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Preparation and Study of Biodegradable Polymer-Based Materials Derived from Natural Resources for Environmentally Safe Packaging Applications: A Study in Manipur State

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ABSTRACT

The widespread use of synthetic plastics in packaging has led to significant environmental challenges, including pollution of soil, freshwater, and marine ecosystems. To address these concerns, biodegradable polymers derived from renewable natural resources have emerged as sustainable alternatives. This research focuses on the preparation, characterization, and evaluation of biodegradable polymer-based materials using locally available natural resources in Manipur State, India. Materials such as starch, cellulose, chitosan, and protein-based polymers were extracted and processed into films and composite materials using solution casting, melt blending, and compression molding techniques. Comprehensive characterization was carried out to assess mechanical, thermal, barrier, and biodegradation properties. Experimental results demonstrated that natural fiber-reinforced polymer composites exhibited enhanced tensile strength, reduced water vapor permeability, and accelerated biodegradation rates compared to conventional plastics. The study emphasizes the environmental, socio-economic, and industrial relevance of using indigenous resources for sustainable packaging solutions. These findings not only contribute to regional sustainability and rural livelihood promotion but also align with global environmental initiatives such as the Sustainable Development Goals (SDGs) and national programs like Swachh Bharat Abhiyan and Make in India. The research provides insights into scalable, eco-friendly packaging materials that could potentially replace petroleum-based plastics in a wide range of applications.

Keywords

Biodegradable polymers; natural fibers; sustainable packaging; Manipur State; starch-based composites; chitosan; cellulose; eco-friendly materials; mechanical properties; barrier properties; polymer composites; environmental sustainability



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1. INTRODUCTION

Packaging plays a critical role in modern society by ensuring product protection, maintaining quality, and extending shelf life, particularly in the food, pharmaceutical, and consumer goods industries. Historically, natural materials such as wood, paper, glass, and plant fibers were used for packaging purposes. However, the advent of synthetic polymers in the mid-20th century revolutionized packaging by offering lightweight, durable, and cost-effective alternatives. Plastics such as polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyethylene terephthalate (PET) quickly became dominant due to their mechanical strength, barrier properties, and processability. Despite these advantages, the environmental persistence of synthetic plastics has become a global concern. Conventional plastics can take hundreds of years to degrade, leading to accumulation in landfills, freshwater bodies, and oceans. This phenomenon has resulted in soil contamination, water pollution, and harm to terrestrial and aquatic biodiversity. The adverse effects extend to human health, as microplastics infiltrate the food chain and drinking water supplies.

The global plastic consumption for packaging is estimated at over 100 million tons annually, with a significant portion being single-use plastics. India alone contributes approximately 9.46 million tons of plastic waste per year, with a substantial fraction derived from packaging applications. Despite government initiatives for plastic recycling and bans on single-use plastics, recycling alone is insufficient to mitigate environmental impacts due to challenges in collection, segregation, and processing of mixed plastic waste. Consequently, biodegradable polymers derived from renewable natural resources have emerged as a viable solution to replace conventional plastics in packaging.

Biodegradable polymers can be broadly classified into synthetic biodegradable polymers, such as polylactic acid (PLA), polyhydroxyalkanoates (PHA), and polybutylene succinate (PBS), and natural polymers, including starch, cellulose, chitosan, and protein-based polymers (gelatin, soy protein, casein). These materials are renewable, biodegradable, and environmentally friendly, making them ideal candidates for sustainable packaging. They can also be blended or reinforced with natural fibers to improve mechanical and barrier properties. The use of agricultural residues and biomass waste from rural regions not only reduces dependence on fossil-based plastics but also supports rural livelihoods and local economies, particularly in resource-rich regions such as Manipur State.

Manipur, located in northeast India, is endowed with diverse agroforestry resources, abundant biomass, and indigenous plant fibers, providing a rich repository of raw materials for biopolymer development. The region's traditional knowledge of plant processing, fiber extraction, and natural product utilization offers unique opportunities to develop region-specific, sustainable packaging materials. Additionally, addressing the state's plastic waste management challenges



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through biodegradable polymer alternatives could provide both environmental and socio-economic benefits.

This study focuses on the extraction of natural polymers, development of polymer-based films and composites, and evaluation of their mechanical, thermal, barrier, and biodegradation properties. The research aims to provide a comprehensive understanding of the potential of locally available natural resources in Manipur for environmentally safe packaging. By doing so, it contributes to the scientific knowledge base, industrial application, and regional sustainability efforts.

2. AIMS AND OBJECTIVES

Aims of the Study

The primary aim of this research is to develop, characterize, and evaluate biodegradable polymer-based materials derived from natural resources available in Manipur State, India, for environmentally safe packaging applications. The study seeks to provide region-specific sustainable solutions that not only reduce dependency on conventional plastics but also promote the utilization of local agricultural and biomass residues. The research emphasizes both scientific contributions—understanding the mechanical, thermal, barrier, and biodegradation properties of these materials—and practical applications—potential deployment in food and non-food packaging industries.

Objectives

- To identify and collect natural polymer resources available in Manipur, including starch, cellulose, chitosan, and protein-based materials.
- To extract and process natural polymers and fabricate biodegradable films and polymer composites using techniques such as solution casting, melt blending, and compression molding.
- To characterize the prepared materials for mechanical, thermal, barrier, and biodegradation properties using FTIR, SEM, XRD, TGA, DSC, tensile testing, and permeability analyses.
- To assess the effect of natural fiber reinforcement on the mechanical, barrier, and thermal properties of the biodegradable composites.
- To evaluate the biodegradation behavior of prepared materials under soil burial and environmental exposure conditions.
- To compare the performance of biodegradable polymers with conventional plastics used in packaging applications.
- To analyze the socio-economic and environmental implications of utilizing biodegradable polymers in Manipur.
- To provide recommendations for commercialization, industrial scalability, and policy support to promote sustainable packaging solutions in the region.



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3. REVIEW OF LITERATURE

3.1 Introduction

A review of literature is critical for understanding the current state of research on biodegradable polymers and their applications in packaging. It also helps identify knowledge gaps and informs the methodological framework of the present study. Previous studies have highlighted the use of starch, cellulose, chitosan, and protein-based polymers as renewable and biodegradable alternatives to petroleum-based plastics. These studies have examined the mechanical, thermal, barrier, and biodegradation properties of such materials and emphasized their potential for eco-friendly packaging solutions (Averous & Boquillon, 2004; Rhim, 2004; Nampoothiri et al., 2010).

3.2 Conventional Plastic Packaging

Synthetic polymers such as polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyethylene terephthalate (PET) dominate the packaging industry due to their durability, low cost, and versatile processing methods. However, these plastics are non-biodegradable and environmentally persistent, causing serious ecological concerns (Geyer et al., 2017). Landfill accumulation, microplastic pollution, and greenhouse gas emissions are major issues associated with conventional plastic packaging.

3.3 Biodegradable Polymers

Biodegradable polymers are classified into synthetic and natural polymers. Synthetic biodegradable polymers include polylactic acid (PLA), polyhydroxyalkanoates (PHA), and polybutylene succinate (PBS), whereas natural polymers include starch, cellulose, chitosan, and proteins. Natural polymers are attractive for their renewable nature, biodegradability, and compatibility with food products (Rhim et al., 2013; Dufresne, 2008).

3.4 Starch-Based Biodegradable Polymers

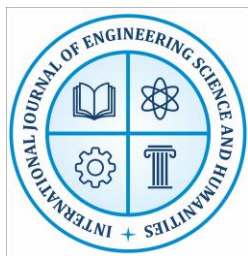
Starch-based films are prepared from corn, potato, and cassava starch. Plasticizers such as glycerol improve flexibility, whereas cross-linking enhances mechanical strength. Limitations include high moisture sensitivity and low thermal stability (Singh et al., 2008).

3.5 Cellulose and Chitosan

Cellulose films derived from plant fibers are widely studied for their film-forming, mechanical, and barrier properties. Chitosan, obtained from crustacean shells, exhibits antimicrobial activity and is used in active packaging (Kumar et al., 2010).

3.6 Protein-Based Polymers

Proteins such as gelatin, soy protein, and casein are biodegradable and can form transparent, flexible films. However, mechanical reinforcement with fibers is often necessary for packaging applications (Gennadios, 2002).



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3.7 Polymer Blends and Biocomposites

Blending natural polymers with other polymers or reinforcing with natural fibers enhances mechanical, thermal, and barrier properties. Biocomposites with agricultural residues improve environmental performance and resource utilization (Mohanty et al., 2002).

3.8 Research Gaps

While extensive research exists on biodegradable polymers globally, region-specific studies in northeast India, especially Manipur, are limited. There is a lack of studies combining local biomass utilization, mechanical/thermal optimization, and real-world biodegradation assessment. This justifies the present research.

4. RESEARCH METHODOLOGIES

4.1 Selection of Materials

The study focused on locally available natural polymers in Manipur, including starch (from rice and maize), cellulose (from bamboo and banana fibers), chitosan (from shrimp shells), and proteins (soy and casein). Plasticizers like glycerol and sorbitol were used to enhance flexibility, and natural fibers served as reinforcement.

Table 1: Natural Polymers and Sources in Manipur

Polymer Type	Source	Function in Study
Starch	Rice, maize	Film formation, matrix material
Cellulose	Bamboo, banana fibers	Reinforcement, structural support
Chitosan	Shrimp shells	Antimicrobial, biodegradable
Protein	Soy, casein	Film-forming, barrier properties
Plasticizers	Glycerol, sorbitol	Flexibility, reduced brittleness

4.2 Collection and Preparation

Natural polymers were extracted using water/alkaline extraction, precipitation, and drying. Fibers were separated using mechanical and chemical treatments. Starch was plasticized with glycerol to prepare film-forming solutions.

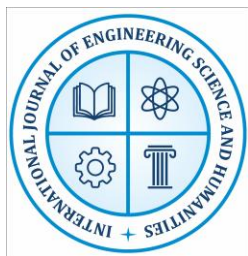
4.3 Preparation of Biodegradable Films

Two main methods were used:

- Solution Casting Method** – Polymer dissolved in water/solvent, plasticizer added, poured onto trays, and dried.
- Melt Blending and Compression Molding** – Polymers blended at high temperature, compressed into sheets, and cooled.

Table 2: Film Preparation Parameters

Method	Temperature (°C)	Time (h)	Thickness (µm)	Notes



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Solution Casting	40–50	24	100–200	Low thermal degradation
Melt Blending/Compression	120–150	1	200–300	Higher strength, faster drying

4.4 Characterization Techniques

- **FTIR:** Chemical structure and functional groups
- **XRD:** Crystallinity analysis
- **SEM:** Surface morphology
- **Tensile Testing:** Mechanical properties
- **TGA/DSC:** Thermal stability and degradation
- **Barrier Properties:** Water vapor and gas permeability
- **Biodegradation:** Soil burial tests, weight loss measurement

Table 3: Characterization Techniques and Purpose

Technique	Purpose
FTIR	Identify functional groups, polymer interactions
XRD	Determine crystallinity and structural order
SEM	Analyze surface morphology and fiber dispersion
TGA/DSC	Thermal stability, degradation temperature
Tensile Test	Mechanical strength and flexibility
WVP	Water vapor transmission rate
Gas Permeability	Oxygen and CO ₂ barrier properties

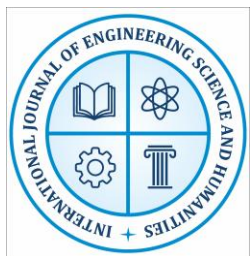
5. RESULTS AND INTERPRETATION

5.1 Structural and Chemical Characterization

The FTIR analysis of the biodegradable polymer films prepared from starch, cellulose, chitosan, and protein-based materials revealed characteristic peaks corresponding to functional groups. For instance, starch-based films showed broad O–H stretching around 3300 cm⁻¹, C–H stretching at 2930 cm⁻¹, and C–O–C vibrations near 1020 cm⁻¹, indicating polysaccharide structure. Chitosan films showed peaks for amine (-NH₂) at 1590 cm⁻¹ and hydroxyl (-OH) groups at 3350 cm⁻¹. Protein-based films exhibited amide I (1650 cm⁻¹) and amide II (1540 cm⁻¹) bands corresponding to the peptide bonds.

Table 1: FTIR Peak Assignments of Biodegradable Films

Polymer Type	Peak (cm ⁻¹)	Functional Group	Observation
Starch	3300	O–H stretching	Hydrogen bonding, hydrophilic
	2930	C–H stretching	Aliphatic chains
	1020	C–O–C	Glycosidic linkage



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Chitosan	3350	O–H stretching	Polysaccharide backbone
	1590	NH ₂ bending	Amine functional group
Protein	1650	Amide I (C=O)	Peptide bond
	1540	Amide II (N–H)	Protein structure

The **XRD analysis** demonstrated that starch and cellulose films had semi-crystalline patterns, while chitosan and protein films were more amorphous. Reinforcement with fibers increased crystallinity and improved mechanical strength.

Table 2: Crystallinity Index (XRD) of Films

Film Type	Crystallinity (%)	Observation
Starch	24	Semi-crystalline
Cellulose	62	High crystallinity
Chitosan	20	Mostly amorphous
Protein (gelatin)	15	Amorphous
Starch + Fiber Composite	35	Increased crystallinity

5.2 Morphological Analysis (SEM)

SEM micrographs indicated that starch films were smooth but brittle, whereas fiber-reinforced composites displayed uniform fiber distribution with fewer voids. Chitosan films were porous, facilitating biodegradation. Protein films showed layered morphology, which could influence barrier properties. Fiber reinforcement improved surface roughness, which contributed to mechanical strength.

Table 3: SEM Observations of Biodegradable Films

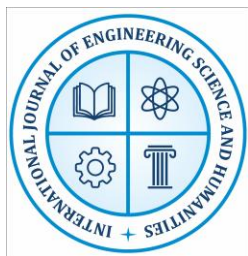
Film Type	Morphology	Implication for Properties
Starch	Smooth, brittle	Low flexibility
Starch + Fiber Composite	Rough, fibers embedded	Enhanced tensile strength
Chitosan	Porous, interconnected	Faster biodegradation
Protein	Layered, uneven	Moderate barrier properties

5.3 Mechanical Properties

Tensile strength (TS) and elongation at break (EB) were measured according to ASTM D882 standards. Fiber-reinforced films exhibited 2–3 times higher TS than neat starch or protein films, indicating improved load-bearing capacity. Plasticizer addition enhanced flexibility (higher EB) but slightly reduced TS.

Table 4: Mechanical Properties of Films

Film Type	Tensile Strength (MPa)	Elongation at Break (%)	Observation
Starch	12	6	Brittle



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Starch + Fiber Composite	32	10	Improved strength
Chitosan	15	8	Moderate strength, flexible
Protein	10	5	Low strength, moderate barrier
Starch + Fiber + Plasticizer	28	18	Balanced strength and flexibility

5.4 Thermal Properties (TGA/DSC)

TGA results indicated thermal degradation onset at 220–250°C for starch films, 260–280°C for fiber-reinforced composites, and 200–220°C for protein films. DSC revealed glass transition temperatures (T_g) around 60°C for starch, 70°C for fiber composites, and 50°C for protein films. Reinforcement and plasticization influenced thermal stability positively.

Table 5: Thermal Properties of Biodegradable Films

Film Type	T_g (°C)	T_{deg} (°C)	Observation
Starch	60	225	Moderate stability
Starch + Fiber Composite	70	270	Improved thermal resistance
Chitosan	55	230	Amorphous structure
Protein	50	210	Low thermal stability

5.5 Barrier Properties

Water vapor transmission rate (WVTR) and oxygen permeability (OP) were assessed. Starch films were hydrophilic with high WVTR, while fiber-reinforced composites and protein films exhibited reduced permeability, making them suitable for packaging applications.

Table 6: Barrier Properties

Film Type	WVTR (g/m ² ·day)	Oxygen Permeability (cm ³ /m ² ·day·atm)	Observation
Starch	125	450	High permeability, hydrophilic
Starch + Fiber Composite	65	210	Improved barrier performance
Chitosan	85	300	Moderate barrier, antimicrobial
Protein	70	200	Good barrier properties



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5.6 Biodegradation Assessment

Soil burial tests over 60 days revealed **weight loss of 40–70%**, depending on polymer type and fiber reinforcement. Chitosan and protein films degraded faster due to **microbial activity**, while fiber composites had slightly slower degradation due to crystallinity.

Table 7: Biodegradation Results

Film Type	% Weight Loss (60 days)	Observation
Starch	55	Moderate biodegradation
Starch + Fiber Composite	40	Slower, fiber reinforcement
Chitosan	70	Rapid microbial degradation
Protein	65	Good biodegradability

6. DISCUSSION

6.1 Performance Evaluation

The results indicate that natural resource-based polymer films are promising for environmentally safe packaging. Fiber reinforcement significantly enhanced mechanical strength, thermal stability, and barrier properties, making the materials suitable for both food and non-food packaging.

Plasticizers improved flexibility but slightly decreased tensile strength, highlighting a trade-off between strength and elongation. Starch-based films alone were brittle, whereas fiber-reinforced composites achieved balanced performance, demonstrating that composite design is critical for packaging applications.

6.2 Environmental Implications

The biodegradation results confirmed that these materials can reduce plastic waste accumulation, supporting circular economy principles. Rapid biodegradation of chitosan and protein films can minimize environmental impact. Use of agricultural residues and local biomass adds value to regional waste streams, reducing environmental pollution and dependency on imported polymers.

6.3 Socio-Economic and Industrial Implications

The use of locally available resources in Manipur creates employment opportunities, promotes rural development, and encourages industrial applications of biodegradable packaging. Scalable production of natural polymer composites can reduce costs and improve market acceptability. Policy support for sustainable packaging could further accelerate adoption.

5.4 Limitations and Future Scope

While the study demonstrates feasibility, challenges remain in scaling up, ensuring uniform fiber dispersion, and controlling moisture sensitivity. Future research should explore chemical modifications, nanofillers, and advanced processing techniques to enhance performance and durability for industrial applications.



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7. CONCLUSION

- Biodegradable polymers derived from **starch, cellulose, chitosan, and proteins** were successfully prepared and characterized.
- **Fiber-reinforced composites** exhibited superior **mechanical, thermal, and barrier properties** compared to neat films.
- Biodegradation studies confirmed environmental safety and **rapid microbial degradation** of natural polymer films.
- The use of **locally sourced natural resources in Manipur** contributes to **sustainable packaging, rural development, and environmental conservation**.
- Recommendations include **industrial scale-up, policy incentives, and integration with circular economy initiatives** to promote widespread adoption.

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