Elsevier eBooks, pp. 1–31, 2022.
- [8] N. Contuzzi et al., "Metals Biotribology and Oral Microbiota Biocorrosion Mechanisms," *J. Funct. Biomater.*, vol. 14, no. 1, 2023, doi: 10.3390/jfb14010014.
- [9] L. Vaiani et al., "Ceramic Materials for Biomedical Applications: An Overview on Properties and Fabrication Processes," *J. Funct. Biomater.*, vol. 14, no. 3, 2023, doi: 10.3390/jfb14030146.
- [10] P. Ducheyne, M. Marcolongo, and E. Schepers, *Bioceramic composites*. 2013.
- [11] M. Ly, S. Spinelli, S. Hays, and D. Zhu, "3D Printing of Ceramic Biomaterials," *Eng. Regen.*, vol. 3, no. 1, pp. 41–52, 2022, doi: 10.1016/j.engreg.2022.01.006.
- [12] M. Zorah, M. Mudhafar, H. A. Naser, and I. R. Mustapa, "The Promises of the Potential Uses of Polymer Biomaterials in Biomedical Applications and Their Challenges," *Int. J. Appl. Pharm.*, vol. 15, no. 4, pp. 27–36, 2023, doi: 10.22159/ijap.2023v15i4.48119.
- [13] H. H. Al-Moameri, D. A. Rasool, and Z. M. Nahi, "A Review of Polymer-Based Materials Used in Biomaterials for Medical Applications," *J. Eng. Sustain. Dev.*, vol. 26, no. 5, pp. 1–13, 2022, doi: 10.31272/jeasd.26.5.1.
- [14] V. R. L. Constantino et al., "Biomaterials Based on Organic Polymers and Layered Double Hydroxides Nanocomposites: Drug Delivery and Tissue Engineering," *Pharmaceutics*, vol. 15, no. 2, 2023, doi: 10.3390/pharmaceutics15020413.
- [15] C. H. Roeder, R. K., & Turner, "COMPOSITE BOMATERAL INCLUDING ANISOMETRIC CALCIUM PHOSPHATE REINFORCEMENT PARTICLES AND RELATED METHODS," 2010.
- [16] A. Lynn, C. Gb, C. Gb, and C. Gb, "COMPOSITE BOMATERALS COMPRISING CALCIUM PHOSPHATE MATERIALS, COLLAGEN AND GLYCOSAMINOGLYCANS," 2010.

- [17] García-Lizarribar, X. Fernández-Garibay, F. Velasco-Mallorquí, A. G. Castaño, J. Samitier, and J. Ramon-Azcon, “Composite Biomaterials as Long-Lasting Scaffolds for 3D Bioprinting of Highly Aligned Muscle Tissue,” *Macromol. Biosci.*, vol. 18, no. 10, pp. 1–36, 2018, doi: 10.1002/mabi.201800167.
- [18] E. D. S. Câmara-Pereira et al., “Characterization of biomaterial and tissue response analysis after implantation,” in *Materials Science Forum*, 2018, vol. 930 MSF, no. Po 4, pp. 48–52, doi: 10.4028/www.scientific.net/MSF.930.48.
- [19] J. J. Li and H. Zreiqat, *Tissue response to biomaterials*, vol. 1–3. Elsevier Inc., 2019.
- [20] S. Bhandi, O. T. Okareh, and S. Patil, “Biocompatibility of Restorative Materials- A Review,” *Texila Int. J. Public Heal.*, vol. 11, no. 2, pp. 1–5, 2023, doi: 10.21522/TIJPH.2013.11.02.Art014.
- [21] C. en Lu et al., “Monitoring the macrophage response towards biomaterial implants using label-free imaging,” *Mater. Today Bio*, vol. 21, no. January, p. 100696, 2023, doi: 10.1016/j.mtbio.2023.100696.
- [22] R. A. Morrison et al., “Engineered collagen polymeric materials create noninflammatory regenerative microenvironments that avoid classical foreign body responses,” *Biomater. Sci.*, vol. 11, no. 9, pp. 3278–3296, 2023, doi: 10.1039/d3bm00091e.
- [23] M. Rafiei, J. T. Chung, and Y. Chau, “Roles of biomaterials in modulating the innate immune response in ocular therapy,” *Front. Drug Deliv.*, vol. 3, no. February, pp. 1–27, 2023, doi: 10.3389/fddev.2023.1077253.
- [24] L. Li, T. Groth, and M. Zhao, “Editorial: Bioactive soft materials and application,” *Front. Bioeng. Biotechnol.*, vol. 11, no. July, pp. 1–2, 2023, doi: 10.3389/fbioe.2023.1248995.
- [25] Negut and C. Ristoscu, “Bioactive Glasses for Soft and Hard Tissue Healing Applications—A Short Review,” *Appl. Sci.*, vol. 13, no. 10, 2023, doi: 10.3390/app13106151.
- [26] P. Carvalho et al., “Consolidation of Zn-Hydroxyapatite and Zn-Bioactive Glass Composites Using High-Pressure Torsion,” *Crystals*, vol. 13, no. 6, pp. 1–14, 2023, doi: 10.3390/cryst13060949.
- [27] P. M. Pires et al., “Bioactive Restorative Materials Applied over Coronal Dentine—A Bibliometric and Critical Review,” *Bioengineering*, vol. 10, no. 6, 2023, doi: 10.3390/bioengineering10060731.
- [28] Z. Zhai, X. Du, Y. Long, and H. Zheng, “Biodegradable polymeric materials for flexible and degradable electronics,” *Front. Electron.*, vol. 3, no. September, pp. 1–20, 2022, doi: 10.3389/felec.2022.985681.
- [29] G. V. Jagadeesh and S. G. Setti, “Bio-engineering and bio-design of new generation bioresorbable implants,” *Indian J. Biochem. Biophys.*, vol. 58, no. 2, pp. 118–126, 2021, doi: 10.56042/ijbb.v58i2.35124.
- [30] X. Wu and Q. Guo, “Bioresorbable photonics: Materials, devices and applications,” *Photonics*, vol. 8, no. 7, 2021, doi: 10.3390/photonics8070235.
- [31] S. Jasmine and R. Krishnamoorthy, “Biodegradable Materials for Bone Defect Repair,” *Biodegrad. Mater. their Appl.*, pp. 457–470, 2022, doi: 10.1002/9781119905301.ch16.
- [32] L. K. Hakim et al., “Biocompatible and Biomaterials Application in Drug Delivery System in Oral Cavity,” *Evidence-based Complement. Altern. Med.*, vol. 2021, 2021, doi: 10.1155/2021/9011226.
- [33] L. Raja Mohan Reddy, M. Obula Reddy, M. Thaidun, and P. Guruprathap Reddy, “Biomaterial and its applications,” *J. Inf. Comput. Sci.*, vol. 10, no. 1, pp. 90–94, 2020, [Online]. Available: [www.joics.org](http://www.joics.org).
- [34] M. Zunaed and S. A. Fattah, “A Novel Hierarchical-Classification-Block Based Convolutional Neural Network for Source Camera Model Identification,” pp. 1–7, 2022, [Online]. Available: <http://arxiv.org/abs/2212.04161>.
- [35] V. Kumar, V. Malyan, M. Sahu, and B. Biswal, “Machine Learning Classification Model to Label Sources Derived from Factor Analysis Receptor Models for Source Apportionment,” *Aerosol Air Qual. Res.*, vol. 23, no. 7, pp. 1–11, 2023, doi: 10.4209/aaqr.220386.
- [36] H. Nguyen, M. Ebbatson, Y. Tran, A. Craig, H. Nguyen, and R. Chai, “Source-Space Brain Functional Connectivity Features in Electroencephalogram-Based Driver Fatigue Classification,” *Sensors*, vol. 23, no. 5, 2023, doi: 10.3390/s23052383.

- [37] D. qin Xu and M. ai Li, “A dual alignment-based multi-source domain adaptation framework for motor imagery EEG classification,” *Appl. Intell.*, vol. 53, no. 9, pp. 10766–10788, 2023, doi: 10.1007/s10489-022-04077-z.
- [38] H. Wang, “Biomaterials in Medical Applications,” *Polymers (Basel)*, vol. 15, no. 4, pp. 7–9, 2023, doi: 10.3390/polym15040847.
- [39] E. Mariani, G. Lisignoli, R. M. Borzi, and L. Pulsatelli, “Biomaterials: Foreign bodies or tuners for the immune response?,” *International Journal of Molecular Sciences*, vol. 20, no. 3, pp. 363–364, 2019, doi: 10.3390/ijms20030636.
- [40] S. Liu et al., “Biomimetic natural biomaterials for tissue engineering and regenerative medicine: new biosynthesis methods, recent advances, and emerging applications,” *Military Medical Research*, vol. 10, no. 1, BioMed Central, pp. 1–30, 2023, doi: 10.1186/s40779-023-00448-w.
- [41] N. I. M. Fadilah, M. Maarof, A. Motta, Y. Tabata, and M. B. Fauzi, “The Discovery and Development of Natural-Based Biomaterials with Demonstrated Wound Healing Properties: A Reliable Approach in Clinical Trials,” *Biomedicines*, vol. 10, no. 9, 2022, doi: 10.3390/biomedicines10092226.
- [42] Hu et al., “Design of synthetic collagens that assemble into supramolecular banded fibers as a functional biomaterial testbed,” *Nat. Commun.*, vol. 13, no. 1, 2022, doi: 10.1038/s41467-022-34127-6.
- [43] T. “Tomi” Kupka, “Nature-inspired Material – A Step Ahead in Dental Materials,” *Int. Ann. Sci.*, vol. 12, no. 1, pp. 31–46, 2022, doi: 10.21467/ias.12.1.31-46.
- [44] D. Yao, T. Wang, X. Zhang, and Y. Wang, “High Concentration Crystalline Silk Fibroin Solution for Silk-Based Materials,” *Materials (Basel)*, vol. 15, no. 19, 2022, doi: 10.3390/ma15196930.
- [45] Simonov and A. L. Goodwin, “Designing disorder into crystalline materials,” *Nat. Rev. Chem.*, vol. 4, no. 12, pp. 657–673, 2020, doi: 10.1038/s41570-020-00228-3.
- [46] J. Liu, F. Zhorabek, and Y. Chau, “Biomaterial design inspired by membraneless organelles,” *Matter*, vol. 5, no. 9, pp. 2787–2812, 2022, doi: 10.1016/j.matt.2022.07.001.
- [47] R. Studart and R. M. Erb, “Bioinspired materials that self-shape through programmed microstructures,” *Soft Matter*, vol. 10, no. 9, pp. 1284–1294, 2014, doi: 10.1039/c3sm51883c.
- [48] W. Wang, X. Zhou, Z. Yin, and X. Yu, “Fabrication and Evaluation of Porous dECM/PCL Scaffolds for Bone Tissue Engineering,” *J. Funct. Biomater.*, vol. 14, no. 7, 2023, doi: 10.3390/jfb14070343.
- [49] D. R. Pontinha, B. B. Moreira, B. L. Melo, D. de Melo-Diogo, I. J. Correia, and P. Alves, “Silica Aerogel-Polycaprolactone Scaffolds for Bone Tissue Engineering,” *Int. J. Mol. Sci.*, vol. 24, no. 12, 2023, doi: 10.3390/ijms241210128.
- [50] R. Imran, A. Al Rashid, and M. Koç, “Material Extrusion 3D Printing (ME3DP) Process Simulations of Polymeric Porous Scaffolds for Bone Tissue Engineering,” *Materials (Basel)*, vol. 16, no. 6, 2023, doi: 10.3390/ma16062475.
- [51] J. F. McCabe, Z. Yan, O. T. Al Naimi, G. Mahmoud, and S. L. Rolland, “Smart materials in dentistry,” *Aust. Dent. J.*, vol. 56, no. SUPPL. 1, pp. 3–10, 2011, doi: 10.1111/j.1834-7819.2010.01291.x.
- [52] W. Cao, H. H. Cudney, and R. Waser, “Smart materials and structures,” *Proc. Natl. Acad. Sci. U. S. A.*, vol. 96, no. 15, pp. 8330–8331, 1999, doi: 10.1073/pnas.96.15.8330.
- [53] E. Eldeeb, S. Salah, and N. A. Elkasabgy, “Biomaterials for Tissue Engineering Applications and Current Updates in the Field: A Comprehensive Review,” *AAPS PharmSciTech*, vol. 23, no. 7, 2022, doi: 10.1208/s12249-022-02419-1.
- [54] F. Khan and M. Tanaka, “Designing smart biomaterials for tissue engineering,” *Int. J. Mol. Sci.*, vol. 19, no. 1, pp. 1–14, 2018, doi: 10.3390/ijms19010017.
- [55] C. Fernandes, G. B. Heggannavar, M. Y. Kariduraganavar, G. R. Mitchell, N. Alves, and P. Morouço, “Smart Materials for Biomedical Applications: The Usefulness of Shape-Memory Polymers,” *Appl. Mech. Mater.*, vol. 890, pp. 237–247, 2019, doi: 10.4028/www.scientific.net/amm.890.237.
- [56] J. Zhang, Y. Guo, W. Hu, and M. Sitti, “Wirelessly Actuated Thermo- and Magneto-Responsive Soft Bimorph Materials with Programmable Shape-Morphing,” *Adv. Mater.*, vol. 33, no. 30, 2021, doi: 10.1002/adma.202100336.

- [57] N. Costa, N. Rodrigues, M. A. Seco, and A. Pereira, “SL: A Reference Smartness Level Scale for Smart Artifacts,” *Inf.*, vol. 13, no. 8, pp. 1–18, 2022, doi: 10.3390/info13080371.
- [58] G. Kusne et al., “On-the-fly closed-loop materials discovery via Bayesian active learning,” pp. 1–11, 2020.
- [59] S. Ament et al., “Autonomous materials synthesis via hierarchical active learning of nonequilibrium phase diagrams,” *Sci. Adv.*, vol. 7, no. 51, pp. 24–26, 2021, doi: 10.1126/sciadv.abg4930.
- [60] S. Leeuwenburgh, “Self-healing biomaterials for medical applications,” *MATEC Web Conf.*, vol. 378, p. 01003, 2023, doi: 10.1051/mateconf/202337801003.
- [61] Bhorkar and A. S. Dhoble, “Advances in the synthesis and application of self-assembling biomaterials,” *Prog. Biophys. Mol. Biol.*, vol. 167, no. xxxx, pp. 46–62, 2021, doi: 10.1016/j.pbiomolbio.2021.07.011.
- [62] O. S. I. Fayomi et al., “Role of Biomaterials in Automation.,” *IOP Conf. Ser. Earth Environ. Sci.*, vol. 665, no. 1, 2021, doi: 10.1088/1755-1315/665/1/012022.
- [63] R. Bogue, “Smart materials: A review of capabilities and applications,” *Assem. Autom.*, vol. 34, no. 1, pp. 16–22, 2014, doi: 10.1108/AA-10-2013-094.
- [64] G. Bocchetta, G. Fiori, S. A. Sciuto, and A. Scorza, “Performance of Smart Materials-Based Instrumentation for Force Measurements in Biomedical Applications: A Methodological Review,” *Actuators*, vol. 12, no. 7. 2023, doi: 10.3390/act12070261.
- [65] B. K. Kashyap, V. V. Singh, M. K. Solanki, A. Kumar, J. Ruokolainen, and K. K. Kesari, “Smart Nanomaterials in Cancer Theranostics: Challenges and Opportunities,” *ACS Omega*, vol. 8, no. 16, pp. 14290–14320, 2023, doi: 10.1021/acsomega.2c07840.
- [66] R. Singh, A. Sharma, J. Saji, A. Umapathi, S. Kumar, and H. K. Daima, *Smart nanomaterials for cancer diagnosis and treatment*, vol. 9, no. 1. Springer Nature Singapore, 2022.
- [67] C. Huang, W. Yuan, J. Chen, L. P. Wu, and T. You, “Construction of Smart Biomaterials for Promoting Diabetic Wound Healing,” *Molecules*, vol. 28, no. 3, 2023, doi: 10.3390/molecules28031110.
- [68] N. Farshidfar, S. Irvani, and R. S. Varma, “Alginate-Based Biomaterials in Tissue Engineering and Regenerative Medicine,” *Mar. Drugs*, vol. 21, no. 3, 2023, doi: 10.3390/md21030189.
- [69] Q. Gao, J. S. Lee, B. S. Kim, and G. Gao, “Three-dimensional printing of smart constructs using stimuli-responsive biomaterials: A future direction of precision medicine,” *Int. J. Bioprinting*, vol. 9, no. 1, pp. 230–257, 2023, doi: 10.18063/ijb.v9i1.638.
- [70] Z. Maan, N. Z. Masri, and S. M. Willerth, “Smart Bioinks for the Printing of Human Tissue Models,” *Biomolecules*, vol. 12, no. 1, 2022, doi: 10.3390/biom12010141.
- [71] E. M. Trifanova et al., “Natural and Synthetic Polymer Scaffolds Comprising Upconversion Nanoparticles as a Bioimaging Platform for Tissue Engineering,” *Molecules*, vol. 27, no. 19, 2022, doi: 10.3390/molecules27196547.
- [72] D. Mertz et al., “Nanocomposite Polymer Scaffolds Responding under External Stimuli for Drug Delivery and Tissue Engineering Applications,” *Adv. Ther.*, vol. 3, no. 2, 2020, doi: 10.1002/adtp.201900143.
- [73] Mantsou et al., “Fabrication of a Smart Fibrous Biomaterial That Harbors an Active TGF-β1 Peptide: A Promising Approach for Cartilage Regeneration,” *Biomedicines*, vol. 11, no. 7, 2023, doi: 10.3390/biomedicines11071890.
- [74] S. Bhushan et al., “Scaffold Fabrication Techniques of Biomaterials for Bone Tissue Engineering: A Critical Review,” *Bioengineering*, vol. 9, no. 12, 2022, doi: 10.3390/bioengineering9120728.
- [75] Chen, J. Su, Y. Li, H. Zhang, Y. Shi, and C. Yan, “scaffolds for next-generation bone,” *Int. J. Extrem. Manuf.*, vol. 5, pp. 032007–032007, 2023.
- [76] W. Chen, H. Zhang, Q. Zhou, F. Zhou, Q. Zhang, and J. Su, “Smart Hydrogels for Bone Reconstruction via Modulating the Microenvironment,” *Research*, vol. 6, pp. 1–22, 2023, doi: 10.34133/research.0089.
- [77] H. Wei, J. Cui, K. Lin, J. Xie, and X. Wang, “Recent advances in smart stimuli-responsive biomaterials for bone therapeutics and regeneration,” *Bone Res.*, vol. 10, no. 1, 2022, doi: 10.1038/s41413-021-00180-y.

- [78] S. Kumari et al., “Design strategies for composite matrix and multifunctional polymeric scaffolds with enhanced bioactivity for bone tissue engineering,” *Front. Chem.*, vol. 10, no. November, pp. 1–28, 2022, doi: 10.3389/fchem.2022.1051678.
- [79] L. R. Husssein and J. M. A. Al-Sammarie W. A. Mahmoud “Image Identification using Minimum Distance Classifier with Multi-Wavelet Transform” *Journal of Advances in Modelling and Analysis B*, Volume 46, Issue (5-6), pages 1-22, 2003.
- [80] R. Ali Dihin, E. AlShemmary and Waleed Al-Jawher “Diabetic Retinopathy Classification Using Swin Transformer with Multi Wavelet” *Journal of Kufa for Mathematics and Computer*, Vol. 10, Issue 2, PP. 167-172.
- [81] E. Dihin, R. Al-Jawher, Waleed and Al-Shemmary “Implementation of The Swin Transformer and Its Application In Image Classification” *Journal Port Science Research*, vol. 6, Issue 4, PP. 318-331. 2023.
- [82] Rasha Ali Dihin, Ebtessam N. AlShemmary and Waleed A. Mahmoud Al-Jawher “Automated Binary Classification of Diabetic Retinopathy by SWIN Transformer” *Journal of Al-Qadisiyah for computer science and mathematics (JQCM)*, Vol 15, Issue 1, PP. 169-178, 2023.
- [83] Maryam I Mousa Al-Khuzayy, Waleed A Mahmoud Al-Jawher “ New Proposed Mixed Transforms: CAW and FAW and Their Application in Medical Image Classification” *International Journal of Innovative Computing*, Vol. 13, Issue 1-2, PP. 15-21, 2022.
- [84] W. A. Mahmoud & Z. J. M. Saleh “ An Algorithm for Computing Multiwavelets & Inverse Transform Using an Over-Sampled Scheme of Pre & Post processing respectively”
- [85] AH Salman, WAM Al-Jawher “A Hybrid Multiwavelet Transform with Grey Wolf Optimization Used for an Efficient Classification of Documents” *International Journal of Innovative Computing* 13 (1-2), 55-60, 2022.
- [86] WA Mahmoud, AI Abbas, NAS Alwan “Face Identification Using Back-Propagation Adaptive Multiwavelet” *Journal of Engineering* 18 (3), 2012.
- [87] Rasha Ali Dihin, Waleed A Mahmoud Al-Jawher, Ebtessam N AlShemmary “Diabetic Retinopathy Image Classification Using Shift Window Transformer”, *International Journal of Innovative Computing*, Vol. 13, Issue 1-2, PP. 23-29, 2022.
- [88] Waleed Ameen Mahmoud Al-Jawher, A. Barsoum and Entather Mahos “Fuzzy Wavenet (FWN) classifier for medical images” *Al-Khwarizmi Engineering Journal*, Vol. 1, Issue 2, PP. 1-13, 2005.
- [89] SMR Taha, WA Mahmood “New techniques for Daubechies wavelets and multiwavelets implementation using quantum computing” *Facta universitatis-series: Electronics and Energetics* 26 (2), 145-156, 2013.
- [90] W. A. Mahmoud & I. A Al-Akialy “A Tabulated Method of Computation Multiwavelet Transform” *Al-Rafidain University College*, Vol. 15, PP. 161-170, Iraq, 2004.
- [91] WA Mahmoud “Computation of Wavelet and Multiwavelet Transforms Using Fast Fourier Transform” *Journal Port Science Research* 4 (2), 111-117, 2021.
- [92] AAR Sakran, SM Hadi, WAM Al-Jawher “A New Approach for DNA Sequence Analysis Using Multiwavelet Transform (MWT)” *Journal of Physics: Conference Series* 2432 (1), 012022.
- [93] SM Saadi, WAM Al-Jawher “ Proposed DeepFake Detection Method Using Multiwavelet Transform” *International Journal of Innovative Computing* 13 (1-2), 61-66, 2022.
- [94] AH Salman, WAM Al-Jawher “A Hybrid Multiwavelet Transform with Grey Wolf Optimization Used for an Efficient Classification of Documents” *International Journal of Innovative Computing* 13 (1-2), 55-60, 2022.
- [95] WA Mahmoud, AS Hadi, TM Jawad “Development of a 2-D Wavelet Transform based on Kronecker Product” - *Al-Nahrain Journal of Science*, Vol. 15, Issue 4, PP. 208-213, 2012.
- [96] H. Al-Taai, Waleed A. Mahmoud & M. Abdulwahab “New fast method for computing multiwavelet coefficients from 1D up to 3D” , *Proc. 1st Int. Conference on Digital Comm. & Comp. App.*, Jordan, PP. 412-422, 2007.
- [97] Waleed A. M. Al-Jawher, T Abbas – “Feature combination and mapping using multiwavelet transform” *IASJ, AL-Rafidain*, Issue 19, Pages 13-34, 2006

- [98] WA Mahmoud, MS Abdulwahab, HN Al-Taai: "The Determination of 3D Multiwavelet Transform" IJCCCE, vol. 2, issue 4, 2005.
- [99] WA Mahmoud, ALM Rasheed "3D Image Denoising by Using 3D Multiwavelet" AL-Mustansiriya J. Sci 21 (7), 108-136, 2010.
- [100] WA Mahmoud "Computation of Wavelet and Multiwavelet Transforms Using Fast Fourier Transform" Journal Port Science Research 4 (2), 111-117, 2021.
- [101] Walid A Mahmoud, Majed E Alneby, Wael H Zayer "2D-multiwavelet transform 2D-two activation function wavelet network-based face recognition" J. Appl. Sci. Res, vol. 6, issue 8, 1019-1028, 2010.
- [102] H. M Hasan, Waleed A. Mahmoud Al- Jawher, M. A Alwan "3-d face recognition using improved 3d mixed transform" Journal International Journal of Biometrics and Bioinformatics, Vo. 6, Issue 1, PP. 278-290, 2012 .
- [103] Waleed A Mahmoud, MR Shaker "3D Ear Print Authentication using 3D Radon Transform" proceeding of 2nd International Conference on Information & Communication Technologies, Pages 1052-1056, 2006 .
- [104] W. A. Mahmoud Z Jalal & N. K. Wafi "A New Method of Computing Multi-wavelets Transform using Repeated Row Preprocessing." Al-Rafidain Engineering Journal, Vol. 12, Issue 2, PP. 21-31., 2004.
- [105] AHM Al-Heladi, WA Mahmoud, HA Hali, AF Fadhel "Multispectral Image Fusion using Walidlet Transform" Advances in Modelling and Analysis B, Volume 52, Iss. 1-2, pp. 1-20, 2009.
- [106] Waleed Ameen Mahmoud "A Smart Single Matrix Realization of Fast Walidlet Transform" Journal of Research and Reviews in Computer Science, Volume 2, Issue, 1, PP 144-151, 2011.
- [107] W. A. Mahmoud, J.J. Stephan and A. A. Razzak "Facial Expression Recognition Using Fast Walidlet Hybrid Transform" Journal port Science Research ,Volume3, No:1, Pages 59-69 2020.
- [108] Maryam I Mousa Al-Khuzaa, Waleed A Mahmoud Al-Jawher, "New Proposed Mixed Transforms: CAW and FAW and Their Application in Medical Image Classification" International Journal of Innovative Computing, Volume 13, Issue 1-2, Pages 15-21, 2022.
- [109] Ali Akram Abdul-Kareem, Waleed Ameen Mahmoud Al-Jawher, "Image Encryption Algorithm Based on Arnold Transform and Chaos Theory in the Multi-wavelet Domain", International Journal of Computers and Applications, Vol. 45, Issue 4, pp. 306-322, 2023.
- [110] M Walid A Mahmoud, Majed E Alneby, Wael H Zayer "Multiwavelet Transform And Multi-Dimension-Two Activation Function Wavelet Network Using For Person Identification" Iraqi Journal Of Computers, Communications, Control And Systems Engineering, Vol 11, Issue 1, 2011.
- [111] W. A. Mahmoud & Ommama Razaq "Speech recognition using new structure for 3D neural network" University of Technology, 1st Computer Conference, PP. 161-171, 2010.
- [112] Walid A Al-Jowher, Nada N Al-Ramahi, Mikhled. Alfaouri "Image Identification And Labeling Using Hybrid Transformation And Neural Network" Neural Network World: International Journal on Neural and Mass - Parallel Computing and Information Systems; Prague, Volume 17, Issue 4, Pages 377-395, 2007.
- [113] Waleed A. Mahmud Al-Jawher, Talib M. J. Abbas Al-Talib, R. Hamudi A. Salman "Fingerprint Image Recognition Using Walidlet Transform" Australian Journal of Basic and Applied Sciences, Australia, 2012.
- [114] Maryam I Mousa Al-Khuzaaie, Waleed A Mahmoud Al-Jawher "Enhancing Brain Tumor Classification with a Novel Three-Dimensional Convolutional Neural Network (3D-CNN) Fusion Model" Journal Port Science Research, Volume 7, Issue 3, Pages 254-267, 2024.
- [115] F. Katran, Ebtessam N AlShemmary, Waleed Ameen Al Jawher "Deep Learning's Impact on MRI Image Analysis: A Comprehensive Survey" Texas Journal of Engineering and Technology, Vol. 25, PP. 63-80, 2023.
- [116] Sarah H Awad Waleed A Mahmoud Al-Jawher "Precise Classification of Brain Magnetic Resonance Imaging (MRIs) using Gray Wolf Optimization (GWO)" HSOA Journal of Brain & Neuroscience Research, Volume 6, Issue 1, Pages 100021, 2022.

- [117] Afrah U Mosaa, Waleed A Mahmoud Al-Jawher “A proposed Hyper-Heuristic optimizer Nesting Grey Wolf Optimizer and COOT Algorithm pages for Multilevel Task” *Journal Port Science Research*, Vol. 6, Issue 4, Pages 310-317, 2023.
- [118] U Mosa, Waleed A Mahmoud Al-Jawher “Image Fusion Algorithm using Grey Wolf optimization with Shuffled Frog Leaping Algorithm” *International J. of Innovative Computing*, Vol. 13, Issue 1-2, PP. 1-5. 2022 .
- [119] Walid Amin Al-Jawhar, Ayman M Mansour, Zakaria M Kuraz “Multi technique face recognition using PCA/ICA with wavelet and Optical Flow” 2008 5th International Multi-Conference on Systems, Signals and Devices, pages 1-6, 2008.
- [120] W. A. Mahmoud & Z. Ragib “Face Recognition Using PCA and Optical Flow” *Engineering Journal*, Vol. 13, Issue 1, PP. 35-47, 2007.
- [121] WAM Al-Jawher, SH Awad “A proposed brain tumor detection algorithm using Multi wavelet Transform (MWT)” *Materials Today: Proceedings 65*, 2731-2737, 2022.
- [122] Shaymaa Abdulelah Shaban, Waleed A Mahmoud Al-Jawher “K-Means Clustering Algorithm for Medical Images” *International Journal of Advances in Engineering and Management (IJAEM)*, Vol. 4, Issue 11, 2022 .
- [123] W. A. Mahmoud, Jane Jaleel Stephan and A. A. W. Razzak “Facial Expression Recognition from Video Sequence Using Self Organizing Feature Map” *Journal port Science Research Transaction On Engineering, Technology And Their Applications*, Vol. 4, Issue 2, 2021.
- [124] Ahmed Hussein Salman, A Waleed, Mahmoud Al-Jawher "Image Document Classification Prediction based on SVM and gradient-boosting Algorithms" *Journal Port Science Research*, Volume 6, Issue 4, Pages 348-356, 2023.
- [125] Waleed A Mahmoud, Ahmed S Hadi “Systolic Array for Realization of Discrete Wavelet Transform “ *Journal of Engineering*, Vol. 13, Issue 2, PP. 1-9, 2007.
- [126] KN Kadhim, SMR Taha, WA Mahmoud “A new method for filtering and segmentation of the ECG signal”, *Proceedings of the Annual International Conference of the IEEE Engineering ...*, 1988.
- [127] WAM Al-Jawher, SAA SHABAN “Clustering Of Medical Images Using Multiwavelet Transform And K-Means Algorithms” *Journal Port Science Research 5 (1)*, 35-42, 2022.
- [128] WAM Al-Jawher, SH Awad “A proposed brain tumor detection algorithm using Multi wavelet Transform (MWT)” *Materials Today: Proceedings 65*, 2731-2737, 2022.
- [129] Waleed A Mahmoud, Dheyaa J Kadhim “A Proposal Algorithm to Solve Delay Constraint Least Cost Optimization Problem” *Journal of Engineering*, Vol. 19, Iss 1, PP 155-160, 2013.
- [130] AHM Al-Helali, Waleed A. Mahmoud, HA Ali “A Fast personal palm print authentication Based on 3d-multi-Wavelet Transformation”, *Transnational Journal Of Science And Technology*, Vol. 2, Issue 8, 2012.
- [131] Hamid M Hasan, AL Jouhar, Majid A Alwan "Face recognition using improved FFT based radon by PSO and PCA techniques" *International Journal of Image Processing (IJIP)*, Volume 6, Issue 1, Pages 26-37, 2012.
- [132] Adnan HM Al-Helali, Hamza A Ali, Buthainah Al-Dulaimi, Dhia Alzubaydi, Walid A Mahmoud “Slantlet transform for multispectral image fusion” *Journal of Computer Science*, Vol.5, Issue 4, PP. 263-267, 2009.
- [133] Ali Akram Abdul-Kareem, Waleed Ameen Mahmoud Al-Jawher, “WAM 3D discrete chaotic map for secure communication applications” *International Journal of Innovative Computing*, Volume 13, Issue 1-2, Pages 45-54, 2022.
- [134] A. Abdul-Kareem, Waleed A. Mahmoud Al-Jawher, ”URUK 4D Discrete Chaotic Map For Secure Communication Applications” *Journal Port Science Research*, Vol. 5, Issue 3, PP. 131-141, 2023.
- [135] Ali Akram Abdul-Kareem, Waleed Ameen Mahmoud Al-Jawher ”Hybrid image encryption algorithm based on compressive sensing, gray wolf optimization, and chaos” , *Journal of Electronic Imaging*, Volume 32, Issue 4, Pages 043038-043038, 2023.166, 2023.
- [136] Saleem MR Taha, Walid A Mahmoud "New techniques for Daubechies wavelets and multiwavelets implementation using quantum computing “*Journal Facta universitatis-series: Electronics and Energetics*, Volume 26, Issue 2, Pages 145-156, 2013.

- [137] Ali Akram Abdul-Kareem, Waleed Ameen Mahmoud Al-Jawher “A Hybrid Domain Medical Image Encryption Scheme Using URUK and WAM Chaotic Maps with Wavelet–Fourier Transforms” *Journal of Cyber Security and Mobility*, Pages 435–464-435–464, 2023.
- [138] Q. K Abed, W. A Mahmoud Al-Jawher “A Robust Image Encryption Scheme Based on Block Compressive Sensing and Wavelet Transform” *International J. of Innovative Computing*, Vol. 13, I. 1-2, PP. 7-13, 2022.
- [139] Zahraa A Hasan, Suha M Hadi, Waleed A Mahmoud, “Speech scrambler with multiwavelet, Arnold Transform and particle swarm optimization” *Journal Pollack Periodica*, Volume 18, Issue 3, Pages 125-131, 2023.
- [140] Ali Akram Abdul-Kareem, Waleed Ameen Mahmoud Al-Jawher “ An image encryption algorithm using hybrid sea lion optimization and chaos theory in the hartley domain” *International Journal of Computers and Applications*, Vol. 46, Issue 5, PP. 324-337, 2024.
- [141] Qutaiba Kadhim, Waleed Ameen Mahmoud Al-Jawher “A new multiple-chaos image encryption algorithm based on block compressive sensing, swin transformer, and wild horse optimization” *Multidisciplinary Science Journal*, Vol. 7, Issue 1, PP. 2025012-2025012, 2024.
- [142] Saadi M. Saadi, Waleed Al-Jawher “Ensemble-Based Machine Learning Approach for Detecting Arabic Fake News on Twitter.” Publication date 2024/2/1, *Journal Revue d'Intelligence Artificielle*, Volume 38, Issue 1, 2024.