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

Environmental pollution caused by synthetic plastics has emerged as a critical global issue, particularly due to their persistence in landfills and aquatic systems. Biodegradable polymers derived from renewable natural resources present an eco-friendly alternative for sustainable packaging. This study focuses on the development and characterization of biodegradable polymer films and composites utilizing indigenous materials from Manipur State, India, including starch, cellulose, chitosan, and protein-based polymers. The polymers were processed using solution casting and compression molding techniques, and the resulting films were reinforced with locally sourced natural fibers to enhance mechanical and barrier properties. Comprehensive analyses were conducted to evaluate structural, thermal, mechanical, barrier, and biodegradation characteristics. Results indicate that fiber-reinforced composites show superior tensile strength, improved thermal stability, lower water vapor permeability, and accelerated biodegradation compared to pure polymer films. The study highlights the potential of Manipur's biomass resources in promoting regional sustainability, supporting rural livelihoods, and offering viable substitutes to petroleum-based plastics in the packaging industry. These findings contribute to the scientific understanding, industrial applications, and policy development for environmentally responsible materials.

Keywords

Biodegradable polymers; natural fibers; Manipur State; starch; cellulose; chitosan; protein-based films; sustainable packaging; mechanical properties; thermal analysis; biodegradation

I INTRODUCTION

The global demand for packaging materials has escalated significantly over the past decades, driven by the rapid growth of the food, pharmaceutical, and consumer goods sectors. Conventional plastic packaging, primarily made from petroleum-based polymers, has provided durable, lightweight, and cost-effective solutions. However, the environmental persistence of these plastics poses serious ecological and health challenges, including soil and water contamination, accumulation of microplastics, and adverse effects on biodiversity. In India, the annual generation of plastic waste exceeds 9 million tons, a large portion of which originates from single-use packaging materials. Despite government regulations and recycling initiatives, the effective management of plastic waste remains limited due to challenges in segregation, collection, and reprocessing.

Biodegradable polymers derived from renewable natural resources have gained attention as a sustainable alternative to synthetic plastics. These polymers, including starch, cellulose, chitosan, and protein-based materials, offer renewability, biodegradability, and minimal environmental impact. Their properties can be further enhanced through blending with other polymers, incorporation of natural fibers, and optimization of processing techniques. Biodegradable polymer composites can potentially replace conventional packaging materials while reducing environmental pollution.

Manipur State, located in the northeastern region of India, is endowed with abundant natural resources, including agricultural residues, bamboo, banana fibers, and indigenous plant biomass. These materials provide an excellent basis for the preparation of biodegradable polymers and fiber-reinforced composites. The region's rich biodiversity and agricultural practices enable the extraction of starch, cellulose, and proteins, which can be processed into environmentally safe packaging materials. Furthermore, the utilization of local resources contributes to rural economic development and employment generation, in addition to mitigating plastic pollution.

The present study aims to explore the preparation, characterization, and evaluation of biodegradable polymer films and composites using Manipur's natural resources. The study systematically examines the mechanical, thermal, barrier, and biodegradation properties of the materials to assess their suitability for packaging applications. By leveraging local biomass, the research also provides a model for sustainable packaging development in northeast India, aligning with national initiatives such as Swachh Bharat Abhiyan, Make in India, and the Sustainable Development Goals (SDGs).

II AIMS AND OBJECTIVES

Aims

The primary aim of this research is to develop, analyze, and evaluate biodegradable polymer-based materials derived from natural resources available in Manipur State, India, for environmentally safe packaging applications. The study focuses on utilizing local biomass, agricultural residues, and indigenous fibers to fabricate biopolymer films and composites with desirable mechanical, thermal, barrier, and biodegradation properties. Additionally, the research emphasizes the environmental, industrial, and socio-economic relevance of adopting these sustainable materials in packaging industries.

Objectives

1. To develop biodegradable polymer films and fiber-reinforced composites using methods like solution casting and compression molding.
2. To characterize the films and composites using FTIR, XRD, SEM, tensile testing, TGA, DSC, and barrier property analyses.
3. To assess the effect of natural fibers and plasticizers on the mechanical, thermal, and barrier properties of the prepared materials.
4. To evaluate biodegradation behavior under soil burial and environmental exposure conditions.
5. To compare the performance of biodegradable films with conventional plastic materials used in packaging.
6. To investigate environmental and socio-economic benefits, including rural employment generation and utilization of biomass waste.
7. To provide recommendations for industrial scalability and commercialization of biodegradable polymer-based packaging materials.

III REVIEW OF LITERATURE

Introduction

The purpose of the literature review is to provide a comprehensive overview of existing research on biodegradable polymers, natural fibers, and sustainable packaging, highlighting knowledge gaps and justification for the present study. The review spans global, national, and regional perspectives, focusing on polymer preparation, characterization, and application in packaging.

Conventional Plastic Packaging

Synthetic polymers, such as polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyethylene terephthalate (PET), dominate the packaging sector due to their lightweight nature, mechanical strength, and cost-effectiveness. However, these materials are non-biodegradable and accumulate in landfills and aquatic environments, causing soil contamination, water pollution, and microplastic formation (Geyer et al., 2017). Recycling is often limited by material heterogeneity, contamination, and economic constraints, making alternative biodegradable materials necessary.

Biodegradable Polymers

Biodegradable polymers are categorized into synthetic biodegradable polymers (PLA, PHA, PBS) and natural biodegradable polymers (starch, cellulose, chitosan, protein). Natural polymers are renewable, environmentally friendly, and compatible with food packaging, but often require reinforcement or blending to improve mechanical and barrier properties (Averous & Boquillon, 2004).

Starch-Based Polymers

Starch is a widely available polysaccharide used to prepare films and biodegradable composites. Plasticizers such as glycerol enhance flexibility, while fiber reinforcement improves tensile strength. Limitations include high water sensitivity and low thermal stability (Singh et al., 2008).

Cellulose and Derivatives

Cellulose, obtained from bamboo, banana, and other plant fibers, provides high mechanical strength, film-forming ability, and biodegradability. Chemical modifications and blending with plasticizers improve flexibility and barrier properties (Kumar et al., 2010).

Chitosan

Chitosan, derived from chitin in crustacean shells, exhibits antimicrobial properties, making it suitable for active packaging applications. Its film-forming capacity and biodegradability are advantageous, though moisture sensitivity is a limitation (Rhim, 2004).

Protein-Based Polymers

Proteins such as gelatin, soy protein, and casein form films with good oxygen barrier properties, though mechanical strength is limited. Blending with fibers and cross-linking improves functionality (Gennadios, 2002).

Polymer Blends and Biocomposites

Blending natural polymers with other biodegradable matrices or reinforcing with agricultural residues enhances tensile strength, thermal stability, and barrier properties. Biocomposites also reduce environmental impact and support sustainable material utilization (Mohanty et al., 2002).

Regional and Indigenous Studies

Few studies exist on northeast India and Manipur. Some reports highlight rice, maize, bamboo, and banana fibers as promising raw materials for biodegradable films (Kaushik & Singh, 2018). There is a knowledge gap in combining local biomass utilization, mechanical optimization, and biodegradation assessment, justifying this research.

IV RESEARCH METHODOLOGY

Selection of Materials

Natural polymers were sourced from Manipur State:

- Starch: rice and maize
- Cellulose: bamboo and banana fibers
- Chitosan: shrimp shells
- Proteins: soy and casein. Plasticizers (glycerol, sorbitol) improved flexibility, and local fibers were used as reinforcement.

Table 1: Materials and Sources

Material Type	Source	Function
Starch	Rice, maize	Matrix material, film formation
Cellulose	Bamboo, banana	Reinforcement, mechanical support
Chitosan	Shrimp shells	Biodegradability, antimicrobial
Protein	Soy, casein	Film-forming, barrier properties
Plasticizers	Glycerol, sorbitol	Flexibility and elongation
Natural fibers	Bamboo, banana	Composite reinforcement

Preparation of Polymers and Fibers

- Starch extraction: hot water gelatinization, plasticized with glycerol.
- Cellulose extraction: alkaline and bleaching treatment to remove lignin and hemicellulose.
- Chitosan preparation: deacetylation of chitin from shrimp shells.
- Protein films: dissolved in water, pH adjusted, plasticized, and cast.

Table 2: Preparation Methods

Polymer Type	Extraction Method	Plasticizer Used	Remarks
Starch	Hot water gelatinization	Glycerol	Film-forming matrix
Cellulose	Alkali + bleaching	None	Fiber reinforcement
Chitosan	Deacetylation of chitin	Glycerol	Antimicrobial property
Protein	Dissolution in water, pH 7	Sorbitol	Barrier properties

Film and Composite Preparation

1. Solution Casting: Dissolved polymers with plasticizer poured into trays and dried.
2. Compression Molding: Melt blending with fibers, hot-pressed into sheets.
3. Fiber loading: 5–20% w/w optimized for strength and barrier properties.

Table 3: Film Fabrication Parameters

Method	Temperature (°C)	Time (h)	Thickness (µm)	Notes
Solution Casting	40–50	24	100–200	Uniform, low thermal degradation
Compression Molding	120–150	1	200–300	Higher strength, faster drying

Characterization Techniques

Table 4: Characterization Techniques

Technique	Purpose
FTIR	Identify functional groups, chemical interactions
XRD	Crystallinity and structural order
SEM	Surface morphology and fiber dispersion
TGA/DSC	Thermal stability, degradation temperatures
Tensile Test	Mechanical strength and flexibility
WVTR	Water vapor permeability
Gas Permeability	Oxygen and CO_2 barrier properties
Biodegradation	Weight loss and soil burial assessment

V RESULTS AND INTERPRETATION

Structural and Chemical Analysis (FTIR and XRD)

The FTIR spectra of the films prepared from starch, cellulose, chitosan, and protein confirmed characteristic functional groups. Starch films showed O–H stretching at 3300 cm^{-1}, C–H stretching at 2930 cm^{-1}, and C–O–C vibration at 1020 cm^{-1}. Chitosan films displayed amine ($-NH_2$) peaks at 1590 cm^{-1} and hydroxyl bands at 3350 cm^{-1}. Protein films exhibited amide I and II peaks at 1650 cm^{-1} and 1540 cm^{-1} respectively.

XRD patterns indicated semi-crystalline nature for starch and cellulose films, whereas chitosan and protein films were largely amorphous. Fiber reinforcement slightly increased crystallinity, enhancing mechanical strength and thermal stability.

Table 1: FTIR and XRD Characterization of Biodegradable Films

Film Type	FTIR Peaks (cm^{-1})	Functional Groups	Crystallinity (%)

Starch	3300, 2930, 1020	O–H, C–H, C–O–C	24
Cellulose	3350, 2900, 1050	O–H, C–H, C–O–C	62
Chitosan	3350, 1590	O–H, NH_2	20
Protein (gelatin)	1650, 1540	Amide I, Amide II	15
Starch + Fiber Composite	3300, 2930, 1020	O–H, C–H, C–O–C	35

Morphological Analysis (SEM)

SEM images revealed:

- Starch films: smooth but brittle surfaces
- Fiber-reinforced composites: well-distributed fibers, improved roughness
- Chitosan films: porous morphology, facilitating biodegradation
- Protein films: layered structure

Table 2: SEM Observations of Films

Film Type	Morphology	Implication
Starch	Smooth, brittle	Low flexibility
Starch + Fiber Composite	Rough, embedded	Improved tensile strength
Chitosan	Porous, interconnected	Rapid biodegradation
Protein	Layered, uneven	Moderate barrier properties

Mechanical Properties

Tensile testing showed fiber reinforcement increased tensile strength (TS) 2–3 times. Plasticizers improved elongation at break (EB) but slightly reduced TS.

Table 3: Mechanical Properties of Biodegradable Films

Film Type	Tensile Strength (MPa)	Elongation at Break (%)	Observation
Starch	12	6	Brittle
Starch + Fiber Composite	32	10	Balanced strength
Chitosan	15	8	Moderate strength
Protein	10	5	Low strength
Starch + Fiber + Plasticizer	28	18	Balanced flexibility

Thermal Properties (TGA/DSC)

- Starch films degraded at 220–250°C, fiber composites at 260–280°C, protein films at 200–220°C.
- Glass transition temperatures (Tg) ranged from 50–70°C.

Table 4: Thermal Properties of Films

Film Type	Tg (°C)	Tdeg (°C)	Observation
Starch	60	225	Moderate stability
Starch + Fiber Composite	70	270	Improved thermal stability
Chitosan	55	230	Amorphous, moderate stability
Protein	50	210	Low thermal stability

Barrier Properties

- WVTR and oxygen permeability were measured. Fiber reinforcement reduced moisture and gas permeability.

Table 5: Barrier Properties

Film Type	WVTR ($g/m^2 \cdot day$)	Oxygen Permeability ($cm^3/m^2 \cdot day \cdot atm$)	Observation

Starch	125	450	High permeability
Starch + Fiber Composite	65	210	Improved barrier
Chitosan	85	300	Moderate barrier
Protein	70	200	Good barrier properties

Biodegradation Assessment

- Soil burial tests over 60 days showed weight loss of 40–70%.
- Chitosan and protein films degraded faster due to microbial activity.

Table 6: Biodegradation Results

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

VI DISCUSSION

The study demonstrates that biodegradable polymers from natural resources in Manipur can be effectively converted into packaging films and composites with desirable properties. Key findings:

1. Structural and Morphological Analysis: FTIR and XRD confirmed chemical integrity and semi-crystalline structures. SEM showed uniform fiber distribution, crucial for mechanical reinforcement.
2. Mechanical Performance: Fiber incorporation significantly enhanced tensile strength while plasticizers improved flexibility, balancing the strength–elongation trade-off.
3. Thermal Properties: Fiber-reinforced composites exhibited higher thermal stability, making them suitable for moderate heat packaging applications.
4. Barrier Properties: Composites demonstrated reduced water vapor and gas permeability, important for food packaging.
5. Biodegradation: Rapid degradation in soil indicates environmental compatibility. Chitosan and protein films degraded faster, highlighting microbial action as a key factor.

The integration of natural fibers, local biomass, and plasticizers resulted in biodegradable materials with mechanical, thermal, and barrier properties comparable to conventional plastics, offering eco-friendly packaging alternatives.

VII CONCLUSION

- Biodegradable films and fiber-reinforced composites were successfully developed from starch, cellulose, chitosan, and protein.
- Fiber reinforcement improved tensile strength, thermal stability, and barrier properties, while plasticizers enhanced flexibility.
- Biodegradation studies confirmed rapid environmental breakdown, minimizing long-term pollution.
- Manipur’s local biomass proved a sustainable, low-cost raw material source for packaging applications.
- The study supports industrial scalability, rural economic development, and environmental sustainability.
- Recommendations include industrial trials, chemical modification of polymers, and commercialization strategies for large-scale production.

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