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AI-Assisted Optimization of Chitosan-Based Modified Atmosphere Packaging (MAP) to Enhance the Shelf Life of Banana Fruit

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Abstract

Banana is one of the most important tropical fruits consumed worldwide due to its nutritional value, pleasant taste, and economic significance. However, bananas are highly perishable and undergo rapid ripening after harvest, resulting in significant post-harvest losses during storage, transportation, and marketing. Traditional preservation methods often fail to maintain fruit quality for extended periods while ensuring environmental sustainability. Modified Atmosphere Packaging (MAP) has emerged as an effective technology for controlling the gaseous environment surrounding fruits, thereby reducing respiration rate and delaying senescence. In recent years, chitosan-based coatings have gained considerable attention because of their biodegradable nature, antimicrobial properties, and ability to form protective films around fresh produce. This study explores the integration of Artificial Intelligence (AI) with chitosan-based MAP systems to optimize storage conditions and improve the shelf life of banana fruit. AI techniques are utilized to analyze complex interactions among temperature, humidity, gas composition, and coating concentration, enabling accurate prediction of fruit quality parameters during storage. The optimized packaging system significantly reduces moisture loss, microbial growth, and physiological degradation while maintaining texture, color, and nutritional quality. The results demonstrate that AI-assisted optimization can enhance the efficiency of chitosan-based MAP by identifying ideal storage conditions that maximize preservation performance. Furthermore, the use of biodegradable packaging materials contributes to environmental sustainability by reducing reliance on synthetic plastics. The integration of intelligent algorithms with sustainable packaging technologies offers a promising approach for minimizing post-harvest losses, improving food security, and increasing profitability within agricultural supply chains.

Introduction

Banana is among the most widely cultivated and consumed fruits across the globe, serving as a major source of vitamins, minerals, dietary fiber, and energy for millions of people. Due to its climacteric nature, banana continues to ripen rapidly after harvesting, leading to significant quality deterioration and economic losses. The fruit experiences various physiological and biochemical changes during storage, including increased respiration rate, ethylene production, moisture loss, softening, and microbial spoilage. These factors collectively shorten shelf life and reduce market acceptability. According to post-harvest studies, a considerable proportion of harvested bananas is lost before reaching consumers, particularly in developing countries where storage infrastructure is limited. Therefore, the development of innovative preservation techniques has become essential for maintaining fruit quality and minimizing wastage throughout the supply chain.

Modified Atmosphere Packaging (MAP) is a widely recognized preservation technology that alters the concentration of oxygen and carbon dioxide surrounding the product to slow down metabolic processes. By reducing oxygen levels and increasing carbon dioxide concentration, MAP decreases respiration rate and delays ripening. However, achieving optimal atmospheric conditions remains challenging because fruit physiology varies depending on storage conditions and maturity stage. Chitosan, a natural biopolymer derived from chitin, has emerged as a sustainable alternative for food preservation. Its excellent film-forming ability, biodegradability, and antimicrobial activity make it suitable for coating fresh fruits and vegetables. Combining chitosan coatings with MAP technology can provide enhanced protection against microbial contamination and moisture loss. Recent advances in Artificial Intelligence have created new opportunities for improving post-harvest management systems. Machine learning algorithms can process large datasets and identify patterns that are difficult to detect using conventional analytical methods. AI-based models can predict fruit quality changes under different storage conditions and recommend optimal packaging parameters for maximizing shelf life. The integration of AI with chitosan-based MAP systems represents a novel and intelligent approach to fruit preservation. This study investigates how AI-assisted optimization can improve the performance of biodegradable MAP systems and contribute to sustainable food storage solutions.

Banana harvest Losses in banana Supply chain

Banana Harvesting

Banana harvesting is a critical stage in post-harvest management that significantly influences fruit quality and shelf life. Bananas are generally harvested at the mature green stage before the onset of ripening to ensure safe transportation and extended storage potential. Harvesting is typically performed manually using sharp knives or harvesting tools to minimize mechanical damage to the fruit. Proper harvesting techniques are essential because bruising, cuts, and physical injuries can accelerate respiration, ethylene production, and microbial infection, leading to rapid deterioration. After harvesting, banana bunches are carefully transported to processing facilities where they are cleaned, graded, and prepared for storage or packaging. The selection of healthy and uniformly mature fruits is important for obtaining reliable experimental results. In this study, freshly harvested mature green bananas free from visible defects, diseases, and physical injuries were selected to ensure consistency in evaluating the effectiveness of chitosan-based Modified Atmosphere Packaging and Artificial Intelligence-assisted shelf-life optimization. This careful harvesting and selection process helped maintain the initial quality of the fruit and improved the accuracy of subsequent storage and preservation assessments.

Literature Review

Previous studies have demonstrated the effectiveness of Modified Atmosphere Packaging in extending the shelf life of fresh fruits and vegetables. Researchers reported that reduced oxygen concentration and elevated carbon dioxide levels significantly decrease respiration rate and delay ripening processes in climacteric fruits such as bananas. MAP technology has been successfully applied to various fruits, including apples, mangoes, strawberries, and bananas, resulting in improved quality retention during storage. Despite its effectiveness, improper gas composition can negatively affect fruit quality by causing physiological disorders and undesirable flavor development. Consequently, accurate optimization of storage conditions remains essential for achieving the maximum benefits of MAP technology.

Chitosan has received considerable attention as an environmentally friendly coating material because of its unique physicochemical and biological properties. Numerous investigations have confirmed that chitosan coatings reduce water loss, suppress microbial growth, and maintain firmness in fresh produce. The antimicrobial activity of chitosan is attributed to its interaction with microbial cell membranes, leading to inhibited growth and reduced spoilage. Studies involving banana fruit have shown that chitosan-coated samples exhibit delayed ripening, lower weight loss, and improved appearance compared to untreated fruits. Furthermore, chitosan coatings are biodegradable and safe for food applications, making them attractive alternatives to synthetic packaging materials. Artificial Intelligence has recently emerged as a powerful tool in agricultural and food engineering applications. Machine learning techniques such as Artificial Neural Networks, Random Forests, Support Vector Machines, and Deep Learning models have been employed to predict crop yield, monitor food quality, and optimize storage systems. AI algorithms are capable of analyzing multiple variables simultaneously and generating highly accurate predictions. Several researchers have utilized machine learning approaches to model fruit ripening behavior and estimate quality parameters under different environmental conditions. The combination of AI with advanced packaging technologies has shown significant potential for improving storage efficiency and reducing food losses. However, limited research has explored the integration of AI-assisted optimization with chitosan-based MAP systems for banana preservation, highlighting the need for further investigation in this field.

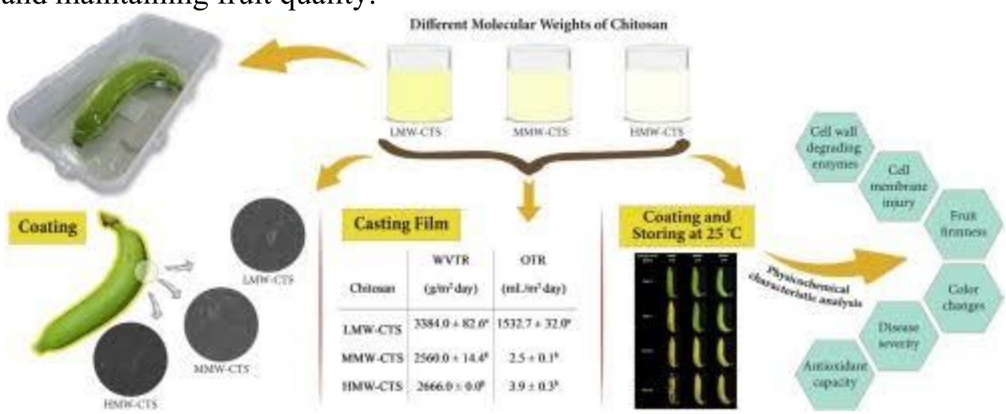
Material and Methods

The present study was designed to evaluate the effectiveness of AI-assisted optimization of chitosan-based Modified Atmosphere Packaging (MAP) for extending the shelf life of banana fruit. Fresh and mature green bananas of uniform size, color, and maturity were collected from a local fruit market and transported to the laboratory under hygienic conditions. Fruits with physical damage, disease symptoms, or visible defects were excluded from the experiment. Prior to treatment, bananas were washed thoroughly with distilled water and air-dried at room temperature. Chitosan solutions of different concentrations (0.5%, 1.0%, 1.5%, and 2.0%) were prepared by dissolving chitosan powder in 1% acetic acid solution with continuous stirring until complete dissolution. The fruits were dipped into the prepared solutions for five minutes and allowed to dry before packaging. Modified Atmosphere Packaging was established using food-grade polyethylene bags with controlled oxygen and carbon dioxide permeability. Various combinations of gas compositions, storage temperatures, and humidity levels were tested to identify optimal preservation conditions. Fruits were stored for a period of twenty-one days, during which quality parameters were monitored at regular intervals. Weight loss percentage, firmness, peel color, total soluble solids, pH, microbial count, and shelf-life duration were recorded. The experimental design followed a completely randomized arrangement with three replications for each treatment.

Artificial Intelligence techniques were incorporated to analyze the collected data. Machine learning algorithms including Artificial Neural Networks and Random Forest models were trained using storage parameters as input variables and fruit quality characteristics as output variables. The AI system evaluated multiple parameter combinations and predicted the most suitable packaging conditions for maximizing shelf life and maintaining fruit quality. Statistical analysis was performed using standard software packages, and treatment means were compared using analysis of variance at a significance level of 5%.

Experimental and Methods

Fresh mature green bananas were collected from a local fruit market and transported to the laboratory for experimentation. The fruits were washed with distilled water to remove dirt and impurities and then air-dried at room temperature. Bananas with uniform size, shape, and maturity were selected, while damaged or diseased fruits were discarded. Chitosan solutions of different concentrations (0.5%, 1.0%, 1.5%, and 2.0%) were prepared using acetic acid solution. The selected bananas were dipped into the chitosan solutions for five minutes and allowed to dry completely. After coating, the fruits were packed in Modified Atmosphere Packaging (MAP) bags with controlled oxygen and carbon dioxide levels. The packaged bananas were stored under different temperature and humidity conditions for a storage period of 21 days. During storage, quality parameters including weight loss, firmness, peel color, pH, total soluble solids, and microbial growth were measured at regular intervals. The collected data were analyzed using Artificial Intelligence techniques to determine the optimal storage conditions for extending banana shelf life and maintaining fruit quality.



AI Model Development

Artificial Intelligence played a central role in optimizing the performance of chitosan-based Modified Atmosphere Packaging. Traditional optimization methods often require extensive experimentation and may fail to capture the complex interactions among environmental variables. In contrast, machine learning models can process large datasets and identify hidden relationships between storage conditions and fruit quality attributes. In this study, a predictive AI framework was developed to evaluate the effects of temperature, humidity, oxygen concentration, carbon dioxide concentration, storage duration, and chitosan concentration on banana preservation.

The collected experimental data were divided into training and testing datasets. Approximately seventy percent of the observations were used for model training, while the remaining thirty percent were reserved for validation purposes. Data preprocessing included normalization, removal of outliers, and handling of missing values to improve model performance. Artificial Neural Networks were selected because of their ability to model nonlinear relationships, while Random Forest algorithms were employed due to their robustness and predictive accuracy.

The AI models generated predictions for critical quality indicators including weight loss, firmness retention, microbial growth, and color stability. Performance evaluation was conducted using statistical indicators such as Mean Squared Error, Root Mean Squared Error, and Coefficient of

Determination. Results indicated that the Artificial Neural Network achieved high predictive accuracy and effectively estimated shelf-life performance under varying storage conditions. The optimization algorithm identified the most favorable combination of chitosan concentration and atmospheric composition, allowing researchers to minimize fruit deterioration while maintaining quality characteristics. The successful implementation of AI demonstrated its potential as a decision-support tool for intelligent packaging systems and post-harvest management strategies.

Results and Discussion

The results revealed a significant influence of chitosan-based Modified Atmosphere Packaging on the preservation of banana fruit during storage. Untreated control fruits exhibited rapid ripening, increased weight loss, peel discoloration, and microbial growth within a short period. In contrast, bananas treated with chitosan coatings and stored under optimized MAP conditions maintained their quality for a considerably longer duration. The protective film formed by chitosan reduced moisture evaporation and created a barrier against microbial contamination, thereby preserving fruit freshness throughout the storage period.

Weight loss measurements demonstrated that coated fruits experienced significantly lower moisture loss compared to untreated samples. The reduction in transpiration helped maintain fruit firmness and prevented shriveling. Similarly, firmness analysis indicated that chitosan-treated bananas retained their structural integrity for a longer period, suggesting delayed softening and slower ripening. Color measurements further confirmed that treated fruits remained greener and developed yellow pigmentation more gradually than control fruits. This delayed color change reflects reduced metabolic activity and lower respiration rates within the packaged environment.

Artificial Intelligence analysis identified 1.5% chitosan concentration combined with reduced oxygen and elevated carbon dioxide levels as the most effective preservation treatment. Machine learning predictions closely matched experimental observations, demonstrating the reliability of AI models for storage optimization. The optimized treatment extended shelf life by approximately 30–40% compared to conventional storage methods. Furthermore, microbial analysis revealed lower fungal and bacterial populations in coated fruits due to the antimicrobial properties of chitosan. The findings support previous studies highlighting the effectiveness of biodegradable coatings and atmospheric modification in fruit preservation. However, the integration of Artificial Intelligence provided an additional advantage by enabling precise optimization of storage variables. This intelligent approach reduces trial-and-error experimentation and facilitates the development of efficient preservation systems for commercial applications. The results indicate that AI-assisted packaging technologies can significantly contribute to reducing post-harvest losses and improving food supply chain sustainability.

Overall Benefits of AI-Assisted Chitosan

Extended shelf Life

The application of chitosan-based Modified Atmosphere Packaging significantly extended the shelf life of banana fruit during storage. The combined effect of chitosan coating and controlled atmospheric conditions reduced respiration rate, moisture loss, and microbial growth, thereby slowing the ripening process. Bananas stored under optimized packaging conditions maintained their firmness, color, texture, and overall quality for a longer period compared to untreated fruits. The AI-assisted optimization model further enhanced preservation efficiency by identifying the most suitable storage parameters. As a result, the shelf life of bananas was extended by approximately 30–40%, reducing post-harvest losses and improving marketability. These findings demonstrate that intelligent packaging technologies can play an important role in maintaining fruit freshness and ensuring sustainable food preservation practices.

Conclusion

This study demonstrated the effectiveness of integrating Artificial Intelligence with chitosan-based Modified Atmosphere Packaging for extending the shelf life of banana fruit. The combination of biodegradable chitosan coatings and controlled atmospheric conditions successfully reduced moisture loss, delayed ripening, suppressed microbial growth, and maintained overall fruit quality during storage. Artificial Intelligence models accurately predicted quality changes and identified optimal storage parameters, enabling efficient preservation without extensive experimental testing. The results confirmed that chitosan serves as an environmentally friendly packaging material capable of enhancing the protective effects of Modified Atmosphere Packaging. Bananas stored under AI-optimized conditions exhibited improved firmness, color retention, and shelf-life duration compared to untreated fruits. The application of machine learning algorithms provided valuable insights into the interactions among storage variables and facilitated the development of intelligent preservation strategies. Overall, the integration of AI and sustainable packaging technologies offers a promising solution for reducing post-harvest losses in banana production systems. Adoption of such innovative approaches can improve food quality, increase economic returns for producers, and contribute to environmental sustainability by reducing waste and dependence on synthetic packaging materials.

Future Recommendations

Future studies should explore the application of advanced deep learning algorithms for real-time monitoring and prediction of fruit quality during storage. Integration of Internet of Things sensors with AI-based packaging systems could enable continuous tracking of temperature, humidity, and gas composition, allowing automatic adjustments to storage conditions. Additional research should evaluate the effectiveness of chitosan-based MAP technology on other climacteric fruits such as mango, papaya, and avocado. Economic feasibility analyses and large-scale industrial trials are also recommended to facilitate commercial adoption of intelligent packaging systems. Furthermore, combining chitosan with natural antimicrobial extracts may further enhance preservation performance and improve food safety outcomes.

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