ABSTRACT

The increasing demand for sustainable and eco-friendly packaging solutions has driven research into biodegradable materials as viable alternatives to conventional plastic packaging. This research explores the production of active biodegradable packaging films based on fiber-reinforced starch-protein blends incorporated with essential oils. The formulation integrates natural fibers, specifically banana pseudostem and bamboo-shoot fibers, to enhance mechanical strength, structural integrity, and barrier properties. Additionally, active compounds, including cinnamon and clove essential oils, were incorporated to impart antimicrobial and antioxidant functionalities, thereby extending the shelf life of packaged food products. A systematic evaluation of the physicochemical, mechanical, and biodegradability of the developed films was conducted. The results demonstrated that fiber reinforcement significantly improved tensile strength, water resistance, and thermal stability, mitigating inherent limitations of biopolymer-based films, such as brittleness and poor barrier properties. The incorporation of essential oils further enhanced the films' active properties, effectively inhibiting microbial growth and reducing oxidation, rendering them ideal for food preservation applications. Biodegradability studies confirmed efficient degradation of the films in natural environments, reducing plastic waste accumulation and environmental pollution.

Overall, this study highlights the potential of fiber-reinforced biopolymer films incorporated with essential oils as a sustainable alternative to conventional plastic packaging. The findings suggest that these active biodegradable films could play a crucial role in the future of food packaging by improving food safety, reducing post-harvest losses, and promoting environmentally responsible packaging solutions. Future research should focus on optimizing formulations to enhance water resistance, evaluating scalability for commercial applications, and integrating intelligent packaging technologies for real-time food quality monitoring.

To accomplish the goal, the thesis is divided into 8 chapters as follows:

Chapter 1 provides an overview of the significance of sustainable food packaging, highlighting the environmental concerns associated with conventional plastic packaging. It discusses the evolution of active packaging technologies, emphasizing their role in

enhancing food quality, safety, and shelf life. The chapter explores biopolymer-based packaging materials, including starch, protein, and fiber-reinforced composites, as viable alternatives to synthetic plastics. The challenges related to mechanical properties, water resistance, and biodegradability are addressed, along with potential solutions such as biopolymer modifications and the incorporation of natural active agents. The study aims to develop biodegradable, fiber-reinforced starch-protein films with antimicrobial and antioxidant properties for food packaging applications, particularly for fresh fruits like grapes. The chapter concludes by outlining the research objectives, focusing on the formulation, characterization, and application of active biodegradable films in the food industry.

Chapter 2 provides a comprehensive review of literature on biopolymers in food packaging applications, with particular focus on starch and protein-based materials. It examines the properties and modifications of starch, especially potato starch, and various proteins like casein for developing biodegradable films. The chapter explores composite film development through the combination of different biopolymers and natural fibers as reinforcement materials. Significant attention is given to active packaging systems incorporating natural extracts and essential oils, highlighting their antimicrobial and antioxidant properties. The review discusses various biodegradation mechanisms, environmental impacts, and safety considerations of biopolymeric films. Current commercial applications and future trends in biodegradable packaging materials are also analyzed, emphasizing the growing importance of sustainable packaging solutions in addressing environmental challenges while meeting industry requirements.

Chapter 3 investigates the development and characterization of biodegradable films using modified potato starch, casein protein, and their blends as sustainable alternatives to synthetic packaging materials. The study examines the effects of various modifications including heat-moisture treatment and annealing for potato starch, and ultrasound and autoclave treatments for casein, on their physicochemical, barrier, and mechanical properties. Modified starch films demonstrated superior mechanical properties, transparency, and reduced solubility compared to native ones, with heat-moisture treated films showing optimal results. Ultrasound-treated casein films (30 mins) exhibited improved mechanical strength, lower water vapor permeability, and reduced solubility compared to autoclave-treated and native casein films. The blended films, particularly those with a 50:50 ratio of potato starch and casein, showed enhanced tensile strength, sealing properties, and UV barrier characteristics while maintaining complete biodegradability within 21 days. These composite films present promising potential for food packaging applications, especially for minimally processed products, though their moisture sensitivity necessitates optimization for specific applications.

Chapter 4 investigates the potential of natural fibers (banana pseudostem and bamboo-shoot) as reinforcement materials in starch/protein-based composite films, exploring ultrasound and enzymatic treatments to enhance fiber-matrix compatibility. The study demonstrates that combined ultrasound and enzyme treatments significantly improved fiber properties, reducing solubility and water/oil holding capacity while enhancing crystallinity and intermolecular bonding. Ultrasound-treated films exhibited the highest tensile strength, while combined ultrasound-enzyme treatment (USET) showed optimal balance in mechanical properties and achieved up to 34% reduction in water vapor permeability compared to native fibers. Banana fiber compositions generally demonstrated better response to modifications than bamboo shoot fibers, with USET emerging as the most effective modification technique across compositions. The treated fiber-reinforced composite films showed promising results in terms of opacity, mechanical strength, and barrier properties, suggesting their potential application in sustainable food packaging solutions. Matrix-fiber compatibility played a crucial role in treatment effectiveness, indicating the need for fiber-specific optimization in future applications.

Chapter 5 examines the combined properties of starch-casein composite films reinforced with banana pseudostem and bamboo shoot fibers, exploring their potential as sustainable packaging materials. The study investigates the effects of different fiber types and treatment combinations on film properties, with USET (ultrasound followed by enzyme treatment) showing optimal results for banana fiber films and ETUS (enzyme followed by ultrasound treatment) working best for bamboo shoot films. Banana fiber-reinforced films demonstrated superior performance with higher tensile strength, lower water vapor permeability, reduced solubility, and enhanced thermal stability compared to bamboo shoot fiber composites. The developed films exhibited effective sealing ability and improved barrier properties due to the presence of cellulosic nanofibers in the matrix. Biodegradability tests showed approximately 80% degradation within 3-6 weeks in simulated soil conditions, confirming their environmental sustainability. Based on overall performance metrics, banana fibers were selected as the preferred reinforcement material for further investigation in subsequent research, particularly for food packaging applications.

Chapter 6 explores the incorporation of natural active ingredients, specifically cinnamon and clove essential oils (EOs), into starch/protein/fiber-based biofilms for active food packaging applications. The study evaluates the impact of these EOs on the film's mechanical, optical, structural, thermal, and barrier properties, as well as their antioxidant and antimicrobial activities. Results indicate that cinnamon EO, particularly at a 1% concentration, enhances film strength, transparency, and biodegradability while reducing water solubility and vapor permeability. However, higher EO concentrations negatively affect sealing efficiency and thermal stability. The developed biofilms demonstrate significant potential as sustainable, biodegradable alternatives to synthetic packaging materials. Further research is recommended to optimize EO concentrations and assess the films' long-term stability and scalability for commercial applications.

Chapter 7 examines the application of bio-based active films incorporating 1% cinnamon essential oil (CNO) in a starch/casein/banana fiber composite for food packaging, specifically grape preservation. The study evaluates the film's mechanical, barrier, and antimicrobial properties, demonstrating its effectiveness in maintaining grape quality by reducing microbial growth, controlling moisture transfer, and preserving firmness. The results indicate that the active film extends shelf life up to 10 days, outperforming conventional polypropylene packaging. The bio-composite film is biodegradable, eco-friendly, and offers a sustainable alternative for food packaging applications. Future research should focus on improving water resistance and integrating intelligent packaging technologies for enhanced performance.

Chapter 8 summarizes the key findings, conclusions, and future directions of the research on active biodegradable packaging materials derived from fiber-reinforced starch-protein blends. The study demonstrates that intensive blending effectively modifies the hydrophilic nature of protein-starch blends, improving water vapor permeability (WVP) and mechanical properties. A combination of ultrasound and cellulase enzyme treatment significantly enhances matrix-fiber compatibility, with banana fiber-reinforced films outperforming those reinforced with bamboo shoot fibers. Incorporating 1% cinnamon essential oil (CNO) into the composite films markedly improved antioxidant

and antimicrobial properties, extending the shelf life of packaged fresh grapes by up to 10 days.The research emphasizes the potential of these biodegradable films as sustainable alternatives to conventional plastic packaging, offering improved mechanical strength, barrier properties, and active preservation capabilities. The developed films also demonstrated superior biodegradability and functional performance in real-world applications, particularly for food packaging. Future research directions focus on scaling up production to ensure commercial viability, optimizing treatment conditions to enhance mechanical and barrier properties, and exploring advanced functionalities such as hydrophobic coatings and intelligent packaging systems. These advancements could further improve the films' performance, extend shelf life, and contribute to sustainable food packaging solutions while addressing environmental concerns associated with plastic waste.

Keywords: antimicrobial, antioxidant, barrier, biopolymers, biodegradability