Sharma *et al.*
Biotechnology for Sustainable Materials (2024) 1:18
https://doi.org/10.1186/s44316-024-00018-7

Biotechnology for Sustainable Materials

REVIEW

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Advanced testing and biocompatibility strategies for sustainable biomaterials

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Abstract

To ensure the quality, dependability, and long life of sustainable biomaterials, we need comprehensive testing methods. These are for use in varied applications. This chapter provides an in-depth examination. It is of both destructive and non-destructive testing techniques. The techniques are for sustainable biomaterials. Recent advancements in testing technologies are also discussed. This includes machine learning and multi-modal imaging. Destructive testing techniques are used. Tensile testing, impact testing, chemical analysis, and accelerated aging evaluations are employed. These gather essential data. The data is regarding properties and performance of materials. In contrast to this, non-destructive testing methods are used. These include ultrasound, infrared spectroscopy, and imaging techniques. They allow for evaluation without causing damage to the biomaterials. Incorporating environmental impact assessments is discussed. It includes life cycle analysis. It underscores the significance of sustainability in evaluating testing procedures. The section focuses on techniques and approaches. These are required to ensure compatibility of materials in various fields. The aim of this chapter is to equip researchers. It is to equip engineers and practitioners with necessary knowledge and resources. The aim is to assess the efficiency and suitability of sustainable biomaterials. The materials are for various applications. This is done by delving into these evaluation techniques.

Keywords Artificial intelligence, Biomaterials, Destructive testing, Eco-toxicity testing, Materials characterization, Multi-modal imaging, Non-destructive testing, Sensor technology

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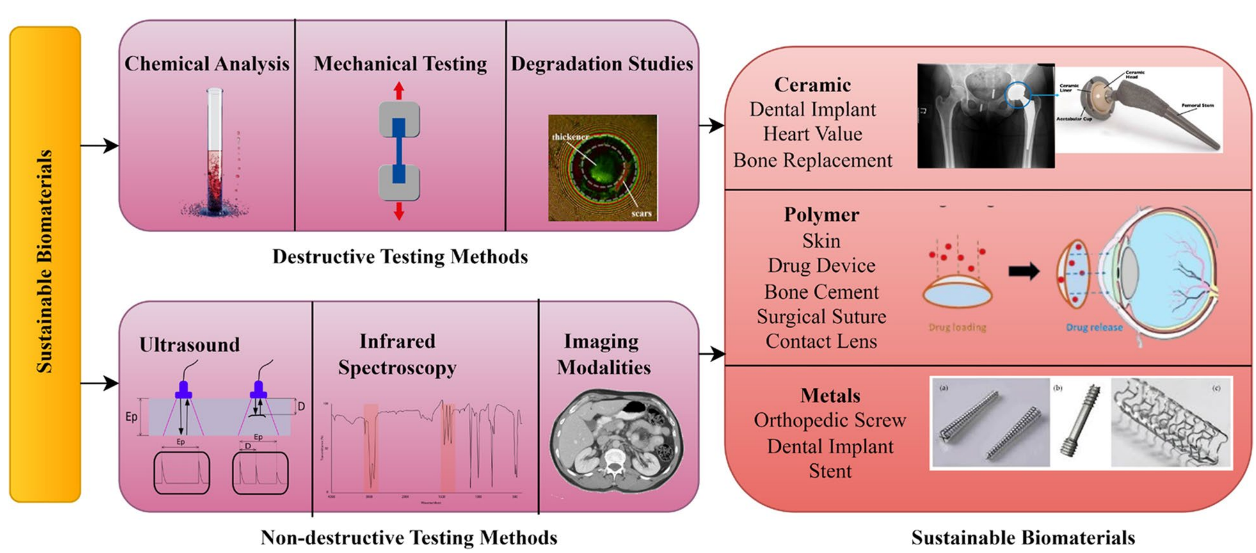
Graphical abstract



Introduction

Biomaterials are materials that are either naturally occurring or man-made, such as Biomaterials consist of naturally occurring or man-made materials, such as metals, polymers, ceramics, and their composites, that the human body can easily absorb and that demonstrate biocompatibility with living tissues. The European Society for Biomaterials Consensus Conference-II defines a biomaterial as any material that interacts with biological systems to support the replacement, treatment, or augmentation of organs, tissues, or bodily functions [1]. The significance of biomaterials extends beyond their interaction with living tissues; extensive testing is required to assure their safety and efficacy in medical applications. Inadequate testing can lead to patient hazards, device failures, and fatal biological reactions, stressing the importance of specific testing methodologies.

Biomaterials are generally categorized based on the characteristics of the materials they consist of, including polymeric materials, biomaterials, biopolymers, ceramic materials, and certain active metals and their composites. These substances are also divided into groups according to how they react or provoke living tissue [2]. Therefore, biomaterials include materials that are biodegradable, biomimetic, bioactive, and biologically inactive. Materials that interact with bodily fluids and parts are crucial for hand surgery involving the bones, hip or knee replacement, nerves, and tendons. These materials are referred to as biomaterials [3].

In Fig. 1, examining the relationship between implanted biomaterials and bones is backscattered electron microscopy (BSEM). In modern medicine, the evolution of biomaterials from mere biocompatibility to actively influencing biological processes is notable. Biomaterials play a crucial role in contemporary medicine, improving patient care by boosting therapy efficacy and facilitating

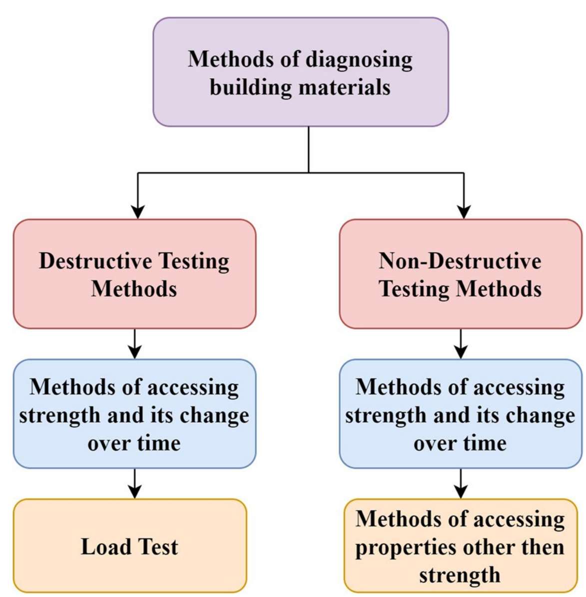


Fig. 1 Methods of diagnosing building materials: destructive and non-destructive testing approaches

tissue regeneration. They enable the restoration or replacement of damaged tissues, saving lives and enhancing the quality of life while minimizing surgical complications. Biomaterial advancements also contribute to the development of innovative medication delivery systems, improving effectiveness while minimizing adverse effects. Their adaptability is crucial for creating advanced medical devices and implants, which will ultimately enhance healthcare outcomes. This method demonstrates how varying densities of implanted biomaterials interact with different stages of bone tissue development, making visible and easily identifiable cracks [4]. This technique employs a photomicrograph to direct electrons towards the biomaterial's surface at a precise angle. The electrons engage with the material and emit energy in various manners, enabling the final energy to be detected and depicted in grayscale [5].

The diverse range of chemical, physical, and mechanical properties necessitated the use of a wide array of materials and composites. Nonetheless, in order for biomaterials to be used in the human body, they must possess certain characteristics and attributes to prevent patient rejection and negative responses [6]. When creating and producing products, as well as when assessing or examining their suitability for a specific purpose, these attributes and qualities must be considered. Medical devices designed to extend life or save lives utilize biomaterials [7]. Their application could potentially tackle significant environmental issues like pollution, resource depletion, and climate change, ultimately leading to a circular economy. The specific context in which the application is used determines the appropriate balance to be achieved. Similar to all medical devices, biomaterials undergo thorough testing to ensure compliance with the legal standards set by regulatory bodies. Biomaterials have evolved from merely interacting with body tissue to actively influencing biological processes, with the ultimate aim of promoting tissue regeneration [8].

Modern medicine relies heavily on biomaterials. These materials span a gamut of natural and synthetic varieties. Polymers, ceramics, metals, and composites are what biomaterials are. They have biocompatibility and can coexist with biological systems [9].Biomaterials aim to enhance organ and body system functionality. They can replace or repair damaged tissues. Biomaterials started out as just biocompatible. Now they have advanced to provoke biological processes. They also foster tissue regeneration. This evolution has powered the creation of state-of-the-art implants. This also spurred on the development of medical devices [10]. For uptake and development of biomaterials, thorough testing is essential. There are protocols in place for this. Both destructive and non-destructive testing techniques are used. The destructive ones incorporate chemical analysis and mechanical testing. These techniques modify or disassemble materials. The aim is to evaluate chemical and physical characteristics [11]. In contrast, non-destructive testing techniques don't interfere with the integrity of biomaterials. Examples are infrared spectroscopy and ultrasound. These techniques still allow examination. The techniques are vital to ensuring the integrity, efficiency, and safety of biomaterials in medical applications. Biomaterials need to pass through rigorous clinical studies. Regulatory requirements must also be sailed through for the biomaterials to be validated for clinical use. This ensures the materials meet quality standards and pose the least danger to patients [12].

Definition and significance

Sustainable biomaterials are eco-friendly materials. They are derived from renewable biological sources. They minimize environmental impact. They offer biodegradability. They have potential for reuse. These materials are advantageous. They outperform conventional materials. These are made from fossil fuels or other non-renewable resources. They do so due to their eco-friendliness and biodegradability [13, 14]. They address pressing environmental challenges. These include pollution and resource depletion. They also address climate change. This is done by lessening greenhouse gas emissions from production and disposal. Sustainable biomaterials reduce dependency on limited supplies. They do this by utilizing renewable resources. In addition, many of these materials degrade spontaneously. They do so without leaving hazardous residues. This action results in a reduction of waste and pollution. In addition to environmental benefits, sustainable biomaterials also offer economic growth. They also promote technological advancement. This is due to their diversity and innovative potential [15, 16].

Governments around the world are investing more. This is in the research and commercialization of these materials. Investment leads to economic growth. It results in job creation in the fast-growing green technology industry. Their value promotes economic growth. Their usage is also beneficial for the environment [17]. Sustainable biomaterials are essential. They are for achieving sustainable development goals. They have a transformative impact. It is on resource economy, conservation, and durability. Their adoption ensures a more sustainable future. A future that is also more affluent for future generations. This is especially true as global efforts to combat environmental worries gain momentum [18].

Numerous industries, including the packaging, building, textile, healthcare, and automotive sectors, use these materials [19]. Bioplastics, which are sourced from corn starch or sugarcane, provide a sustainable substitute for traditional plastics, as shown in Fig. 2. To promote circular economy, it helps in decreasing reliance on petroleum-based plastics [20]. Biomaterials provide the same useful effect. They have lower environmental impact and are used in construction. Composites made of bamboo or hemp are biomaterial examples. They provide strong and lightweight substitutes for conventional materials. Examples include steel and concrete [21].

Characteristics and research findings for biopolymers

Biopolymers are sustainable materials with potential for tissue engineering. They are also biocompatible. The materials have found attention for their promise in medication delivery and medical device use. The features of these materials are noteworthy. Particularly, their biodegradability is important. Their biocompatibility and mechanical strength are also key. Additionally, their adaptability to chemicals makes them useful for many biomedical applications [22]. Recent research has identified types of nanocellulose. These include cellulose nanocrystals (CNCs) and bacterial nanocellulose (BNC). These materials are used in biomedical applications. They have shown significant improvements in mechanical characteristics and stability. Bioactive glasses are also good materials. They include 45S5 bioglass and SiO2-CaO-P2O5 glass. These materials exhibit high bioactivity.

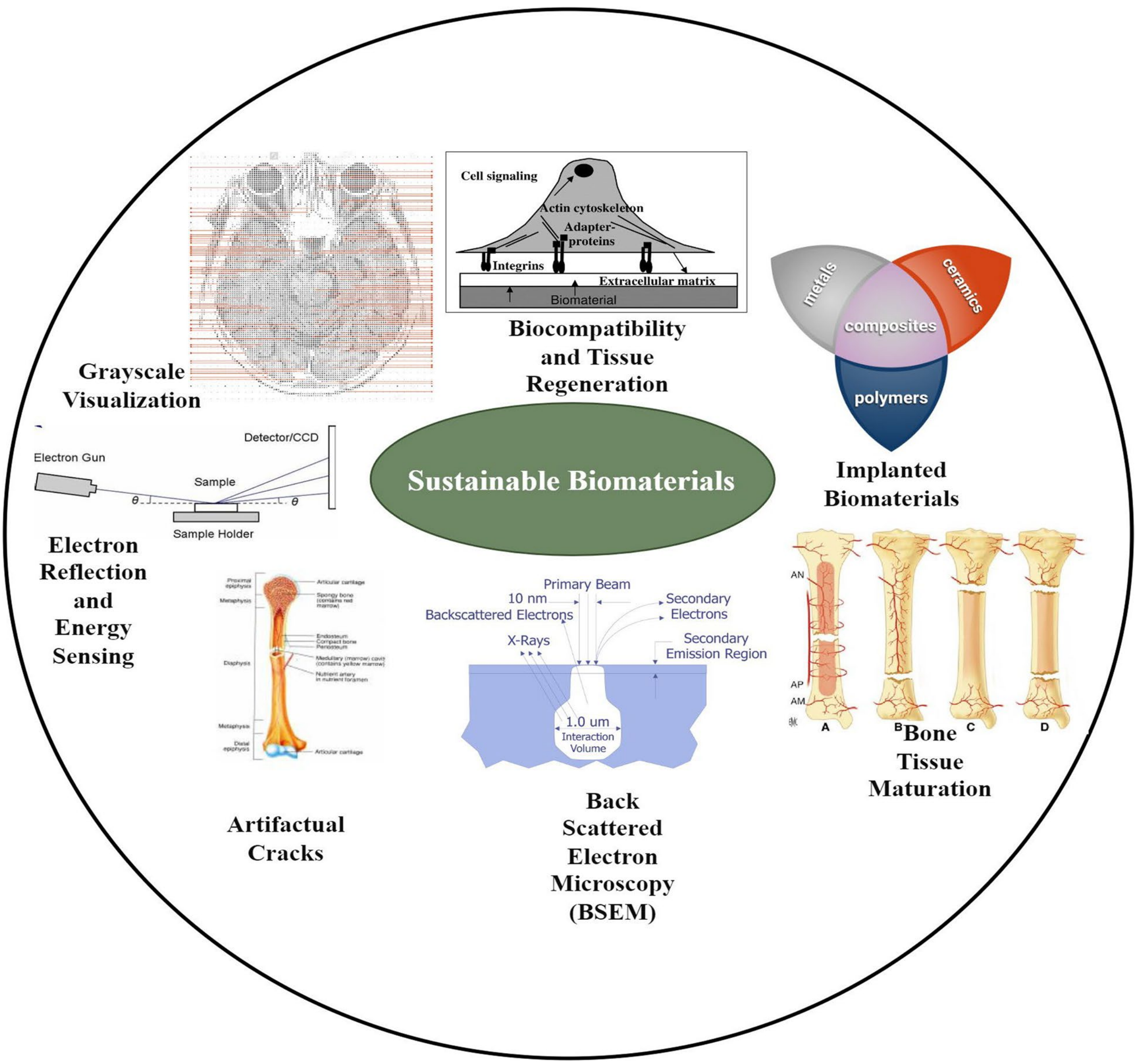


Fig. 2 Infrared spectroscopy analysis of the interaction between implanted biomaterials and bone tissue maturation

They can also interact with bone tissue to aid the healing process [23].

Biopolymer research is intense. Polylactic acid (PLA), polyhydroxyalkanoates (PHA), and chitosan have been studied. The purpose of the study is to understand how they degrade in biological contexts. This allows for controlled breakdown. It allows for assimilation within living tissues. Their biodegradability is especially beneficial. It helps to avoid long-term issues linked with permanent implants. Scientists have advanced their comprehension of the mechanical and chemical stability of biopolymers. They used in vitro studies to do this. For example, tensile tests have shown. Those tests showed PLA and PHA have required strength. They also have required flexibility. This is for their application in load-bearing tissue engineering [24]. These qualities give biopolymers the ability to withstand physiological pressures. They make perfect for specific applications. For example, bone scaffolding and cartilage regeneration. Alginate and chitosan biopolymers have been part of studies too. These studies have been conducted in vivo. The results of these studies have been positive. They show good host reactions. They also show biocompatibility. This suggests these biopolymers could be used directly in biological systems [25].

Related work

A) Biodegradable polymers and nanocomposites

Recent advancements in biodegradable polymers and nanocomposites have brought about a revolution. It is in their utility across a raft of industries. These advancements' emphasis is on enhanced sustainability and performance [26]. Characteristics of biodegradable polymers have experienced significant improvements. This comes from nanomaterials like nanocellulose and nanoparticles. Polyhydroxyalkanoates (PHA) and polylactic acid (PLA) are two examples [27]. In packaging and structural contexts, nanocomposites present an alluring substitute to petrol-based plastics. This is because they offer better mechanical qualities. They boast increased strength and durability [28, 29]. Bioactive substances and growth factors get included in biodegradable polymers relevantly in the biomedical area. Objective is to enhance wound healing and favor tissue regeneration [30]. Here, polymers incorporate nanomaterials. The goal is to make composite scaffolds. They feature a controlled release property. This character is useful for tissue incorporation and cell adhesion. These are both vital in tissue engineering and applications for drug delivery [31, 32]. Additionally, life cycle assessments indicate lower carbon footprints. These assessments also highlight a reduced reliance on nonrenewable resources when compared to typical plastics. This underscores the environmental benefits of both biodegradable polymers and nanocomposites [33]. The aforecited assessments underscore their purpose in advancing eco-friendly behaviors. It is also about reducing ecological consequences tied to plastic waste [34]

B) Bioactive materials for healthcare

Bioactive elements have undergone profound developments lately. The focus is on improving patient results and treatment efficacy [35]. Bioactive substances aim to engage positively with biological systems. This facilitates the body's natural healing, regeneration, and integration. Bioactive glasses, ceramics, and polymers soaked with bioactive chemicals are part of this group [36]. The field of bioactive glasses is well researched. This is due to their capability to lay a hydroxyapatite layer on bone tissue, simulating bone's mineral composition [37]. Materials like these offer a scaffold for new bone's growth. They enhance implant longevity. These materials have been utilized in bone tissue engineering [38]. They improve bone repair and regeneration processes. Bioactive ceramics present a great deal of promise. They are not only beneficial in bone regeneration. They also show value in dental applications. These applications enhance implant longevity and osseointegration. Ceramics release ions. They encourage cell division and proliferation. This process forges robust interfaces [39]. These interfaces connect the implant with surrounding tissues. These contribute to the promotion and maintenance of dental health. Tissue engineering, regenerative medicine, medical device coatings. These are few fields. Bioactive materials are used in healthcare for these and more conventional biomedical uses. Ongoing research has a distinct goal. The aim is to enhance the mechanical traits of these materials [40]. Moreover, to improve their biocompatibility and therapeutic capabilities. This would pave the way for creating novel healthcare solutions. The solutions will enhance patient care and quality of life. Bioactive substances can markedly affect how healthcare technologies evolve in the future. This is possible as long as interdisciplinary collaborations keep progressing in the field [41].

C) Life Cycle Assessments (LCAs) and environmental impact

When we evaluate the environmental influence of products or processes, it requires consideration at every life cycle stage. This spans from raw material extraction to product disposal. We consider life cycle assessments. These are often abbreviated LCAs. They are critical [42]. The environmental toll of every stage is high. This includes resource depletion and energy use. Emissions to air, water, and soil are also concerning. Waste production is another issue. This method provides an all-inclusive approach. It gives a better understanding of environmental costs. It also identifies solutions to reduce such costs. Environmental impact mitigation solutions exist. These include the use of energy-efficient technology. Also alternative materials or logistics and transportation enhancements. LCAs can be valuable in these cases [43]. LCAs assist in making informed choices. They have the ability to reduce ecological footprints. Additionally, they promote sustainability across a range of sectors and industries. This is accomplished by taking the full life cycle into account. Environmental evaluations must include life cycle assessments (LCAs). The rationale is that this ensures a holistic perspective. This aids companies and policymakers. It helps them to prioritize initiatives. These initiatives aim at enhancing environmental performance. Additionally, they support sustainability targets that are long-term [44].

Applications in various industries

Sustainable biomaterials have wide applications. They are found in a number of industries. They are useful in making eco-friendly goods and processes [45, 46]. Figure 3, It showcases broad uses of eco-friendly materials. These are seen across many sectors. These applications include packaging solutions that minimize environmental impact, textiles that offer sustainable alternatives for clothing, biodegradable medical implants and devices, and lightweight components in the automotive industry. Each example highlights the role of sustainable biomaterials in promoting greener, more efficient practices across different fields. Examples of applications for sustainable biomaterials include the following:

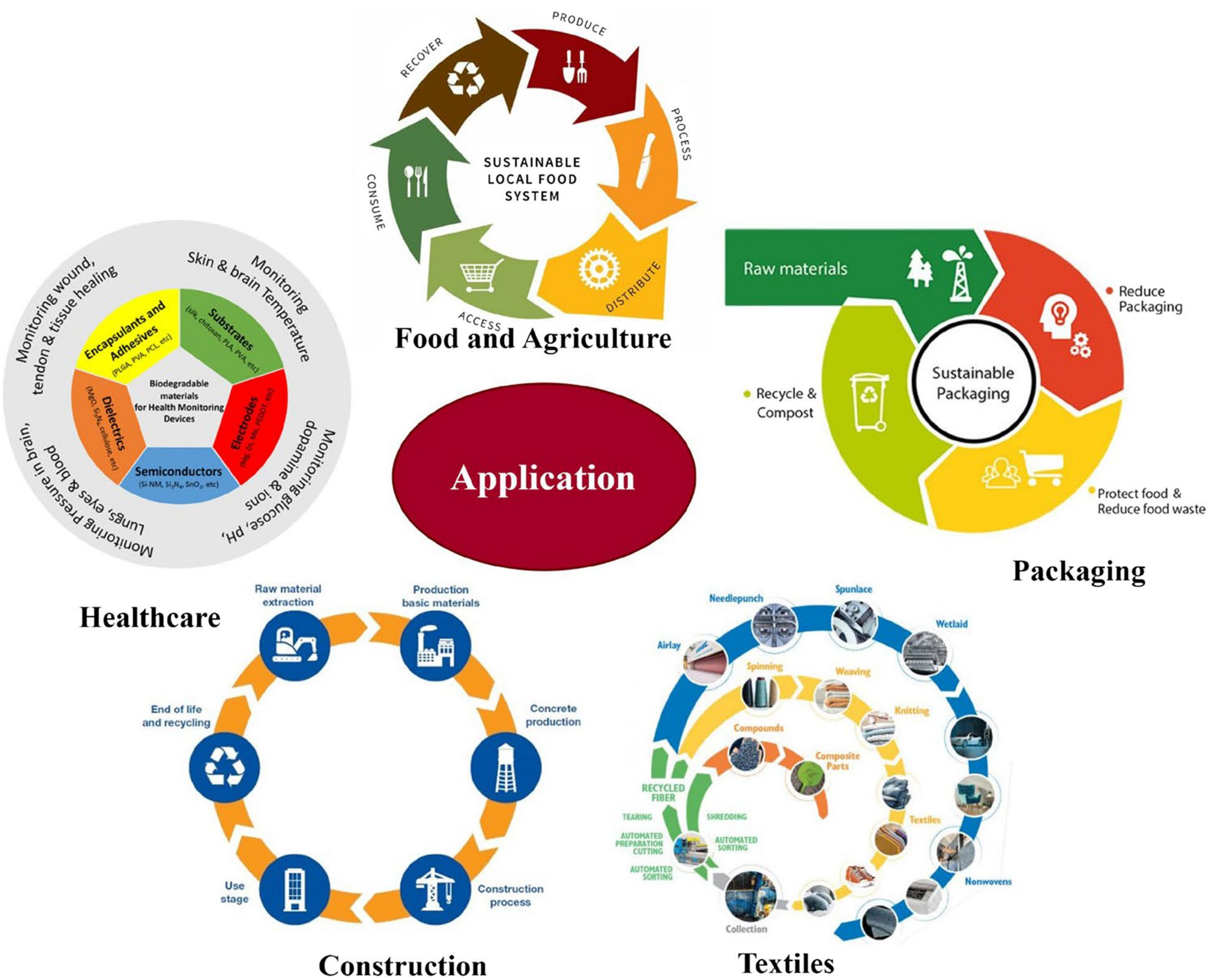


Fig. 3 Applications of sustainable biomaterials in various industries

A) *Packaging:* The use of biomaterials in packaging applications is growing. Examples of these materials include bioplastics made from sugarcane, corn starch, or algae. Because they are biodegradable and compostable, these bioplastics reduce the environmental impact of packaging waste while performing similarly to conventional petroleum-based plastics [47]. Biomaterials are increasingly being used in packaging applications; bioplastics made from sugarcane, corn starch, and algae are a few prominent examples. Because they come from renewable sources, sugarcane-based bioplastics—like bio-based polyethylene—have comparable qualities to traditional plastics but have a substantially lower carbon footprint. These materials are used in bottles and other containers. Polylactic acid (PLA), one of the flexible corn starch-based bioplastics that are used in food containers and packaging films, decomposes naturally in composting environments [48]. Alginate-based bioplastics are becoming more and more popular due to their potential advantages for biodegradation, especially in coastal environments. These biomaterials close the loop through compostability and biodegradability, which not only lessens the environmental impact of packaging waste but also advances the ideas of the circular economy [49].

B) *Textiles:* The production of textiles uses fibers obtained from renewable resources like hemp, bamboo, and organic cotton. These biomaterials provide environmentally friendly substitutes for conventional cotton, which uses a lot of water and pesticides. Moreover, lyocell is a wood pulp-based biodegradable fiber. It serves as an environmentally beneficial substitute for polyester and other synthetic fibers [50]. Fibers are sourced from renewable sources. Hemp, bamboo, and organic cotton are few such examples. These substances provide sustainable alternatives for conventional materials. In particular, textile production often requires high water and pesticide usage [51]. Hemp is robust fiber. It's also environmentally beneficial. It's utilized in textiles and fabrics. Hemp is valued for its quick growth and longevity. Bamboo is another plant that grows quickly. It produces soft fibers that are breathable. These can be utilized for various garment applications [52]. Organic cotton is a fiber that doesn't require artificial chemicals. It is beneficial for soil health and biodiversity and consequently reduces its impact on the environment. A biodegradable cloth made from wood pulp is called lyocell. Its suppleness and ability to absorb moisture are well-known. Additionally, it has little effect on the environment while being made. This makes it a more environmentally friendly option than synthetic fibers like polyester. Biomaterials like these are beneficial [53]. They reduce the amount of water and chemicals used in standard textile production processes. They also encourage the textile industry to be more sustainable [54].

C) *Construction:* Sustainable construction methods lean heavily on the use of biomaterials. These materials include straw bamboo, hempcrete, and mycelium. Hempcrete is a mix of lime and hemp fiber. Mycelium is used as a binding agent and is a fungus. A comparison to conventional building materials such as steel and concrete shows biomaterials have advantages. These include reduced embodied energy and carbon sequestration. They also enhance indoor air quality [55]. Biomaterials such as mycelium, hempcrete, straw, and bamboo are increasingly being used. This is happening in sustainable construction techniques. They offer greener substitutes for conventional building materials. These materials include steel and concrete. Straw bales are readily available agricultural byproducts. They have good thermal performance; hence, they are utilized as structural elements and insulation. Bamboo is used for flooring and structural parts because of its strength and quick growth. During its drying phase, hempcrete—a mixture of lime and hemp fibers—sequesters carbon dioxide while offering insulation [56].

D) *Healthcare:* Tissue engineering, implants, and medical devices all use biomaterials. Biodegradable polymers, such as polyglycolic acid (PGA) or polylactic acid (PLA), find applications in tissue scaffolding, drug delivery systems, and sutures. The requirement for any further surgeries is minimized. These are surgeries needed for the removal of biomaterials. Biomaterials that break down inside the body in a way that's harmless [57]. Tissue scaffolding is a common application. Another one is medication delivery. And also sutures. These are common applications for biodegradable polymers. These polymers are polyglycolic acid (PGA) as well as polylactic acid (PLA). PGA is renowned for exceptional strength. Also, it has a quick rate of breakdown. This polymer appears in absorbable sutures. And also in scaffolds for tissue engineering. PLA is a controlled biodegradable material. It is also a biocompatible one. It can be used for implants. And also for medication delivery applications. It is created from renewable resources such as maize starch [58]. Biomaterials break down in the body over time. This causes no harm. It also minimizes the need for additional procedures to remove implants. This in turn promotes sustainable medical practices. It lowers healthcare costs. It also lessens patient discomfort [59].

E) *Automotive:* To lighten automobiles and enhance fuel economy, biomaterials are employed within automotive components. For instance, biocomposites are products of natural fibers. Fibers like kenaf jute or flax are used in making door trims, seatbacks, and panels for interiors. These biomaterials reduce the vehicle's carbon footprint. They yet provide mechanical properties on par with those of traditional fiberglass composites [60]. Kenaf jute and flax fibers are biomaterials. They are used in interior panels, seatbacks, and door trims. Also in some other parts of vehicles to lessen weight and raise fuel economy. Using this natural fiber biocomposites vehicle's carbon footprint is significantly lowered. The biocomposites still maintain mechanical qualities thatles of sustainable options in car design and manufacture are flax. are comparable to standard fiberglass composites. Examples of sustainable options in car design and manufacture are flax. Flax is used for interior components. Jute serves as seatbacks. Kenaf is appropriate for door panels [61].
F) *Food and Agriculture:* Biodegradable cutlery and mulch for farms. Food packaging all utilizes sustainable biomaterials. You can substitute petroleum-based packaging with biodegradable materials. These materials can be derived from starch or cellulose derivatives. Bioplastics are manufactured using agricultural leftovers. An example is corn stover. Another is sugarcane bagasse. This strategy lessens waste. It also promotes a circularity in farming practices [62]. There are numerous environmentally friendly alternatives. They replace conventional petroleum-based items. Food packaging is one example. Biodegradable cutlery is another. Farm mulch is also on the list. These items showcase the many uses of sustainable biomaterials. These biomaterials are typically found in the food and agriculture industries.Polylactic acid, in short PLA, is one example of a biodegradable packaging material. A second example is polyhydroxyalkanoates, in short, PHA. They are made from starch or cellulose derivatives. These examples are widely used. The reason for this is their compostable nature. They also have a low environmental impact [63]. Bioplastics are derived from agricultural wastes. Corn stover and sugarcane bagasse are two examples. These bioplastics encourage circular farming methods. They also promote waste minimization. Sustainable practices are encouraged. This happens across the food supply chain with these biomaterials. Environmental issues related to plastic waste are tackled as well [64].

Figure 4 provides a breakdown of how sustainable biomaterials are utilized across various sectors.

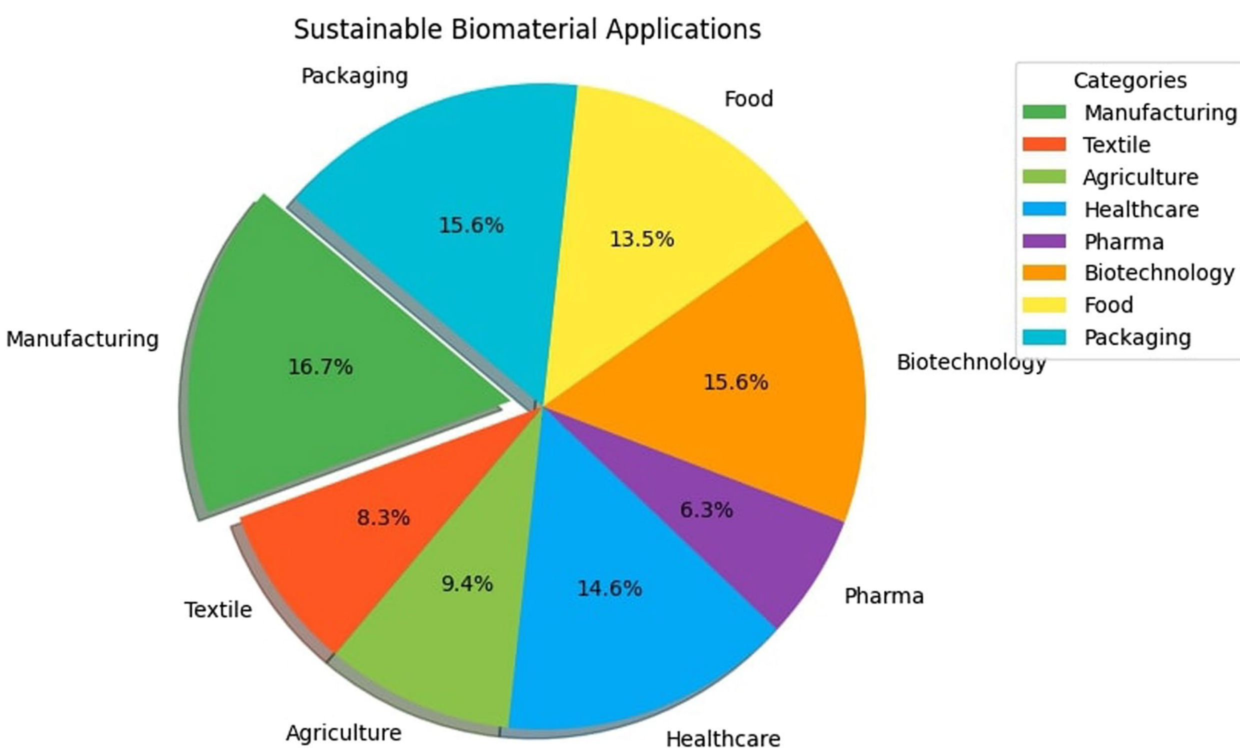


Fig. 4 Distribution of sustainable biomaterial applications across industries

Pharmaceuticals use biomaterials for packaging and delivery systems, making up 6% of the total. Biotechnology accounts for 15% through applications in biofuels, biopharmaceuticals, and biodegradable products. The food industry employs 13% for eco-friendly additives and packaging. Biodegradable materials and bioplastics represent 15% of packaging, while medical devices and implants make up 14%. Agriculture uses biomaterials for mulch and fertilizers at 9%, and the textile sector utilizes 8% for materials like hemp and organic cotton. Manufacturing, which includes automotive and building materials, represents 16% of the applications [59].

Destructive testing methods

Destructive testing is a test technique that pinpoints the precise point of failure of a material, machine, or component in order to comprehend its behavior or performance. The specimen in question is continuously stressed during this process until it finally fails due to material deformation or destruction. Destructive testing can be conducted in accordance with established protocols or designed to produce specific service conditions [65]. High-speed cameras that continuously record until they pinpoint the issue are frequently used in destructive testing to find malfunctions. To start the camera moving, stress gauges or sound detectors send out a signal. The camera will stop recording after the failure, but you can still examine the slow-motion footage to see what transpired prior to, during, and following the catastrophic event [66].

Figure 5 destructive Testing illustrates the use of destructive testing techniques, which are crucial for evaluating components before mass production begins. Original equipment manufacturers (OEMs) can apply the required machine maintenance and operating recommendations by using destructive tests to determine the limits of their products. After undergoing destructive testing, the tested item and its components cannot be used again in normal operation because the damage caused by the test is irreversible. This method still has valid applications, even though destructive testing causes damage to these items that cannot be repaired [67]. For biomaterials, destructive testing is critical to avoid using materials that could fail in clinical settings, hence protecting patient health. Certain working conditions are not suitable for the physical and chemical properties of machines. For instance, using metals that are prone to corrosion in humid environments is not a good idea. In order to keep them from failing for end users, destructive testing highlights these inconsistencies and potential downsides. This test procedure is required by law in some industries [68].

Mechanical testing

Mechanical testing includes a range of techniques for assessing a material's mechanical characteristics. These characteristics, which are essential for comprehending how materials will behave under various mechanical loads, include strength, stiffness, toughness, hardness, ductility, and others [69]. In medical applications, insufficient evaluation of these qualities could lead to significant consequences, jeopardizing patient safety. Here are a few essential techniques for mechanical testing:

Tensile testing

One of the most popular mechanical tests is the tensile test. In this test, a specimen of material is pulled under tension. It is pulled until it fractures. Stress–strain curves can be created. This is because testing allows for the continuous measurement of force. It also allows the measurement of a specimen's deformation. From these curves, it is possible to calculate characteristics. These characteristics include elongation and modulus of elasticity. Yield strength and ultimate tensile strength can also be calculated. These are also known as Young's modulus and UTS [70]. Tensile testing offers important insights. It shows a material's capacity to bear pulling forces without failing.

Tensile testing has shown itself in studies on biopolymers. These biopolymers include polyhydroxyalkanoates (PHA) and polylactic acid (PLA). Tensile testing is an effective method for measuring parameters. These parameters include Young's modulus and ultimate tensile strength. For instance, a study examined PLA composites. These composites were reinforced with cellulose nanocrystals. The study discovered increased tensile strength. This strength was

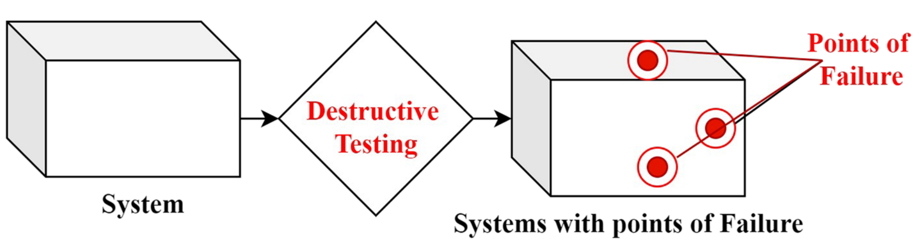


Fig. 5 Destructive testing

suitable for biomedical applications. Tests were performed in vitro. They showed that biopolymer composites stayed intact under tension. This makes them suitable for load-bearing medicinal applications [71].

In tensile testing, for example, stress (σ) is calculated by dividing the applied force (F) by the cross-sectional area (A) of the specimen:

$$\sigma = \frac{F}{A} \tag{1}$$

Similarly, strain (ϵ) is determined by dividing the change in length (ΔL) of the specimen by its original length (L_0):

$$\epsilon = \frac{\triangle L}{L_0} \tag{2}$$

From stress–strain curves obtained during tensile testing, various mechanical properties can be calculated. Young's modulus (E), which represents a material's stiffness, is determined from the initial linear region of the curve:

$$E = \frac{\sigma}{\varepsilon} \tag{3}$$

The stress at which a material starts to deform plastically is known as the yield strength, and it is usually found by locating the point on the curve where linearity breaks down. The highest stress a material can sustain before failing is known as its ultimate tensile strength (UTS), and it is shown at Fig. 6 as the apex of the stress–strain curve.

Compression testing

This type of testing evaluates the behavior of a material under compressive forces. A specimen is put through a compressive force in this test until it fails or deforms. Figure 7 shows the compression testing yields data on compressive strength, modulus of elasticity in compression, and behavior under compression, much like tensile testing does [72].

Compression testing of biodegradable polymers used in tissue engineering, such as chitosan and PLA, proved their capacity to support cellular structures without severe distortion. Studies imitate in vivo circumstances, demonstrating that these materials maintain structural integrity under compressive stress, indicating their applicability for bone scaffold applications [73].

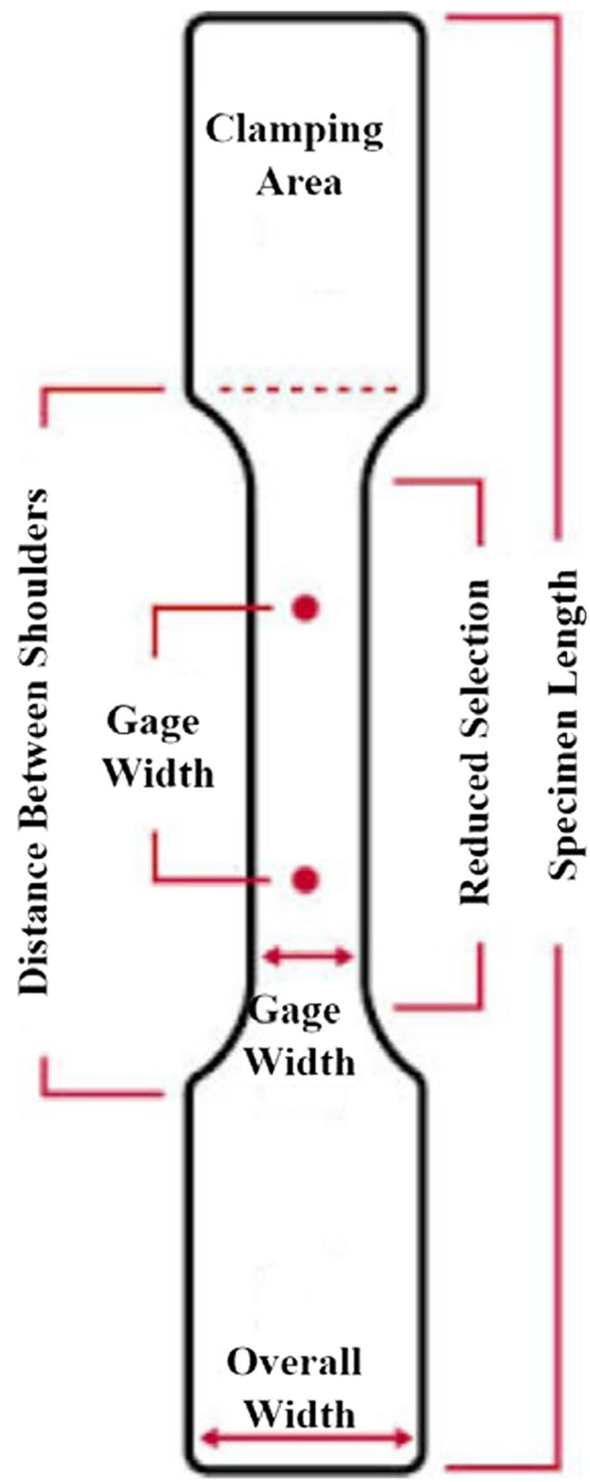


Fig. 6 Tensile Testing

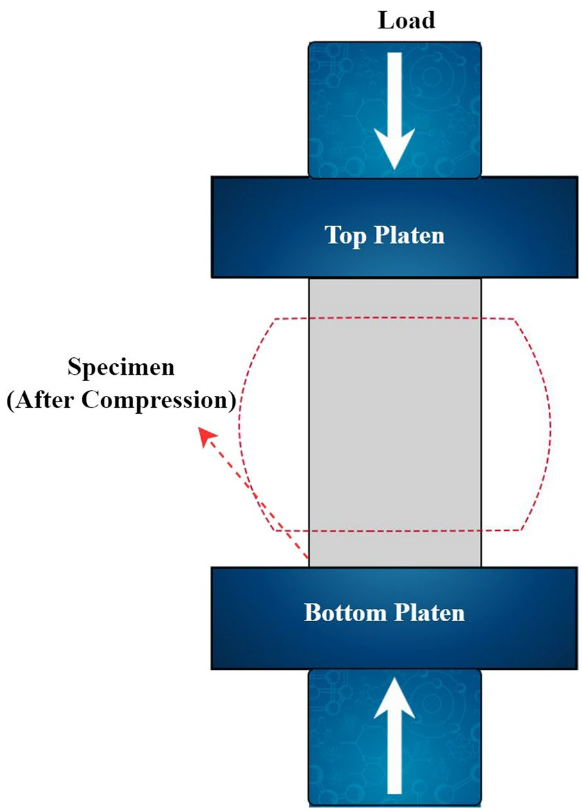


Fig. 7 Compression Testing

Flexural testing

Evaluation of a material's resistance to bending or flexure is done through flexural testing. A three- or four-point bending setup is usually used to apply a bending load to a specimen that resembles a beam. The parameters that flexural testing measures include flexural strength, flexural modulus, and modulus of elasticity in bending. These parameters are critical for materials that are used in applications in Fig. 8, where loads that resemble bending are applied.

Flexural testing was utilized in vitro to determine bending resistance in biocomposites, such as PLA reinforced with biochar [74]. The results demonstrated improved flexural modulus, demonstrating the promise of these biopolymers in medicinal and structural applications that require flexibility and load support.

The material's flexural strength (σ_f) is determined by multiplying the specimen's dimensions and mechanical properties by the maximum bending moment (M) that is applied to it. The flexural strength of a simply supported beam with a concentrated load at its center is determined by:

$$\sigma_f = \frac{3M}{2bd^2} \tag{4}$$

Where, The greatest bending moment applied to the specimen is represented by M.The specimen's breadth is represented by b. d represents the specimen's thickness or depth.

The linear component of the stress–strain curve during flexural testing is used to calculate the flexural modulus (E_f), which indicates the stiffness of the material in bending. It is computed with the following formula:

$$E_f = \frac{L^3}{4bd^3} \cdot \frac{d\sigma}{d\epsilon} \tag{5}$$

Where, L is the length of the span that separates the supports.The stress placed on the specimen is represented by.ϵ is the strain that the specimen is under.

Hardness testing

Measures a material's resistance to dents and scratches through a process called hardness testing. Many hardness testing techniques are available, each appropriate for a particular set of materials and uses, such as the Shore, Brinell, Vickers, and Rockwell hardness tests. The surface hardness of a material can be determined through hardness testing and is frequently linked to its strength and resistance to wear [75].

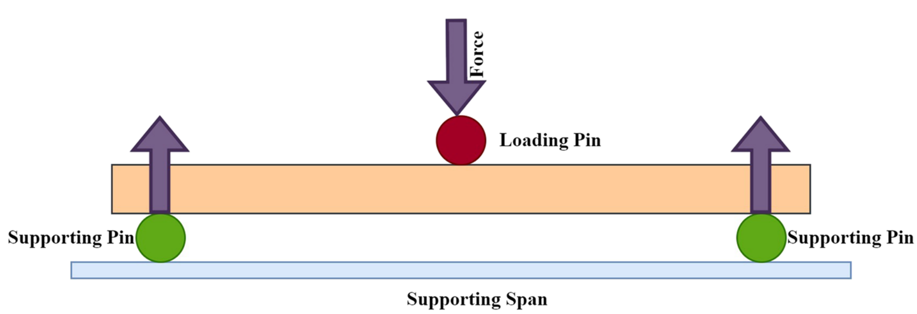


Fig. 8 Flexural Testing

Brinell hardness tests were used to assess the hardness of materials like PLA, particularly in applications such as orthopedic implants. These experiments demonstrated that PLA maintained appropriate hardness under physiological circumstances, improving durability and slowing degradation over time.

The particular computation or formula differs based on the hardness testing technique employed. For instance, the following formula is used to determine the hardness value (HB) in the Brinell hardness test:

$$HB = \frac{2P}{\pi D(D - \sqrt{D^2} - d^2)} \tag{6}$$

Where, The applied load is expressed in kilograms-force (kgf) by P. D is the indenter ball's diameter expressed in millimeters (mm). d is the indentation's diameter expressed in millimeters (mm). The depth to which an indenter penetrates under two loads—a minor load and a big load—determines the hardness value in the Rockwell hardness test. A scale letter and a numerical value are used to express the Rockwell hardness number (e.g., HRC 50).

Destructive testing techniques include applying great stress to materials until they break and providing information about how they function under harsh circumstances via the use of instruments like stress gauges and high-speed cameras. As an illustration, consider the following tests: tensile for strength, compression for compressive strength, flexural for bending resistance, and hardness for durability guarantee. In the aerospace, construction, automotive, and manufacturing sectors, for example, flexural testing is used for lightweight materials, tensile testing is used for alloys, compression testing is used for concrete strength, and hardness testing is used for component durability.

Chemical testing

Chemical testing entails examining a material's atomic and molecular makeup, characteristics, and behavior. It includes a broad range of methods for comprehending the composition, interactions, and reactions of substances in terms of their chemistry [76]. Important components of chemical testing consist of the following:

Elemental composition analysis

This particular type of chemical examination confirms the elements' existence. It measures the concentration in material. Elemental composition of solids is observable. Liquids are measurable. Even gases can be appraised. We use methods such as inductively coupled plasma mass spectrometry. We use atomic absorption spectroscopy. X-ray fluorescence is another method we apply. For instance Bilo and others in 2018. They studied numerous XRF techniques. These were for elemental analysis of particulate matter. It proved the method's value. The method is useful in environmental monitoring [77]. Likewise, Dhara and Misra in 2019. They underscored the utilization of total reflection X-ray fluorescence spectrometry. This was for elemental characterization of nuclear materials. This demonstrated high value for XRF. XRF's utility and accuracy are clear across diverse applications [78]. These techniques are crucial. They guarantee rules of safety are observed. This is particularly in environmental research. It is also in industrial setups.

Chemical bonding analysis

This technique assesses myriad chemical bonds in a material. It gauges their strength. Approaches like nuclear magnetic resonance, or NMR, X-ray photoelectron spectroscopy (XPS), and infrared spectroscopy (IR) illustrate functional groups. They illustrate bonding configurations. They illustrate the molecular structure of diverse matter. For instance, the study of Garrido et al. (2024) looked into emerging 2D materials. This was after chemical functionalization. It stressed how critical bonding analysis is. It is important in understanding material properties [79]. Additionally, Fadley (2010) has written a review on advances in X-ray photoelectron spectroscopy. It emphasizes the importance of this technique in studying surface chemistry. It also zeroes in on electronic states [80]. These methods are essential in understanding molecular architecture. They also help understand reactivity in materials. These materials have a variety of applications.

Thermal behavior

Evaluation of the material's phase transitions is achieved. Thermal stability and decomposition temperatures are analyzed. This is done through thermal analysis techniques. To explore how temperature impacts materials. And to determine the thermal properties of materials, certain techniques are employed. Some of them are differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA). Differential thermal analysis (DTA) is also used. For example, Collier (2016) assembled thermal analysis data. This data is on transition and decomposition temperatures of different cement phases. This provided key insights into thermal behavior [81]. In addition, Blanco and Siracusa (2021) delved into thermal techniques. They wanted to characterize biosourced polymers. The goal was to show the importance of these methods. It's all about understanding the thermal properties of sustainable materials [82]. Evaluations like these are a necessity. They help ascertain the performance and stability of materials in various applications.

Understanding the atomic and molecular properties of materials is complex. Such understanding provides details about materials' composition, interactions, and reactions. It demands chemical testing. To ascertain the existence and concentration of elements in solids, liquids, and gases, elemental composition analysis is used. It employs methods such as atomic absorption spectroscopy (AAS), inductively coupled plasma mass spectrometry (ICP-MS), and X-ray fluorescence (XRF) [83]. In environmental research, for example, trace element analysis in water samples is done. This ensures that safety regulations are maintained. This is achieved using ICP-MS. Chemical bonding analysis studies bonding types and molecular structures. Techniques used are nuclear magnetic resonance (NMR), X-ray photoelectron spectroscopy (XPS), and infrared spectroscopy (IR). IR spectroscopy has applications in the pharmaceutical industry. It is used to verify the chemical makeup of medications, guaranteeing their efficacy and purity. Phase transitions and thermal stability are analyzed by thermal behavior analysis. It uses methods like thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC). In materials science, this is crucial for determining heat-resistant polymers. They are integral in automotive components. Hence, chemical testing is an essential part of every business. Its purpose is to ensure that goods are safe, function well, and meet regulatory requirements [84].

Degradation studies

Exploration of behaviors and processes in material degradation in diverse environmental conditions is an aspect of chemical testing. This involves assessing materials' durability and performance over time. Environmental exposure testing and accelerated degradation testing both play a role. They mimic long-term degradation processes. Such processes include oxidation, corrosion, and chemical reactions [85].

Accelerated degradation testing

Materials or products are subjected to severe conditions. This technique simulates long-term degradation of those materials. It also simulates degradation of those products in a shorter period of time. Prediction of longevity is considered. Robustness and functionality of materials under the conditions of accelerated aging are considered as well. This is a particularly valuable application of this testing. Accelerated degradation testing attempts to hasten degradation processes. These processes include oxidation and hydrolysis. Also, these processes include chemical reactions. Materials are subjected to high temperatures and high humidity. They are also subjected to UV light or other environmental stressors [86]. This is a deliberate attempt at this process. This testing makes it possible for scientists and producers to evaluate the degradation of materials over time. They could also pinpoint potential points of failure or vulnerability. Additionally, accelerated degradation testing is used often. It is used to evaluate the reliability and durability of materials and products. Industries such as automotive aerospace, electronics, and packaging commonly use this testing.

Environmental exposure testing

To fairly evaluate the performance and durability of a material or product in real-world scenarios, natural or simulated environmental conditions should be applied. This testing sets out to mirror long-term effects on materials. These effects stem from environmental factors such as temperature, humidity, UV radiation, salt spray, and chemical exposure [87]. Environmental exposure testing checks a material's ability to endure weathering, corrosion degradation, and other environmental damage. It does this by subjecting the material to these types of conditions. Testing has a key role in ensuring materials remain intact. It also ensures that products maintain performance. This is especially critical over their service life that is set by the manufacturer. Industries like construction, automotive, marine, and outdoor equipment consider testing to be absolutely crucial.

Biocompatibility assessment

In applications related to medicine and healthcare, a particular kind of evaluation is made. It is the biocompatibility assessment. This assessment determines how fitting materials and products are for biological systems. The prime aim of this testing is to ensure safety. The testing also aims at confirming the nontoxicity. It further checks biological compatibility. A variety of tests, such as cytotoxicity, genotoxicity, sensitization, irritation, and implantation tests, are used in biocompatibility testing to evaluate the biological response of materials [88]. These tests determine if a material has the potential to cause negative reactions or damage to the body by analyzing its interactions with cells, tissues, and organs. In order to guarantee patient safety and regulatory compliance, biocompatibility assessment is essential for medical devices, implants, drug delivery systems, and other healthcare products, as shown in Fig. 9.

Table 1 provides a summary of various methods used to assess material performance under extreme conditions. Aggressive Environment Testing evaluates material behavior in corrosive settings with varying temperatures and pressures. Corrosion testing examines aqueous corrosion in different environments, while fracture and

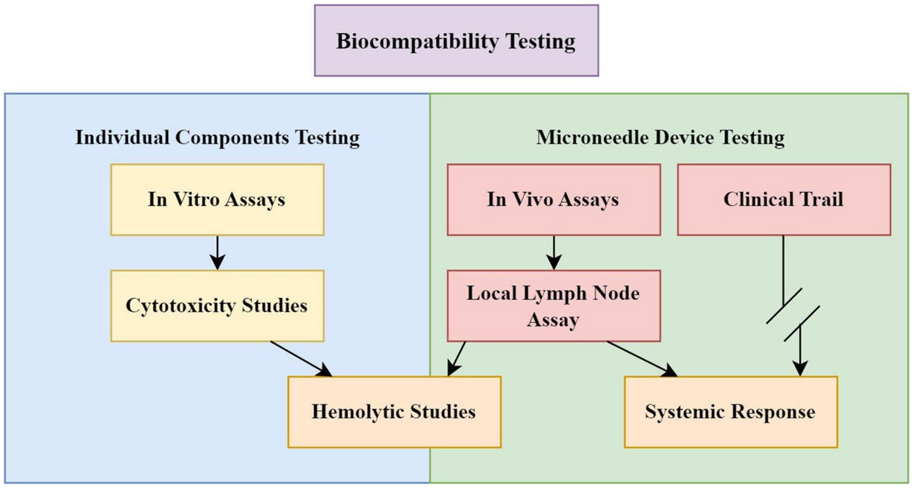


Fig. 9 Biocompatibility Assessment

Table 1 An overview of the various destructive testing techniques

Destructive Testing Method [citation]	Description
Aggressive Environment Testing [1, 3, 4]	Includes fracture and fatigue tests conducted in corrosive environments (e.g., containing salinity, humidity, hydrogen sulfide, carbon dioxide), involving different temperatures and pressures. These tests assess the impact of such conditions on materials and their performance
Corrosion Testing [4, 19]	Covers non-toxic, small-scale, aqueous corrosion tests in various environments, such as fresh and sea water
Fracture and Mechanical Testing [11, 36]	Consists of various methods: Tension tests, bend tests, Charpy impact tests, Pellini drop weight tests, peel tests, crush tests, pressure tests, and fracture tests. These methods assess material quality, energy absorption, nil-ductility transition temperature, weld size, failure type, compressive strength, and structural imperfections
Fatigue Testing [19, 36]	Evaluates the strength of welded joints under frequent or variable amplitude loading, as well as fatigue crack growth testing of welds, base metals, and heat-affected zones, often in salt water or open-air environments
Hydrogen Testing [1, 39]	Conducted at various temperatures and strain rates in substances at risk of corrosion from exposure to hydrogen
Residual Stress Measurement [10, 19]	Determines near-surface and through-thickness residual stress distribution, crucial for engineering evaluations. Measurement methods include neutron diffraction, synchrotron diffraction, and X-ray diffraction
Tensile Testing [12, 88]	Also known as elongation, used in construction materials to certify weld strength and structural integrity. Involves elongating or condensing a part to determine material strength
Hardness Testing [10, 75]	Determines resistance to indentation and hardness of a material, crucial for assessing performance and longevity. Utilizes the Rockwell scale to evaluate permanent deformation under stress
Torsion Testing [19, 39]	Applies twisting forces to determine shearing and deformation limits of materials, with failure occurring when the material succumbs to twisting

mechanical testing includes a range of methods to assess material properties such as tensile strength and energy absorption. Fatigue testing focuses on the durability of materials under repeated loading, and hydrogen testing explores the effects of hydrogen exposure. Residual Stress Measurement uses techniques like neutron and X-ray diffraction to gauge internal stresses.Tensile tests determine strength. They examine structural integrity through elongation. Hardness tests measure resistance to indentation. This is done with the aid of the Rockwell scale. Lastly, torsion tests assess shearing and deformation limits. This is under twisting forces.

Non-destructive testing methods

Non-destructive testing (NDT) is an assortment of inspection methods. In contrast to destructive testing, these allow inspectors to gather information. They can assess materials, systems, or componentry without causing irreversible harm. Yet to identify a test item's flaws, destructive and non-destructive tests are used. Patient safety is guaranteed with these tests. Regulatory compliance is guaranteed by their use. Use lants, drug delivery systems, and other healthcare products [89].

Non-destructive testing utilization (NDT) is imperative in Fig. 10 techniques. This is central, particularly for parts

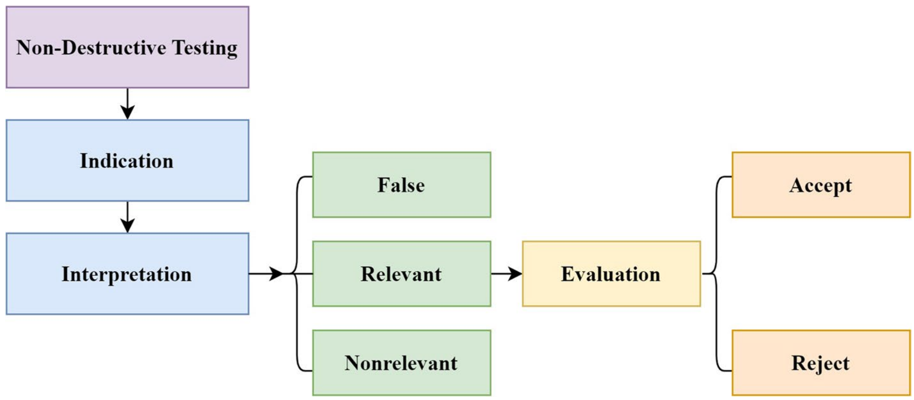


Fig. 10 Non-destructive testing

of aircraft engines. These parts are vital for safety. Possibility of damage makes them non-subject to destructive testing. Hence, routine inspections are necessitated to ensure their integrity. NDT methods like eddy-current testing or ultrasonic testing are employed. They aim to find defects without causing harm. These defects can be cracks. There can also be other flaws in these components. NDT contains visual inspection. This method facilitates the evaluation of external damage. NDT provides a dependable and cost-effective way to ensure safety in critical applications. They guarantee that components can be used safely if they pass inspection.

Ultrasound

Ultrasonography stands as a critical tool in several fields. Its unique ability to penetrate substances sets it apart. It can interact diversely with these substances. The sound it emits belongs to a high-frequency range and is inaudible to humans. Also known as sonography, it is a vital diagnostic tool in medical imaging. This is partly because it provides instant, invasive images of internal organs. These images cover a range of areas. They include tissues and blood vessels. It is incredibly versatile too. Ultrasound can guide medical procedures. Procedures like biopsies or injections. It can also facilitate the safe scanning of pregnant patients. Furthermore, it assists in the diagnosis of multiple conditions. Conditions such as tumors, cysts, or gallstones [90].

Ultrasonography has found wide use in non-destructive testing. This testing is crucial in sectors like aerospace, automotive, manufacturing, and construction. It extends beyond use in medicine. In this scenario, ultrasonic testing (UT) becomes a key method. It enables examination of materials and components for glitches or exceptions. The process ensures no harm to anyone. Ultrasonic testing (UT) makes sure of the integrity and reliability of essentials. Essentials like welds, forgings, castings, and pipes. This is achieved by injecting ultrasonic waves into materials and analyzing the reflected waves. This allows the identification of exceptions. Exceptions like cracks, voids, and inclusions. It can be represented as:

$$c = \sqrt{\frac{K}{\rho}} \tag{7}$$

Where ρ is the material's density, K is the bulk modulus, and c is the speed of sound.

The applications of ultrasound are scientific, industrial, and therapeutic. In the medical field, low-intensity ultrasound facilitates tissue healing, while high-intensity focused ultrasound (HIFU) aids in precise tumor ablation. Ultrasonic cleaning is used in industry for precise and thorough contamination removal in electronics and precision manufacturing. Underwater sonar systems use ultrasonic as a vital communication medium to help with navigation and object detection. Furthermore, ultrasonic methods such as acoustic microscopy enable research, failure analysis, and quality control activities in a variety of industries by offering priceless insights into material structure.

Ultrasonic testing (UT)

Ultrasonic testing (UT) is a popular nondestructive testing (NDT) technique that uses high-frequency sound waves (usually above 20 kHz, the human audible range) to find discontinuities, flaws, or internal defects in materials. The fundamental idea is to use a transducer to transmit ultrasonic waves into the material, which is then responsible for receiving and analyzing the reflected waves [91]. Cracks, voids, inclusions, and variations in material thickness can all cause structural disruptions in the material, which can be used to identify and characterize defects by causing the ultrasonic waves to reflect back to the transducer in different ways.

UT is flexible and can be carried out in a number of ways, such as:

Pulse-echo testing: Ultrasonic pulses are sent and received by a single transducer, which uses the time delay and amplitude of the reflected waves to detect defects. This technique is known as pulse-echo testing.

Through-transmission testing: Two transducers are employed, one for the purpose of sending and the other for the reception of ultrasonic waves through the material. The waves will be weakened or blocked by any obstructions in the material's path, signifying flaws.

Time-of-flight diffraction (TOFD): Measures the diffracted waves from flaws to determine their exact size and location. The term time-of-flight diffraction, or TOFD, refers to this method.

Acoustic microscopy

This is a specialized microscopy. It employs ultrasonic waves for high-resolution images. These images show the internal structure of a material. Traditional optical microscopy does not use ultrasonic waves. It relies on visible light. Acoustic microscopy can provide detailed images. You can see internal features. These features include defects and material boundaries. Images can range from micrometers to nanometers. The range depends on measurements. We measure time-of-flight and intensity. These are reflected waves [92].

Acoustic microscopy is really helpful. It helps, especially with intricate microstructures. It can also characterize minute details. Acoustic microscopy is useful where other methods fail. This is due to the high-resolution images it produces.It finds applications in various fields. These include failure analysis. It is used in materials science research. Semiconductor inspection is among other applications. Biomedical imaging is another. Acoustic microscopy does not need destructive testing techniques. It uses ultrasonic waves. It also uses acoustic microscopy. Both are non-destructive evaluation tools. They provide crucial information. This information is about material integrity and quality. It also includes details about performance.

Ultrasound, also known as sonography, has various advantages, including non-invasive and real-time imaging, making it extremely useful for detecting internal faults in a wide range of materials. However, it has limitations; accurate interpretation necessitates the use of competent experts, and its efficiency can be reduced when applied to extremely thin or tiny components. Ultrasound is vital in real-world applications such as aerospace for assessing aircraft engine components for cracks and manufacturing for evaluating weld quality in pipelines to ensure safety and dependability in critical systems.

Infrared spectroscopy

A potent analytical method for identifying and characterizing molecules based on their infrared light absorption, transmission, or reflection is infrared spectroscopy. It is extremely useful in a variety of fields, including chemistry, materials science, pharmaceuticals, and environmental science, because it offers comprehensive information about molecular structures, functional groups, and chemical bonds [93].

According to the principle of infrared spectroscopy in Fig. 11, molecules absorb infrared radiation at specific frequencies that correspond to the vibrational modes of their chemical bonds. A sample reacts to infrared light in different ways; some wavelengths are absorbed, while others are transmitted or reflected. A spectrum can be produced by examining the absorption pattern over a range of infrared wavelengths. This will show distinctive peaks that represent various kinds of molecular vibrations. So wavelength (frequency) infrared spectroscopy is:

$$\widehat{V} = \frac{1}{\lambda} = \frac{\overline{c}}{\lambda} \tag{8}$$

Where, $\widehat{V}$: Wavenlength (cm^{-1}) and λ: Wavelength (cm) and $\overline{c}$: Speed of light (cm/s)

$$Beer - Lambert\ Law:\ A = \epsilon.l.c \tag{9}$$

Where, A: Absorbance, ϵ: Molar absorptivity (L mol^{-1} cm^{-1}), l: Path length (cm) and c: Concentration (mol/L).

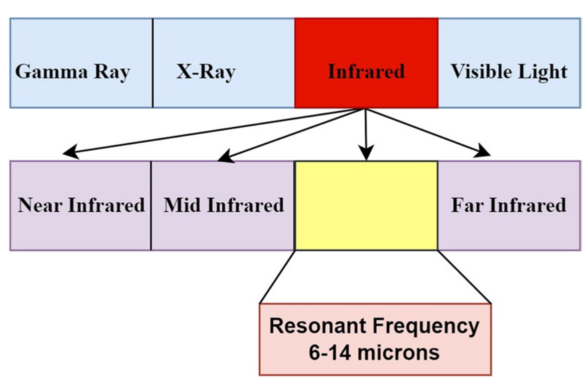


Fig. 11 Infrared spectroscopy

Infrared spectroscopy encompasses various techniques, such as:

Fourier-transform Infrared Spectroscopy (FTIR)

A widely used technique for gauging an object's assimilation of infrared light. As a function of wavelength is Fourier-transform infrared spectroscopy. Commonly referred to as FTIR for short. To rapidly scan broad swaths of infrared wavelengths, FTIR employs a Fourier transform spectrometer. After the scanning, a spectrum is produced. This spectrum uniquely identifies the sample [94]. In FTIR spectra, peaks correspond to vibrational modes of chemical bonds. This allows for a quantitative examination of the sample's composition. It also allows examination of the sample's structure. Such examination is made possible by these peaks. A qualitative examination of the composition and structure is possible too. This is also made possible by the peaks in FTIR spectra. Peaks correspond to vibrational modes of chemical bonds within the sample.

The procedure involves converting sample's interferogram into spectrum. Spectrum illustrates absorption of infrared light at various wavelengths. Intensity of infrared light detected by spectrometer is plotted against time to create an interferogram. Fourier transform of interferogram is expressed mathematically Syntax is as follows.

$$\widehat{F}(\widehat{V}) = \int_{-\infty}^{\infty} f(t).e^{-i2\Pi\widehat{v}t}dt \tag{10}$$

where, the Fourier transform of the interferogram with respect to the wavenumber $\widehat{V}$. which is the inverse of the infrared light's wavelength, is represented by the symbol $\widehat{F}(\widehat{V})$. The interferogram function,f(t), shows the infrared light intensity that was detected as a function of time (t).The wavenumber is represented by $\widehat{V}$ (cm^{-1}). It's that time (s).

Near-Infrared Spectroscopy (NIR Spectroscopy)

NIR spectroscopy measures electromagnetic radiation in the near-infrared wavelength range, which is generally between 780 and 2500 nm. Molecular vibrations are the main emphasis of FTIR, whereas overtones and combinations of molecular vibrations, together with electronic transitions, are the main things that NIR spectroscopy finds [95]. This method is appropriate for online process monitoring and quality control applications since it offers quick and non-destructive sample examination.

Attenuated Total Reflectance (ATR Spectroscopy)

This method is used to examine materials that are challenging to handle or prepare, like liquids, pastes, or solids. The sample is pressed up against a high refractive index crystal, and the infrared radiation that is internally reflected by the crystal is measured. Without sample pretreatment, ATR spectroscopy offers useful information on the composition and surface characteristics of samples.

Using the total internal reflection (TIR) phenomenon, ATR spectroscopy amplifies the interaction between infrared light and the material. The angle of incidence and the refractive indices of the crystal and the sample dictate the depth of penetration of the evanescent wave into the material. The penetration depth (d) of the evanescent wave into the sample is represented by the subsequent equation:

$$d = \frac{1}{2.k.\sqrt{n_s^2 - n_c^2}} \tag{11}$$

Where as, incident infrared radiation's wavenumber is represented by K. Sample's refractive index is n_s. Crystal's refractive index is n_c. The absorbance spectrum from ATR spectroscopy unveils the surface properties of the sample. No extensive preparation is needed. ATR spectroscopy reveals details on the sample's surface properties. Information on the sample's composition is also ascertained. Functional groups and chemical bonds are detectable. Absorbed infrared radiation intensity is evaluated at varied wavelengths. Important insights are gleaned. These insights are into the characteristics of the sample and its chemical structure.

Infrared spectroscopy is a powerful analytical technique. It provides comprehensive molecular information swiftly. Samples escape damage. However, calibration becomes crucial. It's vulnerable to changes in sample conditions. Changes might affect results. In the pharmaceutical sector, infrared spectroscopy is of much use. It helps to scrutinize drug formulations. Quality and uniformity are ensured. Additionally, its application is widespread in environmental research. It is used to scrutinize soil and water quality. It helps to identify contaminants and toxins. In this manner, infrared spectroscopy is used to ensure the safety of our environment. It has wide-reaching applications and benefits.

Imaging modalities

Imaging modalities are techniques or processes that are used to visualize the inside structure of a material or object, or the function of biological tissue. In order to gather data about the item being photographed and create images that offer insightful information for industrial, research, or diagnostic applications, these modalities make use of a variety of physical principles and technology [96].

Imaging modalities are a broad category of methods, each having unique applications, benefits, and guiding principles. Among the popular imaging modalities are:

X-ray imaging

Radiography, another name for X-ray imaging, is a common medical imaging method that uses X-rays to produce images of the body's internal components. X-rays are a type of high-energy radiation that can go through soft tissues but are blocked by harder materials like metal and bones. A detector on the other side of the body detects the transmitted X-rays in X-ray imaging, producing a two-dimensional image [97]. An X-ray beam is directed towards the body. As a result, soft tissues appear in various shades of gray, while bones and other dense structures look white in the grayscale image.

X-rays interact with the tissues as they travel through the body. Because of absorption, the X-ray beam's intensity drops off exponentially as it passes into the tissue. The Lambert–Beer law provides the mathematical formula for X-ray attenuation:

Common uses of X-ray imaging include:

$$I = I_0.e^{-\mu.x} \tag{12}$$

where, The X-ray beam's starting intensity is represented by the symbol I0.Is the X-ray beam's intensity after it has passed through the tissue. The tissue's linear attenuation coefficient is represented by μ.The tissue's thickness is represented by x.

To produce finely detailed images of the body's internal structures, X-ray imaging uses basic mathematical concepts. The density of the tissues that X-rays pass through determines how much attenuation occurs in the radiation. Denser tissues, including bones, appear brighter in a grayscale image due to poorer transmission, which is measured by a detector on the other side of the detector. The X-ray source, detector, and patient are positioned in order to calculate the projection angle and final image in X-ray imaging's basic projection geometry. Further methods used to raise image quality and diagnostic precision include filtering, noise reduction, and contrast enhancement. X-ray imaging is useful for both medical condition diagnosis and action guidance because of these mathematical processes.

1) Identifying joint dislocations, anomalies in the bones, and fractures.
2) Making diagnoses for illnesses like lung cancer, TB, and pneumonia.
3) Examining teeth and jaw health and screening for dental issues.
4) Directing minimally invasive techniques include mammography, fluoroscopy, and angiography.

Magnetic Resonance Imaging (MRI)

MRI is a non-invasive medical imaging method that creates precise images of the body's internal components by using radio waves and strong magnetic fields. In contrast to X-ray imaging, which depends on ionizing radiation, magnetic resonance imaging (MRI) is based on how hydrogen atoms in water molecules within the body respond to magnetic fields. In an MRI, the patient lies inside a sizable magnet while radiofrequency pulses are administered to the body [98]. This causes hydrogen atoms to release signals, which antennas pick up and translate into images.

MRI is especially helpful for:

1) Observing the brain, spinal cord, muscles, and other organs as soft tissues.
2) Making the diagnosis of musculoskeletal injuries, malignancies, strokes, and neurological diseases.
3) Evaluating cerebral perfusion, blood flow, and functional activity.
4) Assessing the degree of anomalies or tissue damage without being exposed to ionizing radiation.

Optical Coherence Tomography (OCT)

OCT is a micrometer-scale imaging method that produces high-resolution, cross-sectional pictures of biological tissues. It is similar to ultrasound imaging but uses light waves instead of sound waves to record reflections from various tissue layers. This is achieved by using low-coherence light [99]. OCT is useful for ocular, dermatological, and cardiovascular applications because it offers high spatial resolution, real-time, non-invasive imaging of tissue morphology and microstructure.

OCT is frequently employed in:

1) In ophthalmology, visualizing retinal structures and identifying abnormalities.
2) Evaluating dermatological diseases, wound healing, and skin lesions.
3) In cardiology, measuring the composition of plaque and imaging coronary arteries.
4) Tracking anatomical changes and therapeutic responses in research and clinical contexts.

Imaging modalities are vital for seeing inside structures, which greatly aids diagnoses and research. X-ray imaging, which is widely used in medical diagnostics,

Table 2 An overview of the various Non-destructive testing techniques

Non-Destructive Testing Methods [citation]	Description
Ultrasound (UT) [89–91]	Diagnostic tool in medical imaging and NDT for flaw detection in materials using ultrasonic waves
Acoustic Microscopy [89, 92]	Provides detailed images of material structures using concentrated ultrasonic waves
Infrared Spectroscopy (IR) [93]	Analytical method for identifying molecules based on infrared light absorption, transmission, or reflection
Fourier-transform Infrared Spectroscopy (FTIR) [94]	Measures an object's absorption of infrared light to identify chemical bonds
Near-Infrared Spectroscopy (NIR Spectroscopy) [95]	Measures electromagnetic radiation in the near-infrared wavelength range to analyze molecular vibrations
Attenuated Total Reflectance (ATR Spectroscopy) [89, 93]	Examines challenging-to-handle materials by measuring infrared radiation internally reflected by a crystal
X-ray Imaging [96, 97]	Produces two-dimensional images of internal components using X-rays
Magnetic Resonance Imaging (MRI) [98]	Creates precise images of internal structures using radio waves and magnetic fields
Optical Coherence Tomography (OCT) [99]	Produces high-resolution, cross-sectional images of biological tissues using light waves

generates images quickly based on tissue density, effectively revealing bone and soft tissue anomalies; however, it exposes patients to ionizing radiation and has limited soft tissue contrast, making it only suitable for diagnosing fractures and dental issues. Magnetic Resonance Imaging (MRI) creates comprehensive images without ionizing radiation, allowing for strong soft tissue contrast; yet, it is typically expensive and time-consuming, making it ideal for assessing brain and spinal cord injury. In real time, optical coherence tomography (OCT) generates high-resolution cross-sectional pictures of tissues using light waves. It is particularly useful in ophthalmology for retinal imaging; however, its penetration depth is limited.

The techniques to inspect materials without causing harm are listed in Table 2. Ultrasound (UT) uses ultrasonic waves to find defects, whereas concentrated ultrasonic waves are used in acoustic microscopy to produce finely detailed images of material structures. The way that molecules interact with infrared light allows infrared spectroscopy (IR) to identify them. Transform of Fourier Using near-infrared radiation, NIR spectroscopy examines molecular vibrations, whereas infrared spectroscopy (FTIR) uses infrared light absorption to determine chemical bond names. By detecting infrared light that is internally reflected, ATR spectroscopy is used to investigate materials that are challenging to analyze. MRI uses magnetic fields and radio waves to provide detailed internal images, while X-ray imaging produces two-dimensional images of internal components. The use of light waves in optical coherence tomography (OCT) allows for the acquisition of cross-sectional pictures of biological tissues with high resolution.

Comparative analysis and case studies

Comparative analysis

Introduction of biopolymer compatibility

Understanding biopolymer compatibility with different testing methods is critical for improving testing results and material selection. Numerous biopolymers show unique traits and behave differently under different tests. These differences can significantly affect results. For instance, certain mechanical tests might be well-suited to flexible biopolymers. Others may be necessary for rigid composites. By assessing compatibility, researchers can rightfully select the best testing procedures. This procedure results in evaluations that mirror the materials' real performance and potential uses.

Destructive and non-destructive testing techniques have their own pros and cons. This is especially true when looking at sustainable biomaterials. Destructive methods like chemical analysis and mechanical testing limit the number of tests possible. However, they offer an in-depth look into the materials' qualities. On the flip side, they can damage or destroy the material sample. Ultrasound and infrared spectroscopy are examples of non-destructive techniques that evaluate materials without compromising their integrity, which makes them appropriate for continuous observation. They might, however, fall short of fully capturing the effects of severe stress or degeneration. Whether thorough analysis or material preservation is the primary concern will determine which approach is best.

A summary of the main conclusions from several investigations is provided in Table 3, Comparative Analysis of Non-Destructive Testing and Destructive Methods. Although there are no in-depth case studies, Khamidov et al. [65] discuss a variety of building testing techniques. With high-speed imaging tailored to plasma science,

Table 3 Comparative Analysis of Non-Destructive Testing and Destructive Methods

Paper Name	Method	Results	Advantages	Limitations	Biopolymer Compatibility
Khamidov et al. [65]	Review of modern methods for testing building structures	Effectiveness of various testing methods for building structures	Provides a broad overview of different testing methods; useful for selecting appropriate techniques	General review; lacks specific quantitative results or detailed case studies	General applicability
Hang et al. [66]	Development of high-speed image acquisition system for plasma control	Successful implementation of a high-speed imaging system for real-time plasma control on EAST	Advances in real-time monitoring technology; enhances control in plasma science applications	Focuses on a specific application in plasma science; may not be applicable to other fields	Limited to specific polymers used
Tydeman & Kirkwood [85]	Design and analysis of accelerated degradation tests for biological standards	Properties of maximum likelihood estimators for degradation tests	Detailed statistical analysis of degradation testing; important for biological standard stability	Specific to biological standards; may not generalize to other types of materials or tests	Biodegradable polymers
Huang et al. [86]	Real-time quantitative acceleration monitoring using a triboelectric nanogenerator	Effective real-time monitoring of bridge cable vibrations	Provides real-time, accurate monitoring; enhances bridge safety and maintenance	Limited to bridge cable applications; requires specific technology (triboelectric nanogenerator)	Applicable to certain composites
Umar et al. [100]	Experimental study on non-destructive evaluation of sustainable concrete	Mechanical characteristics of concrete with industrial waste	Practical insights into sustainable concrete; useful for eco-friendly construction materials	Results are specific to concrete with industrial waste; may not apply to other materials	Specific to concrete biopolymers
Helal et al. [101]	Review of non-destructive testing methods for concrete	Overview of various non-destructive testing methods and their applications	Comprehensive review of testing methods; useful for understanding available techniques	Lacks new experimental data; general review without specific results or detailed analysis	General applicability

Hang et al. [66] enhance plasma control. With limited applicability to other materials, Tydeman & Kirkwood [85] examine degradation testing for biological standards. Triboelectric nanogenerators, useful in certain situations only, are used by Huang et al. [86] for real-time bridge monitoring. Using non-destructive techniques and an emphasis on environmentally friendly materials, Umar et al. [100] evaluate sustainable concrete. Helal et al.'s [101] thorough analysis of concrete testing techniques lacks fresh experimental knowledge.

Recent improvements in biopolymer testing methodologies have greatly improved the evaluation of their properties. Improved imaging techniques, such as high-resolution X-ray computed tomography (CT), enable non-invasive evaluations of the inner structures and faults found in biopolymer composites. In addition, machine learning algorithms are in use. They enhance interpretation of data. This data comes from traditional mechanical tests, with more nuanced insights into material performance. Additional new biosensor technologies have emerged. They enable real-time monitoring. The focus is biopolymer breakdown in natural settings. It improves our understanding of long-term behavior. These developments not only increase testing accuracy. They also broaden the range of biopolymer applications. These applications relate to creating sustainable materials. Emerging advances in biopolymer testing are on the rise. 3D printing is used to create test samples. As a result, evaluation of complicated geometries and qualities is possible. These qualities match real-world applications. In addition, advances in nanotechnology are forthcoming. They are projected to lead to the production of biopolymers. These biopolymers have improved performance characteristics. This necessitates the development of novel testing procedures. These procedures are capable of precisely evaluating their properties at the nanoscale.

Case studies illustrating the application of testing methodologies in sustainable biomaterials

A wide range of biopolymers has shown great promise as sustainable materials. These include the natural polymers chitosan and alginate. They need to be understood. Knowing their distinct features is key. Equally vital is understanding how they can be efficiently examined to promote their extended uses.

Sustainable materials have many uses in testing techniques. Case examples demonstrate this. For instance, non-destructive ultrasonic testing evaluates internal quality. It assesses the structural integrity of bamboo composites. Bamboo composites are often used in sustainable construction. This testing technique has been utilized. [38, 39] However, there's a need to better understand mechanical characteristics. It's important to know degradation patterns of biodegradable polymers. This knowledge is necessary to support the development of environmentally friendly packaging. For this purpose, destructive testing techniques are essential. Tensile and compression tests have been shown to be necessary [100].

Nondestructive methods are useful. They include infrared spectroscopy and acoustic microscopy. These methods are particularly beneficial for wood-based products. The techniques help in detecting defects. They also aid in measuring moisture content, crucial for using resources in a sustainable manner. Nondestructive technologies are also beneficial. These include infrared spectroscopy and acoustic microscopy. They are extremely beneficial when analyzing wood-based products. The procedures help discover defects. They also help evaluate moisture content. Both are necessary for sustainable resource use. Infrared spectroscopy is proven to accurately detect moisture levels in wood. This reduces deterioration. It also extends product longevity through ideal drying settings [102]. This work demonstrates that near-infrared spectroscopy can predict holocellulose. It can also predict lignin levels. This contributes to better knowledge of wood composition. Acoustic microscopy improves quality control in wood manufacturing. This is through identifying internal faults in laminated veneer lumber [103].

In the bio-based composites domain, case studies focused on polylactic acid. The acid was reinforced with natural fibers. Scanning electron microscopy was utilized. This was to assess fiber matrix adhesion. The structural integrity was also examined. This method revealed improvements in mechanical properties. Moreover, research on fungal mycelium composites was explored. Mechanical testing was carried out. It was used to define compressive strength. A certain fact emerged. Certain formulations exceed standard materials. These are used in lightweight construction applications.

Infrared spectroscopy and optical imaging have additional uses. These methods monitor recycled plastic quality. They maintain product integrity. They also aid in waste reduction [104]. The study scrutinizes non-destructive testing. It focuses on carbon fiber-reinforced plastics. A TR probe based on PCB is used. The study exhibits the ability to detect subsurface faults. It can also assess composite material integrity. This is achieved without causing damage. Reliable performance is ensured. The applications are diverse. To uphold product integrity and diminish waste, non-destructive methods are employed. These methods include infrared spectroscopy and optical imaging. They are used in quality control of recycled plastics. The upshot is multiple testing of biodegradable packaging materials [101].Destructive testing is one aspect. Another involves non-destructive methods. Gas permeability analysis and X-ray imaging are examples. They are employed to amass data on the performance of materials. Tensile testing is also employed. It helps shed light on degradation. It also supports the development of sustainable packaging solutions. Significant findings result from these testing methods. In ultrasonic testing of bamboo composites, a 15% increase in structural integrity was noted. This is compared with untreated samples. Similarly, tensile tests on biodegradable polymers show something interesting. Certain formulations achieve mechanical strengths exceeding 50 MPa. This demonstrates their viability for packaging applications. Moreover, there are studies on degradation rates of biopolymers. These studies are under varied environmental circumstances. It has been indicated that chitosan-based films can disintegrate in six months. This makes them a possible alternative to traditional plastics.

Future directions and conclusion

Emerging trends in testing methodologies

The evaluation of biomaterials sees great enhancement due to new developments in test protocols. Efforts to heighten accuracy and automate data analysis quicken test procedures. Machine learning and artificial intelligence, increasingly combined, play a key role in this. Technology enhancements in sensors pave the way for the creation of portable and more sensitive equipment. This equipment enables property monitoring of biomaterials. Monitoring is on-site and in real-time. Sensitivity and resolution increase with multi-modal imaging techniques. They combine X-ray imaging with optical coherence tomography or ultrasound. This makes the characterization of biomaterials more extensive. Emphasis is growing on testing techniques that are non-invasive and in situ. The goal is to reduce test durations. Minimize sample preparation whilst maintaining the integrity of the sample. It leads to a more effective, long-lasting biomaterial evaluation. Additionally, computer modeling becomes crucial. This includes finite element analysis and molecular dynamics simulations. They can predict the behavior of biomaterials prior to physical testing. The progress seen in wearable technology is notable. It allows for continuous real-time monitoring of biomaterials in vivo. This is especially useful in biomedical applications.

Challenges and opportunities for further research

It will require several notable changes. These are to address problems. Plus, they are necessary to harness the benefits of biomaterial testing. Up-and-coming testing technologies need standardization. They must undergo validation. This is key to providing consistent and reliable results. The results must span different labs and research projects. Testing techniques should be complex. Also, they should be able to evaluate biomaterials. This includes multiple properties and behaviors. This evaluation should take place across various environmental circumstances. The need is pressing as these biomaterials only continue to grow in complexity and multifunctionality. Environmental impact studies are crucial. These include life cycle analysis. They also involve ecotoxicity testing. They are part of testing methods. These evaluate biomaterial sustainability. They are also key in diminishing their ecological footprint. Regulatory frameworks are also important. Particularly for novel testing methods in medical applications. These should be detailed directly to speed up the transition from research to clinical use. Advancing awareness and acceptance of new biomaterials is crucial. This helps to build trust between consumers and healthcare professionals. To dig deeper into the sustainability of biomaterials is necessary. To also lessen their ecological footprint, environmental impact evaluations are key. These must be part of testing processes. This includes life cycle analysis and ecotoxicity testing. Addressing the potentials and challenges in biomaterial evolution is crucial. It encompasses every stage from design to the journey to commercialization. Initiating interdisciplinary collaboration is also paramount. Scientists, engineers, physicians, and stakeholders are key players in this.

Conclusion and implications for sustainable biomaterials development

In summary, the advancement of sustainable biomaterials development depends on the creation and application of sophisticated testing procedures. Researchers are able to assess biomaterial qualities, performance, and environmental effect more thoroughly by combining destructive and non-destructive testing methods. The use of modern testing technology and interdisciplinary collaboration will improve evaluation processes even further. This makes it easier to create, optimize, and commercialize eco-friendly and biocompatible materials for a variety of applications. Collaboration, creativity, and investment from the academic, business, and government sectors are needed to go forward, address the issues, and seize the opportunities in testing procedures. Moving forward, a circular economy will be critical, emphasizing biomaterials' potential for recycling and biodegradability and fostering sustainable material design methods. International collaboration will also play an important role in biomaterials research and testing by encouraging information sharing and resource pooling across boundaries. Fostering public awareness and acceptance of sustainable biomaterials will also be vital for their successful implementation. We can quicken the shift to a more resilient and sustainable future where biomaterials are essential in solving global issues related to healthcare, the environment, and other areas by utilizing developing technology, standardizing testing procedures, and emphasizing sustainability.

Authors' contributions

S.J.S. conceived and designed the study, conducted the experimental work, and performed the data analysis. S.J.S. also wrote the main manuscript text and prepared Figs. 1, 2, 3, 4 and 5. R.G. contributed to the design of the testing protocols and provided critical insights into the interpretation of results. R.G. also reviewed and edited the manuscript for clarity and accuracy. M.G. supported the data collection process, conducted additional analyses, and assisted in the preparation of Figs. 6, 7 and 8. M.G. also reviewed and revised the manuscript. All authors have read and approved the final version of the manuscript.

Funding

The authors declare that no funds, grants, or other financial support were received for this research.

Data availability

No datasets were generated or analysed during the current study.

Declarations

Competing interests

The authors declare no competing interests.

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Received: 24 August 2024 Accepted: 8 November 2024
Published online: 01 December 2024

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