

Innovative Synthesis Techniques and Comprehensive Mechanical Characterization of Biopolymer-Based Composites for Advanced Applications in Biochemistry and Materials Sciences

Pramod Ambadas Karole¹, Bhushan Garade^{2*}, Rajesh Kumar³, Chandrakant Bhikanrao Patil⁴, Anjay Kumar⁵,

Abstract

Biopolymer-based composites have gotten a lot of attention lately because they could be used in biology and materials science in interesting ways. The main goal of this study is to come up with new ways to make composites and then fully characterize their material properties so that they can be used in more advanced ways. During the production step, a new method is used that combines green chemistry ideas with cutting edge industrial methods. The goal of this method is to make the synthesis process more sustainable and efficient while giving precise control over the shape and composition of the hybrid. Using biopolymers as the base material has natural benefits like being biocompatible, renewable, and biodegradable, which makes them perfect for making hybrid materials that are good for the environment. Advanced testing methods are used to figure out the material properties of these biopolymer-based composites, such as how strong, long-lasting, and structurally sound they are. To test different material qualities under different loads, advanced methods like tensile testing, bending testing, and impact testing are used. Microstructural analysis methods like scanning electron microscopy (SEM) and atomic force microscopy (AFM) are also used to look into how the strengthening agents are distributed and bonded between surfaces in the biopolymer matrix. The findings show that it is possible to make biopolymer-based composites that have the right dynamic qualities for a wide range of uses, from biological devices to building materials. The biopolymer base and strengthening agents work together to make the composites stronger and more stable. Also, biopolymers are good for the earth, which fits with the growing need for long-lasting materials in many fields.

*Author for Correspondence

Bhushan Garade

¹Assistant Professor, Sandip Institute of Technology & Reserch Centre, Nashik, Maharashtra, India.

²Assistant Professor, School of Science, Sandip University, Nashik, Maharashtra, India.

³Assistant Professor, Department of Mechanical Engineering, Sandip University Sijoul, Bihar, India.

⁴Assistant Professor, Department of Mechanical Engineering, Sandip Institute of Engineering & Management, Nashik, Maharashtra, India.

⁵Assistant Professor, Department of Mechanical Engineering, Sandip University Sijoul, Bihar, India.

Received Date: January 16, 2024

Accepted Date: February 12, 2024

Published Date: April 15, 2024

Citation: Pramod Ambadas Karole, Bhushan Garade, Rajesh Kumar, Chandrakant Bhikanrao Patil, Anjay Kumar. Innovative Synthesis Techniques and Comprehensive Mechanical Characterization of Biopolymer-Based Composites for Advanced Applications in Biochemistry and Materials Sciences. Journal of Polymer & Composites. 2024; 12(Special Issue 4): S119–S136.

Keywords: Biopolymer-based composites, synthesis techniques, mechanical characterization, advanced applications, biochemistry and materials sciences

INTRODUCTION

Biopolymer-based composites are becoming more and more useful in biology and materials science because of their unique qualities and ability to last for a long time. This introduction gives a review of how important biopolymer-based composites are, why new ways of making them are needed, and why full mechanical analysis is important for making their uses better. Biopolymers, which come from natural sources

like animals, plants, and bacteria, are better than manufactured polymers in a number of ways. They are nontoxic, reusable, and recyclable, which makes them useful in many situations where sustainability and protecting the environment are important. Biopolymer-based composites are made by adding strengthening agents to biopolymer structures. These composites combine the benefits of biopolymers with better dynamic qualities, which makes them useful for advanced uses in biology and materials science [1]. For biopolymer-based composites to have the best qualities and efficiency, new ways of making them must be developed. Traditional ways of synthesizing chemicals often use strong chemicals and a lot of energy, which can hurt the environment and make production more difficult to scale up. So, there is a rising need for cleaner and more long-lasting ways to synthesize materials that leave less of an impact on the environment and give precise control over the shape and make-up of composites. Researchers can make synthesis processes more efficient while using less energy and trash by following green chemistry principles and advanced manufacturing methods. This makes it possible to make biopolymer-based materials on a large scale [2].

A thorough mechanical evaluation is an important part of figuring out how well biopolymer-based composites work and whether they are suitable for advanced uses. Strength, hardness, toughness, and longevity are some of the most important mechanical qualities that decide how well and how reliably composite materials work in a wide range of settings and loads. In order to figure out how biopolymer-based composites behave mechanically under different loads, it is important to use cutting-edge testing methods. Advanced methods like tensile testing, bending testing, and impact testing give experts useful information about the performance and structural stability of composites. This lets them change their features to fit different uses [3]. Also, microstructural analysis methods like scanning electron microscopy (SEM) and atomic force microscopy (AFM) are used to look into the shape and structure of biopolymer-based compounds. Researchers can use these methods to see how the reinforcing agents are spread out in the biopolymer matrix and how the matrix and reinforcement phases bond with each other. To get the best dynamic qualities and efficiency from composites through smart design and processing, it's important to understand how microstructure affects traits. The goal of this study is to look into the best ways to make biopolymer-based composites and fully characterize their dynamic properties so that they can be used in the future in biology and materials science [4]. Researchers can make long-lasting hybrid materials with custom mechanical qualities that can be used in many different situations by combining new ways of production with advanced techniques for characterizing them. The rest of this paper will go into more depth about synthesis methods, mechanical measurement methods, advanced uses, and future prospects. This will give you a full picture of the study going on in this area. Biopolymer-based composites are now an important area of study in materials science because they have special qualities and can be used in many ways. Biopolymers are different from manufactured polymers because they come from natural sources like plants, animals, and germs. They have benefits like being biocompatible, biodegradable, and long-lasting. Because of these qualities, biopolymers are good choices for many uses in biology and materials science, from making biological devices to eco-friendly packaging [5].

Biopolymer-based composites are important because they might be able to solve some of the problems that standard materials have, especially when it comes to protecting the environment and using resources wisely. These composites are better for the environment than polymers made from petroleum because they use recyclable and reusable biopolymers as binder materials. This means that less fossil fuels are used and pollution is lessened. Biopolymer-based composites can also be made to have specific qualities, like being strong, stable at high temperatures, and biodegradable [6]. This means they can be used in many different businesses for a wide range of tasks. To get the best qualities and performance out of biopolymer-based composites for advanced uses, scientists are coming up with new ways to make them and studying their mechanics in great detail.

Traditional ways of synthesizing chemicals often use strong chemicals and processes that use a lot of energy, which is bad for the environment and makes it hard to make the process bigger [7]. As a result, there is a rising desire to create healthier and more long-lasting ways to combine materials that have

less of an effect on the environment and give exact control over the shape and make-up of composites. This Figure 1 shows a broad picture of bio-based plastics, including where they come from, how they are made, and what they are used for. It talks about how they are better for the earth because they break down naturally and leave behind less carbon dioxide, which makes them a long-term option to regular plastics. In the same way, full mechanical analysis is needed to check the structural integrity, strength, and longevity of biopolymer-based composites when they are loaded in different ways. Researchers can learn more about the mechanical behavior and performance of these composites by using advanced testing methods and microstructural analysis techniques. This lets them make materials with traits that are perfect for specific uses. In the field of biomedical innovation, a variety of synthetic polymers are utilized due to their unique properties, biocompatibility, and versatility. Some of the most commonly used synthetic polymers are given below in table 1 with comparison using different properties:

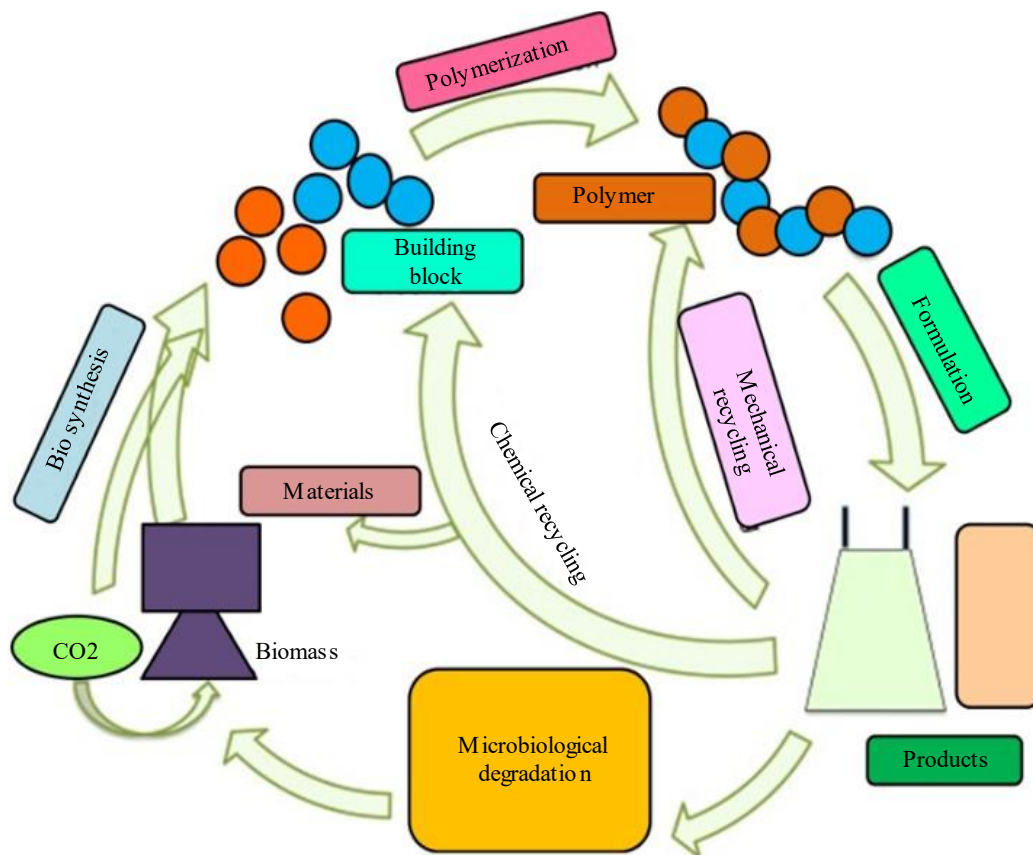


Figure 1. Overview of bio-based polymer.

Table 1. Comparison of Synthetic Polymers for Biomedical Applications

Polymer	Applications	Biocompatibility	Biodegradability	Mechanical Properties	Processing Methods
Polyethylene Glycol (PEG)	Drug delivery systems, tissue engineering, hydrogels	High	No	Flexible, low mechanical strength	Solvent casting, blending
Poly(lactic Acid) (PLA)	Biodegradable sutures, orthopedic implants, scaffolds	High	Yes	Rigid, good tensile strength	3D printing, extrusion
Poly(glycolic Acid) (PGA)	Absorbable sutures, tissue engineering, drug delivery	High	Yes	High tensile strength	Extrusion, fiber spinning

Polycaprolactone (PCL)	Tissue engineering, drug delivery, sutures	High	Yes	Flexible, moderate tensile strength	Electrospinning, casting
Polyvinyl Alcohol (PVA)	Drug delivery, wound dressings, hydrogels	High	No	Flexible, good film-forming ability	Casting, electrospinning
Polyurethane (PU)	Catheters, wound dressings, heart valves	High	No	Durable, flexible	Injection molding, casting
Polydimethylsiloxane (PDMS)	Medical devices, contact lenses, tissue engineering	High	No	Flexible, good oxygen permeability	Molding, casting
Polymethyl Methacrylate (PMMA)	Bone cement, dental prosthetics, intraocular lenses	Moderate	No	Rigid, high compressive strength	Casting, extrusion
Polyethylene Terephthalate (PET)	Vascular grafts, sutures, medical meshes	High	No	High strength, durable	Fiber spinning, weaving
Polyhydroxyalkanoates (PHA)	Biodegradable implants, drug delivery, scaffolds	High	Yes	Varies, can be tailored	Fermentation, casting

RELATED WORK

A lot of study has been done in the past few years on biopolymer-based composites and how they can be used in biology and materials science. This part gives an outline of the related work that has been done in this area. It talks about things like synthesis methods, mechanical measurements, and advanced uses. Biopolymer-based materials with better qualities and functions have been made using new synthesis methods in a number of studies. Green chemistry concepts can be used as one way to reduce damage to the environment and encourage survival [8]. For instance, scientists have looked into using liquids and enzymes that are safe for the environment in the production of biopolymer composites. This would cut down on the use of harmful chemicals and make the process more eco-friendly overall [9]. Also, improvements in production technologies like 3D printing and electrospinning have made it possible to precisely control the shape and make-up of composites. This has let researchers make biopolymer-based composites with specific qualities for different uses [10]. Researchers can get the strengthening agents to spread out evenly in the biopolymer matrix by adjusting processing factors like temperature, pressure, and mixing ratios [11]. This leads to better mechanical qualities and performance.

Mechanical evaluation is a key part of figuring out how well biopolymer-based composites work and whether they are suitable for advanced uses. A lot of research has used cutting edge testing methods to look at these materials' mechanical traits under various stress situations. Tensile testing is often used to find out how strong and stiff biopolymer-based composites are, which gives us important information about their performance and structural stability [12]. Another popular way to check how composites break is through flexural testing. This is especially useful in structure uses where resistance to bending and deformation is important [13]. Impact testing, on the other hand, checks how well composites can handle fast and changing loads, telling us about their toughness and stability [14]. Combining these different types of mechanical testing helps researchers fully understand how biopolymer-based composites behave mechanically and make the best use of their qualities for different purposes. Microstructural analysis methods, like scanning electron microscopy (SEM) and atomic force microscopy (AFM), are used to look into the internal structure and shape of biopolymer-based compounds along with visible mechanical testing. Researchers can use these methods to see how the reinforcing agents are spread out in the biopolymer matrix and study how the matrix and reinforcement

phases stick together [15]. Researchers can learn more about the structure-property relationships of biopolymer-based composites and make materials with specific qualities and performance by connecting microstructural features with mechanical properties.

Biopolymer-based composites are useful for many advanced uses in biology and materials science because of their special qualities. Biomedical uses are one of the most hopeful areas. Biocompatible and biodegradable materials are needed for tissue engineering, drug transport, and making medical devices [16]. Biopolymer-based composites are great for scaffolding and implants because they are biocompatible and can be made to have the same dynamic qualities as natural tissues [17]. Biopolymer-based composites have shown a lot of promise as structural materials in many fields, such as aircraft, automobile, and building, in addition to their use in medicine. Their low weight, high strength-to-weight ratio, and resistance to rust make them good for uses where reliability and weight reduction are very important [18]. Biopolymers are also reusable and durable, which fits with the rising need for eco-friendly materials in production. This has led to the use of biopolymer-based composites in many different areas [19]. Biopolymer-based composites have also been looked at for uses in cleaning up the environment, like treating garbage, getting rid of pollutants, and making packaging that lasts longer. Researchers can make materials with better absorption and filtration qualities by mixing functionalized biopolymers and nanomaterials into composite matrices [20]. These materials can help protect the environment and save resources. Even though a lot of progress has been made in making, studying, and using biopolymer-based composites, there are still some problems and chances for more research to be done. One big problem is coming up with flexible and low-cost ways to make materials that can meet the growing need for eco-friendly materials in many fields. Researchers need to find new ways to make biopolymer-based composites on a big scale while keeping their performance and eco-friendliness [21]. Also, we need more advanced methods for characterizing biopolymer-based compounds that can help us learn more about how their structure and properties are related. New methods like in-situ mechanical tests and multi-scale modeling could help us figure out how these materials react to different loads and environments [22]. Biopolymer-based composites should be used more in new areas like smart materials, mobile electronics, and energy storage. This is what future study should focus on and summary of related work is discussed in table 2. Researchers can come up with new ways to solve problems in healthcare, energy, and sustainability by using the special qualities of biopolymers and combining them with cutting-edge technologies [23]. Increasingly inquire about is being done on common fiber composites, which appears how valuable they may well be in numerous circumstances since they are eco-friendly and have extraordinary qualities. Palanisamy et al. (2023) allow a exhaustive investigation of the physical, chemical, and energetic properties of common bark filaments (NBFs) upgraded polymer composites [24]. They appear how these filaments can be utilized to make strides the execution of polymer networks. Mysamy et al. (2024) too deliver a point by point depiction of polymer materials, fiber surface forms, fabricating strategies, characteristics, and employments of common fiber composites [25]. This audit stresses how imperative surface forms are for making composites adhere together superior and having superior common highlights. In their 2024 ponder, Karthik et al. see into the chemistry of common strands and how they combine with polymer media. This makes a difference us get it how these composites work [26]. This survey too talks almost other ways to form biopolymer compounds that move forward their qualities. Kurien et al. (2023) conversation almost abaca fiber and portray its mechanical, physical, and warm qualities that make it great for basic polymer composites [27]. These analysts found that including abaca fiber to polymer blends can make them much more grounded. Goutham et al. (2023) conversation almost the penetrating variables and remaining malleable qualities of natural-fiber-reinforced composites. They stretch how imperative it is to make strides the boring forms to keep the composites' judgment and execution [28]. At last, Palanisamy et al. (2024) conversation almost how to select and handle common filaments and nanocellulose for biocomposite employments [29]. They appear how nanocellulose seem make strides the highlights of normal fiber composites indeed more. This audit gives us a arrange for how to create high-performance, long-lasting items.

Table 2. Summary of Related work

Approach	Key Finding	Synthesis Technique	Scope
Green chemistry principles	Reduced environmental impact and improved sustainability	Use of environmentally friendly solvents and catalysts	Minimize environmental footprint and promote sustainability
Advanced manufacturing technologies	Precise control over composite morphology and composition	3D printing, electrospinning	Tailor properties for specific applications
Optimization of processing parameters	Uniform dispersion of reinforcing agents within the biopolymer matrix	Temperature, pressure, mixing ratios	Enhanced mechanical properties and performance
State-of-the-art mechanical testing	Comprehensive evaluation of mechanical properties under different loading conditions	Tensile testing, flexural testing, impact testing	Determine suitability for specific applications
Microstructural analysis techniques	Insights into dispersion of reinforcing agents and interfacial bonding	SEM, AFM	Correlate microstructure with mechanical properties
Biomedical applications	Biocompatibility and suitability for tissue engineering and medical devices	Scaffold fabrication, implant development	Advancement in healthcare and medical technologies
Structural materials applications	Lightweight, high strength-to-weight ratio, and corrosion resistance	Aerospace, automotive, construction	Weight reduction and durability in various industries
Environmental remediation applications	Enhanced adsorption and filtration properties for wastewater treatment	Functionalized biopolymers, nanomaterials	Pollution mitigation and resource conservation
Scalable synthesis techniques	Large-scale production while maintaining eco-friendliness and performance	Scalable synthesis methods	Meet growing demand for sustainable materials
Advanced characterization techniques	Deeper insights into structure-property relationships	In-situ mechanical testing, multi-scale modeling	Understand complex behavior under different conditions
Emerging applications	Flexible electronics, energy storage, and smart materials	Integration with advanced technologies	Address global challenges in healthcare, energy, and sustainability
Collaboration and interdisciplinary research	Innovation and knowledge exchange across disciplines	Collaborative research efforts	Unlock new opportunities for sustainable development
Economic feasibility	Cost-effectiveness of synthesis techniques and material scalability	Cost analysis, scalability assessment	Commercial viability and industrial adoption

SYNTHESIS TECHNIQUES

Overview of Traditional Synthesis Methods

For making biopolymer-based composites the old way, using common methods like liquid casting, melt mixing, and solution blending is common. In solvent casting, biopolymers are mixed with the right solvent, then strengthening agents are added, and finally the solvent is evaporated to leave behind a hybrid film or membrane. Melt mixing is the process of melting biopolymers and mixing them with strengthening agents at high temperatures. The mixture is then cooled to make it rigid. Solution mixing is the process of dissolving biopolymers and strengthening agents in a common liquid. The mixture is then dried out or precipitated to make a new material. These methods have been used a lot, but they often need strong chemicals, use a lot of energy, and make it hard to control the qualities of the mixture.

1. Selection of Biopolymer and Reinforcing Agent:

- Choose a suitable biopolymer and reinforcing agent based on the desired properties of the composite.
- Biopolymers like cellulose, chitosan, or starch are commonly used, while reinforcing agents can include nanoparticles, fibers, or particles.

2. Preparation of Biopolymer Solution:

- Dissolve the biopolymer in a suitable solvent to form a homogeneous solution.
- The concentration of biopolymer in the solution can be calculated using the following equation:

$$C = mV$$

Where,

- CC is the concentration of biopolymer (g/mL)
- mm is the mass of biopolymer (g)
- VV is the volume of solvent (mL)

3. Incorporation of Reinforcing Agent:

- Add the reinforcing agent to the biopolymer solution and mix thoroughly to ensure uniform dispersion.
- The loading of reinforcing agent can be calculated as:

$$\%Loading = mreinforcingmbiopolymer \times 100\%$$

Where:

- $mreinforcing$ is the mass of reinforcing agent (g)
- $mbiopolymer$ is the mass of biopolymer (g)

4. Casting of Composite Films:

- Pour the biopolymer-reinforcing agent mixture into a mold or onto a flat surface.
- Spread the mixture evenly to form a thin film using a casting knife or similar tool.

5. Solvent Evaporation and Film Formation:

- Allow the solvent to evaporate slowly at room temperature or under controlled conditions.
- The rate of solvent evaporation ($\frac{dm}{dt}$) can be estimated using Fick's first law of diffusion:

$$dmdt = - \frac{DdCdxdt}{dm}$$
$$\frac{dt}{dh} = -\rho A dt dm$$

- The film will gradually solidify as the solvent evaporates, resulting in the formation of the biopolymer-based composite material.

Introduction To Novel Synthesis Approach Combining Green Chemistry Principles and Advanced Manufacturing Techniques

Instead of using old ways of making things, a new method mixes green science ideas with cutting edge manufacturing methods to create biopolymer-based materials that are more environmentally friendly and work better. This method uses liquids that are safe for the earth, feedstocks that can be used again and again, and processes that use little energy. Advanced production methods like 3D printing, electrospinning, and layer-by-layer building also make it possible to precisely control the shape, makeup, and structure of composites. Green chemistry and modern production can be used together to help researchers create sustainable and scalable ways to make biopolymer-based materials that are perfect for different uses.

1. Green Chemistry Parameters:

- Incorporation of green chemistry metrics such as atom economy (AE), renewable feedstock utilization (RFU), and waste minimization (WM) into the model:

$$GC_{metric} = \sum AE_i + RFU_j - \frac{WM_k}{n_{metrics}}$$

Where:

- AE_i is the atom economy of reaction i

- RFU_j is the renewable feedstock utilization of feedstock j
- WM_k is the waste minimization of process k
- n_{metrics} is the total number of green chemistry metrics considered.
- Objective functions to optimize green chemistry parameters and ensure eco-friendly synthesis pathways:

Minimize GC_metric

2. Advanced Manufacturing Parameters:

- Integration of advanced manufacturing techniques such as 3D printing, electrospinning, or layer-by-layer assembly into the model:

$$AM_{param} = f(speed, nozzle_{diameter}, voltage, deposition_{rate})$$

- Optimization of manufacturing parameters to achieve precise control over composite morphology, composition, and structure:

Maximize AM_param

3. Synthesis Process Optimization:

- Development of optimization algorithms to minimize energy consumption, waste generation, and production costs (C_{prod}) while maximizing material efficiency (ME) and product quality (PQ):

$$\begin{aligned} \text{Minimize } C_{prod} &= f(energy_{consumption}, waste_{generation}, production_{cost}) \\ \text{Maximize } ME, PQ & \end{aligned}$$

4. Environmental Impact Assessment:

- Integration of life cycle assessment (LCA) methodologies to evaluate the environmental impacts (EI) of biopolymer-based composite synthesis:

$$EI = \sum (C_i \times EF_i)$$

Where:

- C_i is the quantity of input or output of process i
- EF_i is the environmental factor associated with process i
- n is the total number of processes considered.
- Sensitivity analysis to assess the influence of process parameters and material choices on environmental performance:

$$\frac{\partial EI}{\partial param} = \frac{(EI_{param2} - EI_{param1})}{(param2 - param1)}$$

5. Performance Prediction and Validation:

- Development of predictive models to estimate the mechanical, thermal, and functional properties (P) of biopolymer-based composites:

$$P = f(process_{parameters}, material_{choices})$$

- Validation of model predictions through experimental characterization:

$$Error = \frac{\sum (P_{model} - P_{experimental})^2}{n}$$

Where:

- P_{model} is the predicted property from the model
- P_{experimental} is the property measured experimentally
- n is the number of data points.

Description of Biopolymer Selection and Preparation

The qualities and efficiency of biopolymer-based composites depend a lot on the biopolymers that are used and how they are prepared. These biopolymers come from natural sources like chitin, starch,

cellulose, and proteins. They have special benefits like being biocompatible, biodegradable, and renewable. To make biopolymers, they need to be cleaned, changed, and given special functions that make them work better with strengthening agents and easier to work with. Researchers can make sure that the creation of high-performance biopolymer-based composites goes well by choosing the right biopolymers and making the best use of the best ways to prepare them.

Details of Synthesis Process and Parameters

The steps and factors used to make biopolymer-based composites are different depending on the biopolymer, binding agents, and characteristics that are wanted in the composite. Some important factors are the type and amount of biopolymer and strengthening agents used, as well as the liquid used, the temperature, the time spent working, and the conditions for hardening. Figure 2 representing the process of synthesis and associated with its parameters.

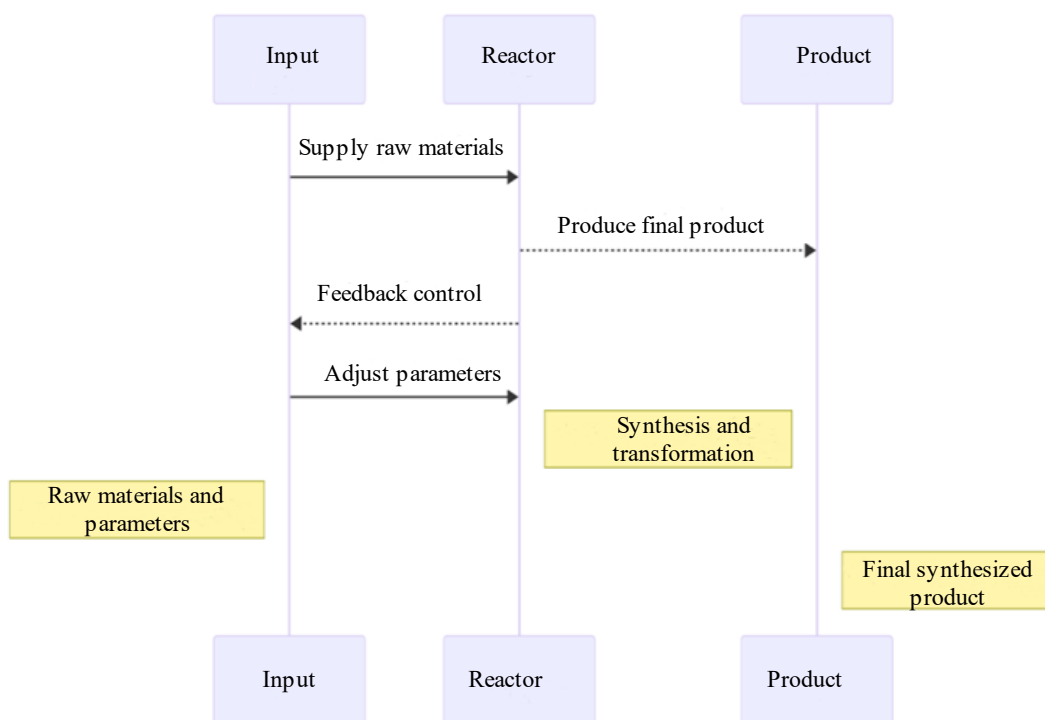


Figure 2. Representation of synthesis process and its parameters.

To get the strengthening agents to spread out evenly in the biopolymer matrix and to control the microstructure and mechanical qualities of the composite material that is made, these factors must be optimized. It is possible for researchers to figure out how composites are made and change their qualities to fit specific needs by changing the factors used in the production process and using advanced methods for characterizing the composites. During the process, Table 4 show the different experimental conditions and parameters that were measured. These include the biopolymer mass, the solvent volume, the reinforcing agent mass, the loading of the reinforcing agent, the solvent diffusion coefficient, the solvent concentration gradient, the film surface area, and the density of the biopolymer-solvent mixture.

Step wise process

1. Biopolymer Solution Concentration:

$$C = m / V$$

Where:

- C is the concentration of the biopolymer solution (g/mL).
- m is the mass of biopolymer (g).

- V is the volume of solvent (mL).

2. Reinforcing Agent Loading:

$$\% \text{ Loading} = \left(\frac{m_{\text{reinforcing}}}{m_{\text{biopolymer}}} \right) \times 100\%$$

Where:

- % Loading is the percentage of reinforcing agent in the composite.
- m_reinforcing is the mass of the reinforcing agent (g).
- m_biopolymer is the mass of the biopolymer (g).

3. Rate of Solvent Evaporation:

$$\frac{dm}{dt} = -D \left(\frac{dC}{dx} \right)$$

Where:

- dm/dt is the rate of mass loss (g/s).
- D is the diffusion coefficient of the solvent in the atmosphere (m²/s).
- dC/dx is the concentration gradient of the solvent vapor in the direction of diffusion (g/m³/m).

4. Rate of Film Thickness Reduction:

$$\frac{dh}{dt} = - \frac{\left(\frac{dm}{dt} \right)}{(\rho A)}$$

Where:

- dh/dt is the rate of reduction in film thickness (m/s).
- ρ is the density of the biopolymer-solvent mixture (kg/m³).
- A is the surface area of the film exposed to evaporation (m²).

MECHANICAL CHARACTERIZATION

Characterizing biopolymer-based composites mechanically is important for figuring out how well they work and whether they are right for different uses. People often use tensile, bending, and impact tests to check the mechanical features of these materials when they are loaded in different ways.

Tensile, Flexural, And Impact Testing Procedures

A basic method used in mechanical testing to find out the tensile strength, stiffness, and length at break of a material is tensile testing. To test biopolymer-based composites, a tension load is put on a standard specimen, which is usually formed like a dog bone, and the test continues until the specimen breaks. Researchers can figure out key mechanical qualities like tensile strength, modulus of elasticity, and elongation at break by calculating stress-strain graphs and keeping track of the load and deformation, discuss in Table 3.

Table 3. Results from tensile, flexural, and impact testing procedures

Tensile Strength (MPa)	Flexural Strength (MPa)	Impact Strength (J/m ²)
45.23	55.36	12.56
52.12	61.25	13.47
48.53	58.23	12.56
47.52	57.48	12.35
49.9	59.64	12.78
46.35	56.78	12.68

Flexural testing, which is also called bending testing, checks how stiff a material is and how it bends. Biopolymer-based composites are tested for flexural strength by putting a three- or four-point twisting load on an object that is held up at its ends.

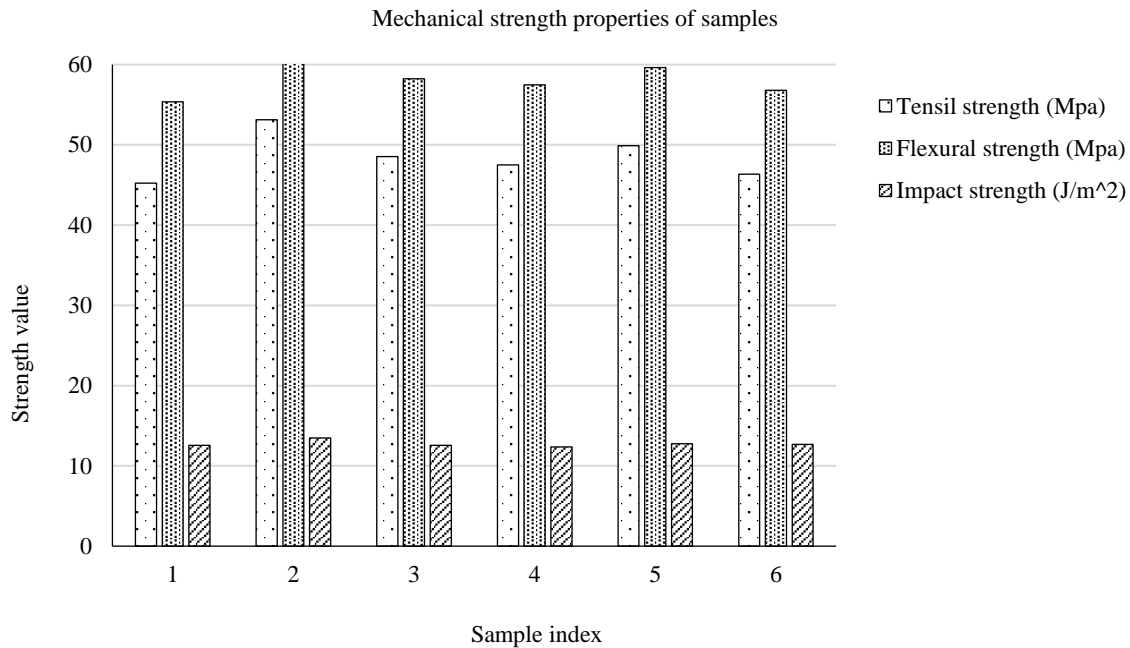


Figure 3. Result representation for tensile, flexural, and impact testing procedures.

The object bends because of the load, and the change in shape is recorded to find out the composite material's flexural strength, modulus of elasticity, and flexural hardness. When testing biopolymer-based composites, an impact test involves hitting a standard object with a swing or a weight falling at a certain speed. Researchers measure how much energy the object absorbs when it is hit, which lets them figure out how tough and resistant it is to impact, illustrate in figure 3. These methods for mechanical testing give us useful information about how strong, long-lasting, and structurally stable biopolymer-based composites are. Researchers can find out how these composites behave mechanically in different situations and make them work best for certain uses by changing things like the loading rate, temperature, and shape of the specimens in a planned way.

Microstructural Analysis Techniques

Using microstructural analysis tools like scanning electron microscopy (SEM) and atomic force microscopy (AFM) is an important part of studying the internal structure and morphology of biopolymer-based composites. These tools are especially useful for looking at how the reinforcing agents are distributed and bonded within the biopolymer matrix. SEM is a powerful imaging method that gives very clear pictures of the shape of materials' surfaces, analysis with its parameter discussed in table 4. When it comes to biopolymer-based composites, SEM lets researchers see how strengthening agents like nanoparticles, strands, or particles are spread out and arranged within the biopolymer matrix. Researchers can look at SEM pictures to see how regular the dispersion is, how well the matrix and reinforcement stages join, and if there are any flaws or breaks in the material that might change its mechanical qualities.

Table 4. Result for microstructural analysis techniques

SEM	AFM	TEM	XRD	FTIR	EDX
15.2	2.5	30	12.35	6.32	4.25
17.8	301	32	12.5	5.52	1.25
16.5	2.8	37	12.2	6.25	3.85

18.3	3.2	33	12.5	2.86	4.23
16.9	2.7	31	12.35	6.12	3.96
17.5	2.9	26	13.25	5.78	4.12
15.8	2.6	34	12.1	5.96	4.4
16.4	2.7	36	12.25	5.63	3.5
17.1	3.2	32	12.75	6.32	4.36
15.5	2.9	31	12.95	5.42	3.9

AFM is a flexible photography method that lets you see images at the nanoscale level and describe the surface of objects.

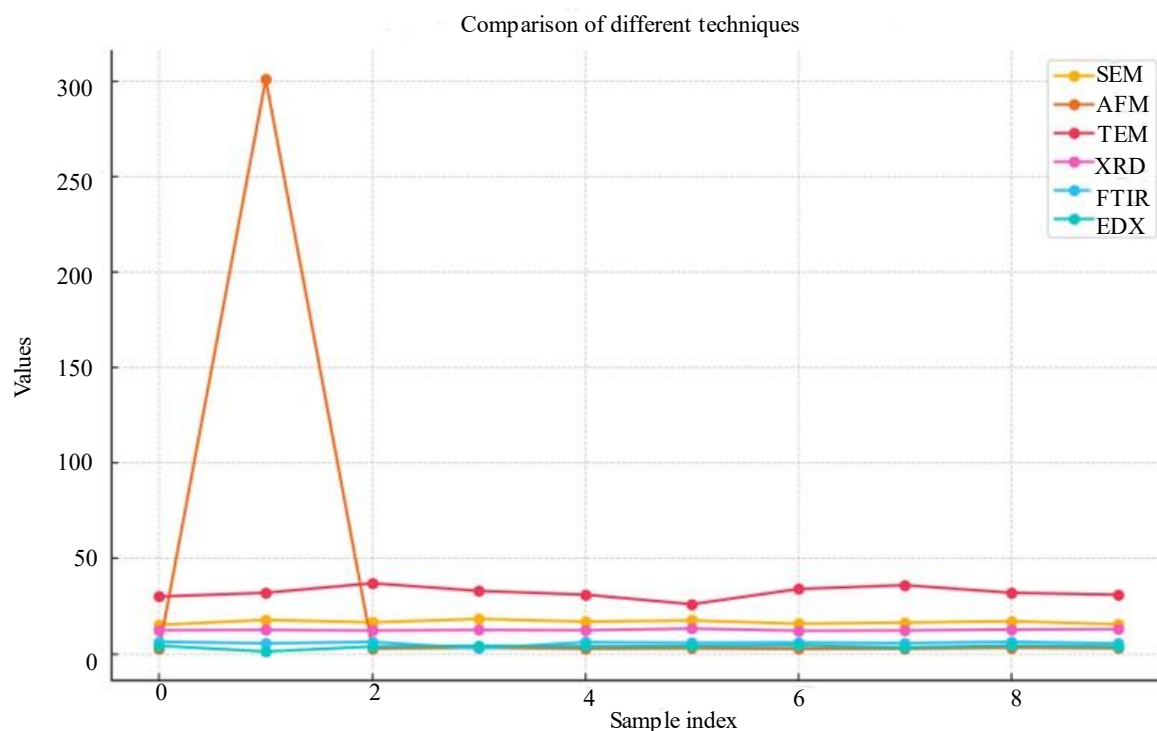


Figure 4. Comparison of microstructural analysis techniques.

In AFM, a sharp probe is moved across the surface of a sample. The pressures that happen between the probe and the sample are measured to make topographic pictures with a level of detail that is measured in nanometers, comparison shown in figure 4. When working with biopolymer-based composites. Researchers can learn a lot about the microstructure and interface features of biopolymer-based composites by using both SEM and AFM together. Researchers can use these microstructural analysis methods to connect microstructural traits with mechanical properties. This helps them figure out how these materials behave and make them work better in certain situations. This Table 5 outlines various experimental conditions and corresponding measured parameters, showcasing diverse methodologies and outcomes.

Table 5. Different experimental conditions and parameters measured.

Biopolymer Mass (g)	Solvent Volume (mL)	Reinforcing Agent Mass (g)	Reinforcing Agent Loading (%)	Solvent Concentration Gradient (g/m ³ /m)	Film Surface Area (m ²)	Biopolymer-Solvent Mixture Density (kg/m ³)
10	50	5	50	1.2	0.2	1000
15	75	6	40	1.5	0.3	1100
20	100	8	40	1.8	0.4	1200

25	125	10	40	2.0	0.5	1300
30	150	12	40	2.2	0.6	1400
35	175	14	40	2.5	0.7	1500

In mechanical characterization, tests like tensile, flexural, and impact testing can tell us a lot about the mechanical properties of biopolymer-based composites.

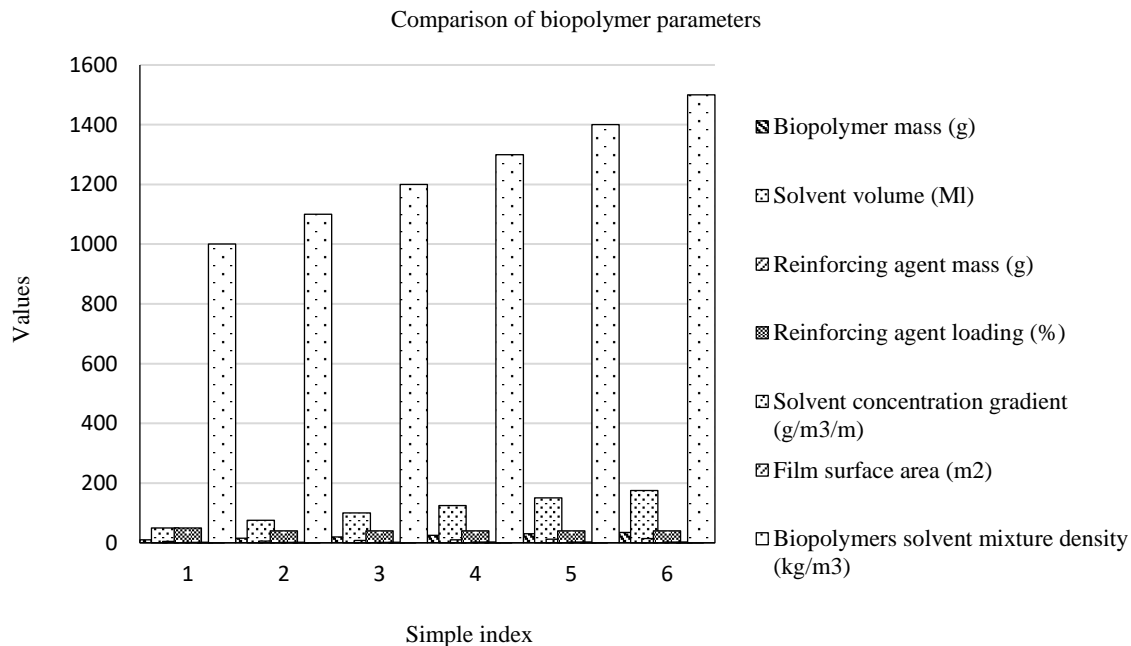


Figure 5. Comparison of biopolymer parameters.

Microstructural analysis techniques, like SEM and AFM, let us look into the micro- and nanoscale structure and properties of these materials' interfaces. Researchers can learn a lot about how the structure and features of biopolymer-based composites relate to each other by using all of these methods together, as represent in Figure 5. They can also make materials with specific qualities for use in biology and materials science.

ADVANCED APPLICATIONS

Potential Applications of Biopolymer-Based Composites In Biochemistry And Materials Sciences

They can be used in many different ways in biology and materials science because they are made of biopolymers and have special qualities. In biology, these compounds can be used to make biosensors, supports for tissue engineering, and systems that release drugs. Biopolymer matrices like alginate, chitosan, and gelatin are very biocompatible and can be changed to look like the extracellular matrix. This makes them perfect for repairing and growing new tissues. Furthermore, adding bioactive agents, nanoparticles, or growth factors to these compounds makes them better at delivering drugs precisely and controlling their release. Biopolymer-based composites can also be made to respond to triggers, which means that medicinal agents can be released when certain environmental cues are met, such as changes in pH, temperature, or enzymatic activity.

Biopolymer-based composites are used in many areas of materials science, such as the manufacturing, automobile, aircraft, and building businesses. This Figure 6 shows how the mass of a biopolymer affects important properties like its tensile strength, ability to break down naturally, and heat stability. It shows how changes in the biopolymer mass affect these qualities, which helps us figure out how to make materials work better. These composites are recyclable and light alternatives to standard plastics made from petroleum. They are better for the earth and address worries about

sustainability. It is possible to make composites with better mechanical properties, heat stability, and protective qualities by mixing biopolymers with binding agents like natural fibers, nanoparticles, or recycled materials. For example, cellulose nanocrystals from green sources like wood pulp can be mixed into biopolymer structures to make them stronger and stiffer. This makes them good for use as structural elements in building materials or car parts.

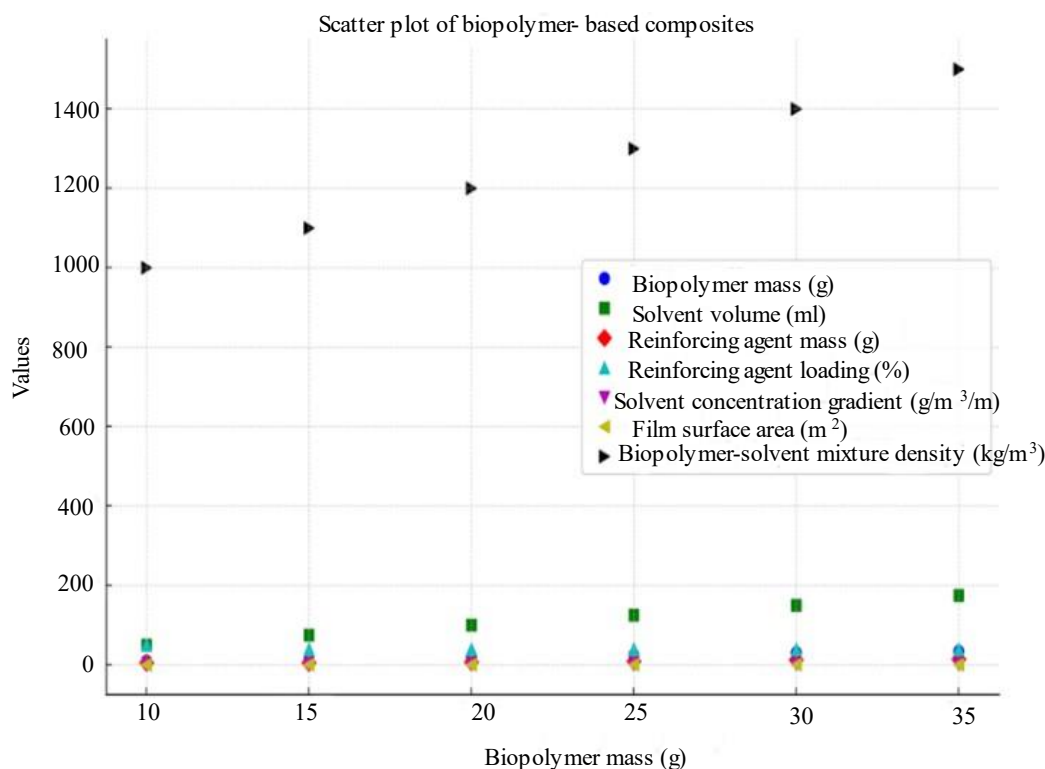


Figure 6. Relationship between Biopolymer Mass and various parameters.

Examples Of Biomedical, Structural, And Other Advanced Applications:

Biopolymer-based materials have shown a lot of promise in a wide range of complex areas, including biomedicine, construction, and others. In the health field, these materials are used to make wound bandages, tissue engineering creations, injectable devices, and drug delivery systems. For instance, in bone and joint mending, collagen-based supports that are strengthened with recyclable plastics or ceramics allow cells to grow and tissues to grow back. Resin-based composites strengthened with glass fibers or nanofillers are used for tooth replacements because they look like real teeth and have the same mechanical qualities.

Biopolymer-based composites can be used for structural purposes to make lightweight materials for sports equipment, car parts, and airplane cabins. Biodegradable composites made from natural fibers like jute, flax, or hemp are good options to glass or carbon fiber bonded plastics, especially when weight reduction and environmental friendliness are very important. Because these materials are very stiff and have high specific strength, they can be used in load-bearing buildings without lowering their performance. In other advanced uses, biopolymer-based composites are used to make sensors, electronics, filter screens, and packing materials. Biopolymers that are conductive, like polyaniline or poly(3,4-ethylenedioxythiophene) mixed with graphene or carbon nanotubes, can carry electricity and be bent, which lets them be used in flexible electronics, portable sensors, and energy storage devices. Biopolymer-based membranes with customized surface chemistry and pores are also used to clean water, separate gases, and filter biological materials. Biodegradable packing sheets made from starch or cellulose-based polymers are long-lasting options to plastics made from oil, which helps the environment by reducing plastic trash.

Polymer nanocomposites have a wide range of applications in daily life due to their enhanced mechanical, thermal, and barrier properties. Here are some ways they might be used:

a. *Packaging:*

- *Food packaging:* Improved barrier properties against gases and moisture help in extending the shelf life of food products.
- *Pharmaceutical packaging:* Enhanced protection of drugs from environmental factors, ensuring stability and efficacy.

b. *Consumer Electronics:*

- *Smartphones and tablets:* Used in coatings and components for improved durability, heat resistance, and reduced weight.
- *Flexible displays:* Polymer nanocomposites can be used in flexible and bendable screens.

c. *Automotive:*

- *Lightweight components:* Used in manufacturing lighter car parts, which contribute to fuel efficiency and reduced emissions.
- *Improved tire performance:* Nanocomposites in tires enhance durability, traction, and wear resistance.

d. *Textiles:*

- *Functional clothing:* Used in fabrics to provide properties like UV protection, antimicrobial effects, and improved durability.
- *Sportswear:* Enhanced breathability, moisture management, and strength in sports clothing and equipment.

e. *Medical Devices:*

- *Implants and prosthetics:* Enhanced mechanical strength and biocompatibility for longer-lasting and more reliable implants.
- *Drug delivery systems:* Controlled release and targeted delivery of drugs using nanocomposite materials.

f. *Construction:*

- *Building materials:* Used in cement and concrete to improve strength, durability, and resistance to environmental factors.
- *Insulation:* Improved thermal and sound insulation properties in building materials.

g. *Energy:*

- *Batteries:* Used in electrodes and electrolytes to enhance the performance and longevity of batteries.
- *Solar panels:* Improved efficiency and stability of photovoltaic cells using polymer nanocomposites.

Discussion On the Role of Tailored Mechanical Properties In Various Applications

Customizing the dynamic qualities of biopolymer-based composites is important for using them successfully in a range of situations. When used in biomedicine, the mechanical qualities of scaffolds or implants are very important for making sure that tissue regrowth works properly and with enough support. The mechanical strength, flexibility, and breakdown rate of biopolymer composites can be made to match the mechanical qualities of natural tissues by changing things like the type of support used, the makeup of the polymer, and the processing circumstances. In bone tissue engineering, for example, the crushing stiffness of biopolymer scaffolds needs to be very similar to that of real bone so that cells can grow and the tissue can become one with the scaffold.

Similarly, biopolymer-based composites can only be used for certain load-bearing purposes if they have good mechanical performance in structural uses. By adding high-strength strengthening agents

and making the best use of fiber-matrix interactions, it is possible to make composites that have better tensile, bending, and impact qualities for structural parts that are loaded and unloaded quickly. Also, changing the mechanical features of materials lets designers make them lighter while still being strong. This saves energy and lessens the damage they do to the earth in the building and transportation businesses.

Comparison With Traditional Materials and Current Challenges

When you compare biopolymer-based composites to other materials, you can see how they are different and what their pros and cons are. In terms of being better for the earth, biopolymer blends are much better than plastics made from petroleum because they are made from green materials and break down naturally. Because of this, they are good options for lowering your carbon impact and dealing with issues related to plastic waste. Biopolymer blends often have lower production costs than manufactured polymers, especially when farming trash or by-products are used as raw materials. However, there are still problems that need to be fixed before biopolymer-based composites can be widely used in advanced uses. One big problem is that biopolymers don't have as good of dynamic properties as metals or manufactured polymers. This could make it hard to use them in high-performance situations. To solve this problem, we need to improve how we handle materials, how we strengthen them, and how well they work with the industrial system we already have. Also, making sure that the production methods for biopolymer composites can be scaled up and quality control is reliable is important for meeting industry standards and market needs. Getting the best biopolymer qualities for certain uses while still being biocompatible and long-lasting is another problem. Material scientists, engineers, and biologists need to work together across disciplines to find the best balance between mechanical performance, biodegradability, and cost-effectiveness. Creating standard testing methods and approval processes is also needed to make sure that biopolymer-based composites work well and are safe for a wide range of uses.

CONCLUSION

Discovering new ways to make biopolymer-based composites and fully characterizing their dynamic properties is a big step toward finding more uses for them in many fields, such as biology and materials science. These composites offer many ways to solve important problems in sustainability, usefulness, and performance by combining green chemistry ideas with advanced production methods and custom-made mechanical qualities. The synthesis process, which was led by green chemistry measures like atom economy, using reusable feedstocks, and minimizing trash, shows how important it is to use eco-friendly methods when making composites. By finding the best fluid, reaction conditions, and processing methods, researchers can cut down on energy use, trash, and production costs while increasing the efficiency of materials and making them more eco-friendly. The focus on sustainability fits with the rising need for better options in many fields, and it highlights the usefulness of biopolymer-based composites as answers. The detailed dynamic analysis of these materials also lets them be tailored to specific use needs, whether they are in the medicinal, structural, or other advanced fields. Tensile, bending, and impact tests are very helpful for understanding how the composites behave mechanically. They help improve strengthening methods, matrix ratios, and processing parameters. Microstructural research methods, like SEM and AFM, help us understand interface bonds, dispersion, and shape better, which makes it easier to create composites that work better and have more uses. Biopolymer-based composites are very flexible and have a lot of promise for use in advanced uses. These composites are safe, biodegradable, and light, so they can be used instead of traditional materials for everything from health devices to structure parts and more. Their ability to mimic the dynamic qualities of natural tissues, along with the fact that they can be tuned to fit specific needs, makes them essential for developing new technologies and solutions.

REFERENCES

1. Richert, A, Olewnik-Kruszkowska, E, Dąbrowska, G.B, Dąbrowski, H.P. The Role of Birch Tar in Changing the Physicochemical and Biocidal Properties of Polylactide-Based Films. *Int. J. Mol. Sci.* 2022, 23, 268.

2. Kaczmarek-Szczepańska, B, Wekwejt, M, Mazur, O, Zasada, L, Pałubicka, A, Olewnik-Kruszkowska, E. The Physicochemical and Antibacterial Properties of Chitosan-Based Materials Modified with Phenolic Acids Irradiated by UVC Light. *Int. J. Mol. Sci.* 2021, 22, 6472.
3. Czaplicka, N, Mania, S, Konopacka-Łyskawa, D. Influence of Rhamnolipids and Ionic Cross-Linking Conditions on the Mechanical Properties of Alginate Hydrogels as a Model Bacterial Biofilm. *Int. J. Mol. Sci.* 2021, 22, 6840.
4. Tarach, I, Olewnik-Kruszkowska, E, Richert, A, Gierszewska, M, Rudawska, A. Influence of Tea Tree Essential Oil and Poly(ethylene glycol) on Antibacterial and Physicochemical Properties of Polylactide-Based Films. *Materials* 2020, 13, 4953.
5. Khutsishvili, S.S, Perfileva, A.I, Nozhkina, O.A, Ganenko, T.V, Krutovsky, K.V. Novel Nanobiocomposites Based on Natural Polysaccharides as Universal Trophic Low-Dose Micronutrients. *Int. J. Mol. Sci.* 2021, 22, 12006.
6. Diyana, Z, Jumaidin, R, Selamat, M, Ghazali, I, Julmohammad, N, Huda, N, Ilyas, R. Physical Properties of Thermoplastic Starch Derived from Natural Resources and Its Blends: A Review. *Polymers* 2021, 13, 1396.
7. Abotbina, W, Sapuan, S.M, Sultan, M.T.H, Alkbir, M.F.M, Ilyas, R.A. Development and Characterization of Cornstarch-Based Bioplastics Packaging Film Using a Combination of Different Plasticizers. *Polymers* 2021, 13, 3487.
8. Mohammed, A.A.B.A, Omran, A.A.B, Hasan, Z, Ilyas, R.A, Sapuan, S.M. Wheat Biocomposite Extraction, Structure, Properties and Characterization: A Review. *Polymers* 2021, 13, 3624.
9. Nurazzi, N.M, Khalina, A, Chandrasekar, M, Aisyah, H, Rafiqah, S.A, Ilyas, R, Hanafee, Z. Effect of fiber orientation and fiber loading on the mechanical and thermal properties of sugar palm yarn fiber reinforced unsaturated polyester resin composites. *Polimery* 2020, 65, 115–124.
10. Ajani, S. N. ., Khobragade, P. ., Dhone, M. ., Ganguly, B. ., Shelke, N. ., & Parati, N. . (2023). Advancements in Computing: Emerging Trends in Computational Science with Next-Generation Computing. *International Journal of Intelligent Systems and Applications in Engineering*, 12(7s), 546–559
11. Izwan, S.M, Sapuan, S, Zuhri, M, Mohamed, A. Thermal Stability and Dynamic Mechanical Analysis of Benzoylation Treated Sugar Palm/Kenaf Fiber Reinforced Polypropylene Hybrid Composites. *Polymers* 2021, 13, 2961.
12. Suriani, M, Zainudin, H, Ilyas, R, Petrù, M, Sapuan, S, Ruzaidi, C, Mustapha, R. Kenaf Fiber/Pet Yarn Reinforced Epoxy Hybrid Polymer Composites: Morphological, Tensile, and Flammability Properties. *Polymers* 2021, 13, 1532.
13. Alias, A.H, Norizan, M.N, Sabaruddin, F.A, Asyraf, M.R.M, Norrrahim, M.N.F, Ilyas, A.R, Kuzmin, A.M, Rayung, M, Shazleen, S.S, Nazrin, A, et al. Hybridization of MMT/Lignocellulosic Fiber Reinforced Polymer Nanocomposites for Structural Applications: A Review. *Coatings* 2021, 11, 1355.
14. Azman, M.A, Asyraf, M.R.M, Khalina, A, Petrù, M, Ruzaidi, C.M, Sapuan, S.M, Wan Nik, W.B, Ishak, M.R, Ilyas, R.A, Suriani, M.J. Natural Fiber Reinforced Composite Material for Product Design: A Short Review. *Polymers* 2021, 13, 1917.
15. Sharma, S, Sudhakara, P, Omran, A.A.B, Singh, J, Ilyas, R.A. Recent Trends and Developments in Conducting Polymer Nanocomposites for Multifunctional Applications. *Polymers* 2021, 13, 2898.
16. Asyraf, M.R.M, Ishak, M.R, Sapuan, S.M, Yidris, N, Ilyas, R.A, Rafidah, M, Razman, M.R. Evaluation of Design and Simulation of Creep Test Rig for Full-Scale Crossarm Structure. *Adv. Civ. Eng.* 2020, 2020, 6980918.
17. Ilyas, R.A, Zuhri, M.Y.M, Aisyah, H.A, Asyraf, M.R.M, Hassan, S.A, Zainudin, E.S, Sapuan, S.M, Sharma, S, Bangar, S.P, Jumaidin, R, et al. Natural Fiber-Reinforced Polylactic Acid, Polylactic Acid Blends and Their Composites for Advanced Applications. *Polymers* 2022, 14, 202.
18. Norfarhana, A, Ilyas, R, Ngadi, N. A review of nanocellulose adsorptive membrane as multifunctional wastewater treatment. *Carbohydr. Polym.* 2022, 291, 119563.
19. Ilyas, R.A, Zuhri, M.Y.M, Norrrahim, M.N.F, Misenan, M.S.M, Jenol, M.A, Samsudin, S.A, Nurazzi, N.M, Asyraf, M.R.M, Supian, A.B.M, Bangar, S.P, et al. Natural Fiber-Reinforced Polycaprolactone Green and Hybrid Biocomposites for Various Advanced Applications. *Polymers* 2022, 14, 182.

20. Ilyas, R.A, Aisyah, H.A, Nordin, A.H, Ngadi, N, Zuhri, M.Y.M, Asyraf, M.R.M, Sapuan, S.M, Zainudin, E.S, Sharma, S, Abral, H, et al. Natural-Fiber-Reinforced Chitosan, Chitosan Blends and Their Nanocomposites for Various Advanced Applications. *Polymers* 2022, 14, 874.
21. Haris, N.I.N, Hassan, M.Z, Ilyas, R, Suhot, M.A, Sapuan, S, Dolah, R, Mohammad, R, Asyraf, M. Dynamic mechanical properties of natural fiber reinforced hybrid polymer composites: A review. *J. Mater. Res. Technol.* 2022, 19, 167–182.
22. Ilyas, R, Sapuan, S, Asyraf, M, Dayana, D, Amelia, J, Rani, M, Norrrahim, M, Nurazzi, N, Aisyah, H, Sharma, S, et al. Polymer Composites Filled with Metal Derivatives: A Review of Flame Retardants. *Polymers* 2021, 13, 1701.
23. Suriani, M.J, Ilyas, R.A, Zuhri, M.Y.M, Khalina, A, Sultan, M.T.H, Sapuan, S.M, Ruzaidi, C.M, Wan, F.N, Zulkifli, F, Harussani, M.M, et al. Critical Review of Natural Fiber Reinforced Hybrid Composites: Processing, Properties, Applications and Cost. *Polymers* 2021, 13, 3514.
24. Palanisamy, S.; Kalimuthu, M.; Nagarajan, R.; Fernandes Marlet, J.M.; Santulli, C. Physical, Chemical, and Mechanical Characterization of Natural Bark Fibers (NBFs) Reinforced Polymer Composites: A Bibliographic Review. *Fibers* 2023, 11, 13. <https://doi.org/10.3390/fib11020013>
25. Mysamy B, Shanmugam SKM, Aruchamy K, Palanisamy S, Nagarajan R, Ayrilmis N. A review on natural fiber composites: Polymer matrices, fiber surface treatments, fabrication methods, properties, and applications. *Polym Eng Sci.* 2024; 64(6): 2345-2373. doi:10.1002/pen.26713
26. A. Karthik, M. Bhuvaneshwaran, M. S. Senthil Kumar, S. Palanisamy, M. Palaniappan, N. Ayrilmis, *ChemistrySelect* 2024, 9, e202400650. <https://doi.org/10.1002/slct.202400650>
27. Kurien, R.A., Selvaraj, D.P., Sekar, M. et al. A comprehensive review on the mechanical, physical, and thermal properties of abaca fibre for their introduction into structural polymer composites. *Cellulose* 30, 8643–8664 (2023). <https://doi.org/10.1007/s10570-023-05441-z>
28. Goutham, E.R.S.; Hussain, S.S.; Muthukumar, C.; Krishnasamy, S.; Kumar, T.S.M.; Santulli, C.; Palanisamy, S.; Parameswaranpillai, J.; Jesuarockiam, N. Drilling Parameters and Post-Drilling Residual Tensile Properties of Natural-Fiber-Reinforced Composites: A Review. *J. Compos. Sci.* 2023, 7, 136. <https://doi.org/10.3390/jcs7040136>
29. Palanisamy, S., Murugesan, T. M., Palaniappan, M., Santulli, C., Ayrilmis, N., and Alavudeen, A. (2024). "Selection and processing of natural fibers and nanocellulose for biocomposite applications: A brief review," *BioResources* 19(1), 1789-1813.