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Development of Red Cabbage Extract-Based Chitosan Films: A Sustainable Approach to Intelligent Food Packaging

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Abstract – Fresh meat, a highly nutritious and widely consumed food source, is particularly susceptible to spoilage due to its high moisture content and protein richness. Current packaging solutions, often petroleum-based plastics, fail to adequately preserve meat quality or provide real-time freshness monitoring while contributing to environmental pollution. This study explores the development and evaluation of chitosan-based films incorporated with varying concentrations of red cabbage extract (0%, 20%, 40%, and 60% w/w) as a sustainable alternative for intelligent food packaging. The integration of red cabbage extract significantly enhanced the films' functional properties, including reduced moisture content, lower swelling behavior, and increased hydrophobicity, improving their durability and stability under diverse storage conditions. The films exhibited pH-sensitive color changes, ranging from reddish hues in acidic environments to greenish-blue tones in alkaline conditions, making them effective freshness indicators. Tests on chicken fillets demonstrated the films' ability to visually indicate spoilage progression, ensuring consumer safety and reducing food waste. Additionally, the films' biodegradability and reliance on renewable materials underscore their potential to replace conventional plastics, aligning with global sustainability efforts. This study highlights the dual benefits of functionality and environmental stewardship offered by red cabbage extract-based chitosan films and provides a foundation for further research to optimize their application in food packaging.

Keywords – Intelligent Food Packaging, Red Cabbage, Chitosan, Biodegradable Film, pH Responsive Film.

I. INTRODUCTION

Fresh meat, despite being a highly nutritious and widely consumed food source, is exceptionally prone to spoilage and has a limited shelf life due to its high moisture content and protein richness. These inherent properties lead to significant resource wastage and pose serious food safety concerns. In current market practices, fresh meat is typically packaged in petroleum-based plastics and stored at approximately 4 °C to maintain its quality. However, freezing at around -18 °C, followed by thawing, often deteriorates the sensory and nutritional properties of meat. Moreover, these plastic materials are non-biodegradable, contributing to severe environmental pollution. They also fail to effectively inhibit microbial growth or provide freshness indicators, restricting the shelf life of fresh meat to just 2–4 days, thereby exacerbating waste [1]. This scenario underscores the urgent need for innovative, biodegradable, and multifunctional packaging solutions to extend the shelf life of fresh meat while addressing environmental and consumer safety concerns.

The rapid degradation of fresh foods, including meat, is further intensified by inadequate packaging and the absence of effective freshness monitoring systems. Consumers often purchase and consume spoiled or subpar food unknowingly, resulting in potential health hazards. Consequently, ensuring the quality and edibility of fresh foods through advanced packaging technologies that actively preserve and monitor their state is paramount [2]. Packaging also plays a crucial role in protecting processed foods, vegetables, and fruits during transport and storage. Proper packaging prevents spoilage caused by microbial contamination, oxidation, and moisture fluctuations due to poor handling, thereby reducing waste and minimizing associated health risks. Modern packaging solutions must strike a delicate balance between cost-efficiency, consumer convenience, and the imperative to maintain food quality, safety, and environmental sustainability [3].

Active packaging systems, which offer more than just passive barriers, have emerged as a viable alternative. These systems interact positively with the product and its environment, enhancing shelf life, safety, and sensory attributes. By modifying internal conditions, active packaging can maintain the quality of packaged food and overcome the limitations of traditional methods [4]. In comparison, "intelligent packaging" and "smart packaging" incorporate advanced monitoring capabilities. These terms are sometimes used interchangeably, but smart packaging encompasses both intelligent and active functionalities. Smart packaging systems not only monitor changes in the internal and external environment of the packaged product but also respond to these changes through external communication interfaces, such as electrical or optical systems [5].

Smart packaging serves multiple objectives, such as extending product shelf life, maintaining freshness, providing real-time quality information to consumers, enhancing safety, and improving traceability across supply chains. Intelligent packaging focuses on monitoring the condition of packaged food and delivering insights into its quality during transportation and storage. This capability ensures that both consumers and distributors are well-informed about the product’s safety and edibility [6]. The "smartness" of packaging is characterized by functionalities tailored to different product types, whether food, beverages, pharmaceuticals, or household items. These functionalities include preserving product integrity, preventing spoilage, enhancing sensory attributes such as appearance and flavor, responding to environmental changes, communicating product history, and ensuring authenticity while mitigating counterfeiting risks.

Advanced smart packaging integrates sensors and indicators to monitor freshness by detecting chemical changes, microbial activity, and volatile compounds such as CO_2, O_2, H_2S, ethylene, and NH_3. These systems also track pH variations, temperature fluctuations, and humidity changes to provide real-time data on product quality. Among these technologies, freshness indicators based on natural colorants and biodegradable films have gained significant attention. These indicators are non-toxic, eco-friendly, cost-effective, and renewable, making them ideal for sustainable packaging. Embedded in biopolymeric matrices, these natural colorants undergo color changes in response to physiological variations in food, signaling spoilage and enhancing consumer awareness [7].

Freshness indicators enable visual monitoring of microbial proliferation and the accumulation of metabolites within packaged food, often accompanied by pH shifts. While electrochemical pH detectors are highly accurate, they are expensive, prompting the development of cost-effective alternatives like pH-responsive pigments. These pigments change color in response to microbial activity, providing a simple, accessible method for spoilage detection [8]. Among natural pigments, anthocyanins stand out for their broad pH-responsive color spectrum and clearer transitions compared to other indicators like curcumin. Anthocyanins alter their chemical structure across different pH levels, resulting in distinct color changes that enable precise monitoring of food quality during storage [9].

Biodegradable materials like chitosan are widely used in smart packaging due to their excellent film-forming properties and antimicrobial activity. Chitosan, derived from the deacetylation of chitin, is biodegradable, non-toxic, and biocompatible. It has been extensively used in food packaging to combat pathogens and extend shelf life. Enhancements to chitosan-based films, such as incorporating essential oils and plant extracts, improve antimicrobial efficacy and durability. These properties make chitosan an ideal candidate for sustainable smart packaging systems [10].

The integration of red cabbage extract into chitosan-based films represents a significant advancement in the development of intelligent packaging materials. These films effectively combine the antimicrobial and structural benefits of chitosan with the pH-sensitive properties of anthocyanins, resulting in innovative, eco-friendly solutions for food packaging. By addressing critical challenges in food preservation and safety, such technologies promise to revolutionize the packaging industry and contribute to global sustainability efforts.

II. MATERIALS AND METHOD

II.A. Preparation of Smart Films

Initially, fresh red cabbage was cut into small pieces and extracted with distilled water at a solid/liquid ratio of 1/10 (w/w) at room temperature for 2 hours. The solution was filtered using Whatman Filter Paper. The extract was stored at 4°C in the refrigerator before use. The chitosan solution was dissolved in 1% (w/w) acetic acid solution on a magnetic stirrer at room temperature. The red cabbage extract was added to chitosan solution at 0%, 20%, 40% and 60% weight ratio. The chitosan amount was constant at all film formulations. Glycerol (1g) was added to all solution. The solutions were cast into petri dishes and dried at 35°C.

II.B. Determination of the Physical Properties of Films

The moisture content, moisture uptake and sweeling index of the films were determined. Also, the pH changes of the films were observed. Additionally, color and pH changes of the films were observed both by placing them in various buffer solutions and by placing them on chicken.

Moisture content was determined by the mass loss of 1 g of film after 24 h of oven drying at (105±1) °C, and expressed as the percentage of initial film mass loss during drying. Three repetitive analysis of each film were made and the results were expressed [11]. The moisture uptake of the films were also investigated. The films were kept in a closed container at 100% relative humidity until they reached constant weight.

The films were cut, weighed and immersed in distilled water for 24 h to determine the swelling index of the films. Wet samples were wiped with filter paper to remove excess liquid and weighed. The amount of absorbed water was calculated by subtracting the initial mass of air-dried films from the mass of the wet samples and expressed in percentage. The measurement was repeated at least five times for each type of film [11].

To investigate color indicator changes under acidic and basic conditions, the films were immersed in the phosphate buffer solutions with different pH values ranging between 2-11 for 5 min at room temperature [12].

The pH measurement of chicken fillet samples were carried out at room temperature. The dry films were put on the fillets and color changes of the films were observed.

III. RESULTS

III.A. Physical Properties

Figure 1 illustrates the variation in moisture content of chitosan films containing different concentrations of aqueous red cabbage extract (0%, 20%, 40%, and 60% w/w).

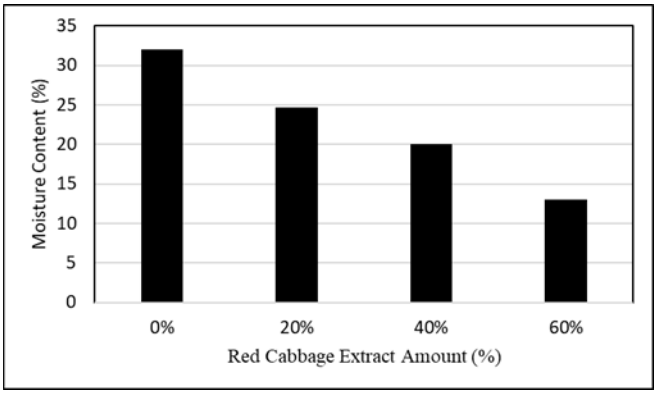

Fig. 1. The moisture content of the films

The moisture content is highest in the absence of red cabbage extract, reaching approximately 30%. This finding suggests that pure chitosan films retain a significant amount of moisture, likely due to the hydrophilic nature of chitosan. The introduction of 20% (w/w) red cabbage extract reduces the moisture content slightly, indicating the extract's potential to decrease water retention.

As the concentration increases to 40% (w/w), the moisture content declines further, suggesting that higher levels of red cabbage extract enhance the hydrophobic characteristics of the film and reduce its water absorption capacity. At the maximum concentration of 60% (w/w), the moisture content reaches its lowest value among all samples, highlighting the significant role of red cabbage extract in limiting moisture retention. This reduction could result from structural changes in the chitosan matrix or specific interactions between the extract’s components and the polymer. Additionally, films with higher concentrations of red cabbage extract demonstrated improved microbial growth inhibition, underscoring the extract’s functional benefits. The moisture uptake values are given in Fig. 2.

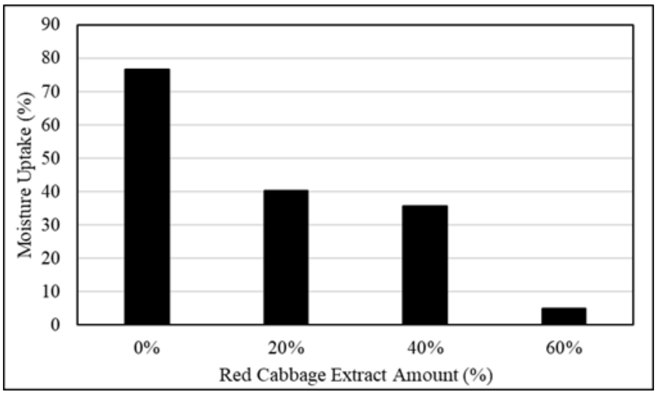

Fig. 2. The moisture uptake values of the films

Figure 2 shows the variation in moisture uptake for chitosan films with varying concentrations of red cabbage extract (0%, 20%, 40%, and 60% w/w). The moisture uptake is highest at 0% extract, reaching approximately 76.7%, reflecting the hydrophilic nature of pure chitosan films. Introducing 20% (w/w) red cabbage extract reduces moisture uptake significantly, highlighting the extract’s role in decreasing the hydrophilicity of the films.

At 40% (w/w), moisture uptake declines further, indicating that higher red cabbage extract concentrations enhance the hydrophobicity of the film. At 60% (w/w), moisture uptake reaches its lowest level, approximately 5%, suggesting that the hydrophobic components of the extract and possible structural changes within the film matrix effectively limit water penetration. This marked reduction in moisture uptake is crucial for improving the stability of biodegradable films under varying environmental conditions. Enhanced moisture resistance ensures prolonged shelf life and broadens the applicability of these films in diverse packaging environments [13]. Figure 3 illustrates the swelling index of chitosan films containing different concentrations of aqueous red cabbage extract (0%, 20%, 40%, and 60% w/w).

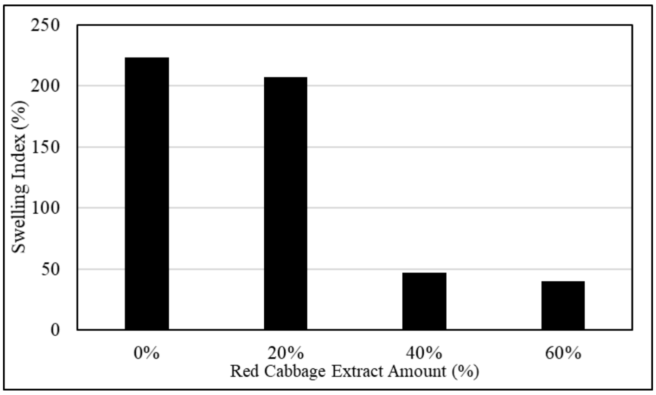

Fig. 3. The swelling index percentages of the films

The swelling index, which measures the film's capacity to absorb water and expand, decreases significantly as the concentration of red cabbage extract increases. In the absence of red cabbage extract, the swelling index exceeds 200%, indicating that pure chitosan films have a strong tendency to absorb water and swell due to their highly hydrophilic nature. Adding 20% red cabbage extract reduces the swelling index slightly, suggesting that the extract starts to influence the film's water absorption and swelling behavior. At 40% red cabbage extract, the swelling index decreases substantially, demonstrating a marked reduction in the film's ability to absorb water. At 60% extract, the swelling index reaches its lowest value, indicating minimal water absorption and expansion. This pronounced reduction in swelling behavior is likely due to the hydrophobic components introduced by the red cabbage extract and structural changes within the chitosan matrix that restrict its ability to expand.

The swelling behavior of edible films is a critical parameter for assessing their biodegradability and suitability for packaging high-moisture foods, such as peeled fruits [11]. Although the initial experiments showed high swelling percentages, indicating good biodegradability, the reduction in the swelling index with increased red cabbage extract concentration highlights the extract's ability to enhance moisture resistance and structural integrity. Films with lower swelling indices are more stable in humid or aqueous environments, making them ideal for applications where water resistance is essential.

III.B. pH and Color Sensitivity

The experimental results confirm the pH-sensitive behavior of chitosan films containing red cabbage extract, as illustrated in Figures 4 and 5. These films exhibit visible color changes in response to varying pH levels, emphasizing their potential as effective freshness indicators.

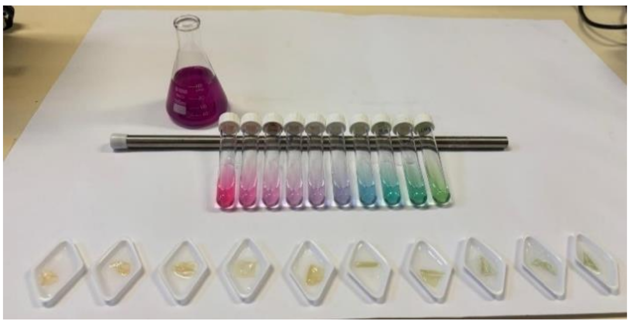

Fig. 4. The color change of the films

At acidic pH levels (2–4), the films display reddish or pinkish hues, indicating the dominance of the protonated form of anthocyanins present in red cabbage. At neutral pH levels (around 7), the films transition to purplish or violet tones, reflecting molecular changes in anthocyanins as they adapt to a less acidic environment. In alkaline conditions (pH above 8), the films shift to green or bluish tones, corresponding to the deprotonated forms of anthocyanins.

Figure 5 demonstrates the practical application of these films, particularly the 60% red cabbage extract film placed on a chicken fillet. The film's color change effectively reflects the pH environment of the meat, serving as a visual freshness indicator. Reddish hues correspond to the acidic conditions of fresh meat, while greenish or bluish tones indicate alkaline conditions caused by microbial activity or spoilage.

Fig. 5. The color change of the film on the chicken fillet

These findings validate the pH-sensitive properties of red cabbage extract-based chitosan films and their applicability as intelligent packaging materials. By visually indicating food quality through pH-dependent color shifts, these films provide a practical tool for real-time freshness monitoring. This capability not only ensures consumer safety but also reduces food waste, enhancing the sustainability of food packaging solutions.

IV. DISCUSSION

The findings from this study underscore the substantial potential of chitosan films integrated with red cabbage extract as a multifunctional and sustainable solution for food packaging. The incorporation of red cabbage extract significantly enhances the functional properties of the chitosan films, including improved moisture resistance, reduced swelling behavior, and pH-sensitive color changes. These attributes establish these films as highly effective intelligent packaging materials capable of addressing critical challenges in food preservation and quality monitoring.

V. CONCLUSION

This study successfully demonstrates the development of chitosan-based films containing red cabbage extract as a promising alternative for intelligent and sustainable food packaging. The films' enhanced moisture resistance, reduced swelling behavior, and pH-sensitive color changes position them as effective tools for extending the shelf life of perishable foods while enabling real-time freshness monitoring. These features address critical challenges in food preservation, including microbial growth, spoilage detection, and environmental sustainability.

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