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Performance of Biodegradable Packaging Films Containing Essential Oils for Food Quality Maintenance

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Abstract

Biodegradable packaging films have appeared as a promising alternative to conservative plastic packaging, offering significant environmental benefits and functional properties for food preservation. Essential oils (EOs), known for their natural antibacterial and antioxidant assets, have gained attention for their potential to increase food quality and shelf life while decreasing environmental effects. Its goal is to investigate how well biodegradable packaging sheets with essential oils function in terms of preserving food quality. Using solvent casting, films were created using biopolymeric materials and mixed with essential oils such as thyme, oregano, clove, rosemary, cinnamon, and lemon oil. The Thiobarbituric acid reactive substances (TBARS) test and the DPPH radical scavenging assay were used to measure antioxidant activity, which showed decreased oxidative degradation. A Universal Testing Machine (UTM) was used to assess mechanical parameters, such as tensile strength (TS) and elongation at break (EB), guaranteeing adequate flexibility and durability. To evaluate the moisture and oxygen barrier qualities, gravimetric sorption analysis, or GSA, was used. According to the results, the film extracts had 5%–8% less antioxidant activity than pure essential oils, according to the DPPH experiment. TBARS oxidation demonstrated that films containing essential oils significantly reduced oxidation ($p < 0.05$) compared to controls. Mechanical tests revealed a reduction in tensile strength and elongation at break ($p < 0.05$), but no significant effects on permeation or migration ($p > 0.05$). It highlights that biodegradable packaging films containing essential oils can enhance food safety, extend shelf life, and provide a sustainable alternative to conventional plastic packaging.

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Introduction

Food bargains serve three essential functions: protecting food quality maintenance while extending shelf life together with ensuring food safety (Karimov & Bobur, 2024). For years the food industry chose plastic-based packaging materials because of their low prices, suitability, and long lifespan (Vasile & Baican, 2021). The investigation for eco-friendly alternatives started because environmental contamination grew into a serious problem primarily due to excessive plastic waste accumulation. Biodegradable packaging films gained popularity as an environmentally friendly replacement due to their natural decomposition ability that poses no risk to the environment (Onyeaka et al., 2022). These films were viable substitutes for plastic packaging since biodegradable materials were often composed of renewable resources such as proteins, cellulose, chitosan, and starch (Stevovic et al., 2023). Preventing oxidation, moisture loss, and microbiological contamination, all of which contribute to food spoilage, were significant difficulties in food packaging (Nilsen-Nygaard et al., 2021). It was done by adding active ingredients like essential oils to biodegradable films to increase their protective qualities (Sungur et al., 2020). Essential oils are organic substances derived from plants that possess inherent antibacterial and antioxidant qualities that prevent bacterial development and delay oxidation (Sadgrove et al., 2022). These oils could prevent microbiological spoilage and enhance freshness by slowing down the deterioration of food (Priya & Dharmaraj, 2023). Therefore, packaging might actively prevent spoiling for longer shelf life with fewer additional preservatives in foods if essential oils were utilized with biodegradable films. The type of essential oil utilized, its concentration, and the regularity of its dispersion inside the film all affect how successful biodegradable packaging films containing essential oils are (Bolouri et al., 2022). Its mechanical and physical characteristics, such as its strength, flexibility, and barrier qualities, or resistance to oxygen and moisture, were important (Supriya & Dhanalakshmi, 2024). To guarantee that the essential oils maintain the desired preservation effects without adversely affecting the film's structure, proper formulation was required.

In terms of environmental effects, the food packaging industry was shifting toward eco-friendly and sustainable options. Conventional plastic was used extensively; however, it had significant biodegradation issues, which contributed to plastic pollution worldwide. Therefore, biodegradable films made from natural polymers, including cellulose, chitosan, starch, and protein-based compounds, have attracted a lot of interest lately (Sharmeen et al., 2021). The biodegradation of these films was an extra benefit that lowered trash accumulation while still offering the required protective qualities for food preservation. Essential oils and other active ingredients were also receiving more scientific interest because these might be used in biodegradable films that had superior barrier qualities than plastics (Stoleru & Brebu, 2021). Candidates for creating such films include essential oils made from the extracts of herbs such as thyme, oregano, clove, and cinnamon, which have shown inhibitory effects on oxidation and bacterial development. When added to biodegradable films, these oils could enhance food preservation, reduce microbiological contamination, and postpone spoiling, providing the benefits of a natural and chemical-free substitute for artificial preservatives (El Alami El Hassani et al., 2024).

An evaluation of essential oil (Eos) antimicrobial properties in food preservation together with bacterial inhibition and anti-inflammatory and antioxidative activity appeared in (Rout et al., 2022). Directional encapsulation increases EOs' solubility level and stability while enhancing their bioavailability for water. Scientific evidence indicates that essential oils exhibit the potential to lengthen food preservation times even when considering both pesticide risks and food safety requirements (Dziurakh et al., 2024). It evaluated how essential oils function in smart packaging technology.

Zehra et al., (2022) adopted an approach to enhance postharvest collard greens quality by creating biodegradable films from chitosan with thyme essential oil (TEO) and adding zinc oxide (ZnO), polyethylene glycol (PEG), nano-cellulose (NC), and calcium chloride ($CaCl_2$). The evaluation results demonstrated better tensile strength alongside increased water vapor resistance together with stronger biodegradability that came with reduced weight loss while maintaining chlorophyll levels and inhibiting microbial growth. These films represented an eco-friendly method to maintain refrigerated products for longer periods. Food items, together with alterations in storage environments, lead to varied performance outcomes. Vianna et al., (2021) described how essential oils advance starch-based films as a recyclable food packaging and food quality maintenance system through modern filmmaking techniques. It analyzed how essential oils affected the physicochemical and sterile response of the developed films and included sections about limitations and disadvantages together with statistical data analysis of the outcomes. These active films require additional optimization investigation to achieve useful applications at the maximum performance potential.

The progress of antibacterial active food packing films and coatings based on plant EO has made recent progress through extended-release mechanisms as described by (Zhang et al., 2022). Among the methods used were electrospinning, multilayer systems, and Nano emulsions. The effectiveness of these strategies varies, and each has advantages and disadvantages. Optimizing EO encapsulation to enable extended antibacterial activity was a crucial aspect of food preservation and the investigation challenge. A composite bilayer film was fabricated using corn starch (CS) and polylactic acid (PLA) with microcapsules of eucalyptus essential oil (EOM) added into the inner layer. Chen et al., (2022). Enhanced tensile strength, barrier properties, and antimicrobial activity were found at an optimum EOM concentration of 15 mL/100 mL. Shelf life was enhanced for Agaricus bisporus under preservation experiments. It illustrated the potential for using bioactive film materials for food preservation while also showing some drawbacks in terms of film quality at higher concentrations of EOM. Through the maintenance of temperature, moisture, and microorganisms, Active Packaging (AP) spreads the shelf life of food through contact with the environment by (Sharma et al., 2021). The calculation of EO to APs enhances their antibacterial and antioxidant qualities, particularly when applied to films and coatings. Although the results of several investigations varied in terms of chemical composition, it all demonstrate statistical efficacy, with some indicating limitations about oil stability and microstructure modification. To optimize the inclusion of essential oils that improve the performance of AP.

Khalid et al., (2024) suggested that adding EOs, which were made from food waste, to biodegradable coatings might improve food's capacity to be preserved while lowering gas permeability, moisture loss, and microbial spoiling. Estimating impacts on factors including pH, color, and hardness was one of the methods used. Shelf life improvements nevertheless, variations in oil extraction and coating efficacy represent a constraint. The goal of the development was to produce packaging options that are sustainable and waste-free. Using chitosan and sodium alginate-amphiphilic starch summarised cinnamon EO (CMS-LS-CO), the biodegradable antibacterial film and Chitosan Sodium Alginate (CSC) were created by (He et al., 2021). The findings demonstrated that a 0.5% addition of CMS-LS-CO enhanced mechanical and preservation qualities, with an inhibition rate of 30%. Aureus and 36% coli. The films showed outstanding performance in terms of preservation together with antibacterial capabilities by reaching a 70% biodegradation level during 28 days. The preserving properties of CSC film made it possible to maintain fruits.

To assess how well biodegradable packaging sheets that include essential oils function in improving the preservation of food quality and providing sustainable substitutes for traditional plastic packaging, it focuses on evaluating their mechanical qualities, barrier functions, and antioxidant activity.

Primary Functions

Development of Biodegradable Films with Essential Oils – To explore the formulation of biodegradable packaging films integrated with essential oils, offering an eco-friendly alternative to traditional plastic packaging while contributing to food preservation.

Enhanced Antioxidant Properties - It demonstrates that films containing essential oils, such as thyme, oregano, and rosemary, significantly reduces oxidative degradation, improving food quality and shelf life.

Mechanical and Barrier Assets - While the films show some reduction in TS and EB, that maintain effective barrier properties for moisture and oxygen, proving suitable for food preservation without compromising sustainability.

Materials and Methods

The preparation of biodegradable packaging films using biopolymeric materials such as chitosan, sodium alginate, and starch along with essential oils, namely thyme, oregano, clove, rosemary, cinnamon, and lemon, is discussed in this section. The approach outlines the methods for film production with detailed steps regarding solvent casting, antioxidant analysis, mechanical testing, and barrier assessment procedures for food preservation evaluation. Figure 1 illustrates the general flow of biodegradable packaging films with essential oils for maintaining food quality.

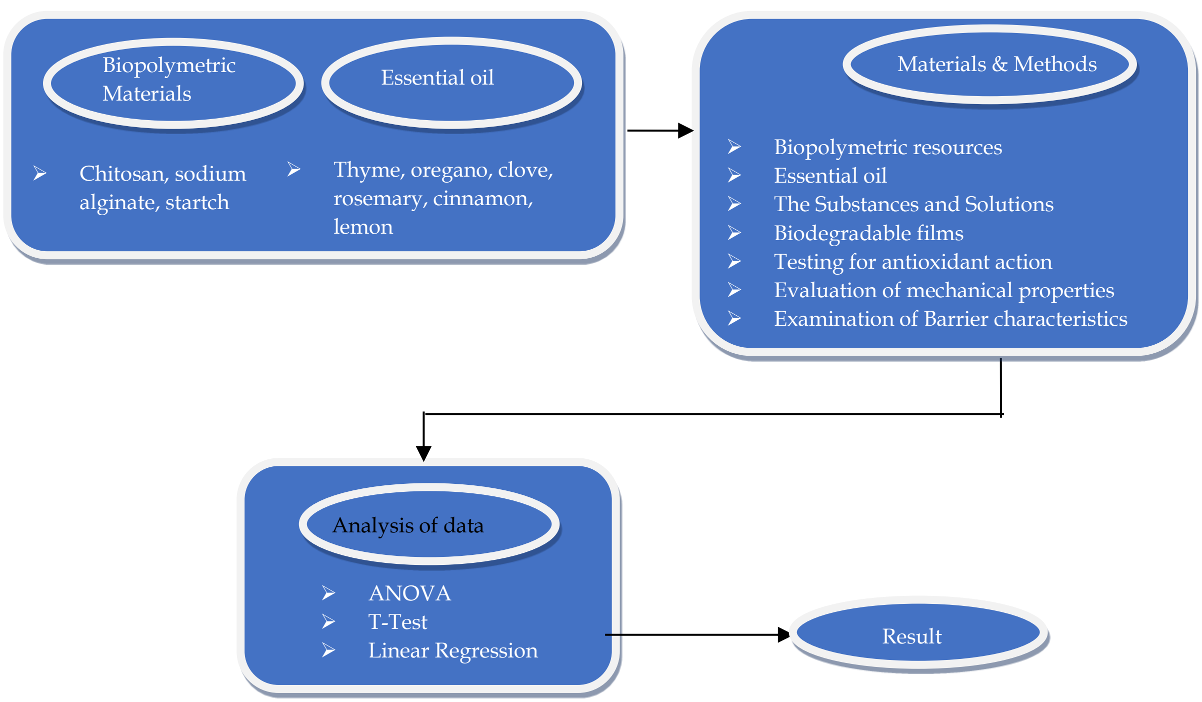

Figure 1. The Overall flow of biodegradable packaging films with essential oils for preserving food quality

Materials

Biopolymeric Resources - Different biopolymers with film-forming abilities were utilized to generate the films. The selection of chitosan, sodium alginate, and starch biopolymers allowed essential oils to be added to films to achieve mechanical properties and biodegradation capabilities.

Essential Oils (EOs) - The chosen essential oils demonstrate established antioxidant and antibacterial abilities, which enhance food stability and shelf life. A few of the essential oils are implemented for this application. The selected food preservation oils, which include thyme oil and oregano oil, together with clove oil and rosemary oil, along with cinnamon oil and lemon oil, prevent food spoilage by inhibiting both biological growth and stopping oxidative degradation of food.

The Substances and Solutions - The film production utilized water together with ethanol while incorporating essential oils. Thiobarbituric acid reactive substances (TBARS) and 2,2-Diphenyl-1-Picrylhydrazyl (DPPH) were employed to assess antioxidant activity. Sodium chloride, sodium hydroxide, and distilled water were used for film production, antioxidant, and barrier property testing. To measure the effectiveness of employing packaging sheets based on essential oils and bio-based materials, which will improve the quality of the food that is maintained.

Methods

Biodegradable Films - The biopolymeric material, chitosan, and sodium alginate were mixed in a solvent combination of water and ethanol to create the films using a solvent casting approach. After adding essential oils (1–5% v/v) to the solution, it was transferred into Petri dishes and allowed to dry into thin, flexible films at room temperature.

Testing for Antioxidant Action - Test DPPH Radical Scavenging Assay: The ability to seek for free essentials in the films covering essential oils was assessed by calculating the percentage decrease in absorbance. The TBARS test examines lipid oxidation and evaluates how effectively a film inhibits oxidative degradation by comparing films containing and without essential oils.

Evaluation of Mechanical Properties - TS, which is the highest stress a film can withstand before breaking, is measured with a UTM. EB: Determined via UTM testing, this indicates the film's capacity to stretch before breaking.

Examination of Barrier Characteristics - Moisture Barrier Property: The films' ability to prevent food from losing or gaining moisture was assessed using GSA. Oxygen Barrier Property: evaluated the films' ability to keep out oxygen that might cause food to oxidize. It could help in evaluating the effectiveness of the essential oils in biodegradable films, which enhance food safety, prolong shelf life, and serve as an environmentally friendly packaging material.

Analysis of Data

Examining the effectiveness of biodegradable packaging sections with essential oils for improving food quality and preservation. The statistical analysis of ANOVA, t-test, and linear regression methods was approved by using IBM SPSS version 25.0; the effects of biodegradable packaging sheets containing essential oils on food quality and preservation characteristics. ANOVA functioned to detect variations between variables that included contrasting experimental formulations and their mechanical properties as well as antioxidant levels. Analysis using a t-test showed distinct levels of antioxidant properties, total solids, and extensibility between oil-free and oil-based food films. The food preservation examination data was gathered through barrier measurements. By measuring their effect on food preservation, linear regression analysis demonstrated the extent to which essential oils affect several variables, including mechanical qualities and antioxidant activity. Through quantitative data, the features that essential oils promote food preservation were demonstrated by the statistical investigations. Additionally, it demonstrated that the essential oils had no impact on penetration or migration.

Result and Discussion

Biodegradable packaging sections with essential oils showed significant effects on food preservation throughout tests. It used ANOVA to confirm changes in the mechanical assets of TS and EB and the antioxidant assets of DPPH and TBARS. By demonstrating that essential oils produced superior preservation results, linear regression established a direct correlation between essential oil content and preservation rates. The t-test also revealed that adding essential oils improved preservation qualities. The films' barrier properties, permeation, and migration revealed no adverse effects; however, there were minor alterations in the tensile strength and elongation. It demonstrates how nutritional films, a sustainable packaging alternative to conventional plastic containers, can maintain food quality.

Food Preservation Efficiency of Biodegradable Films

ANOVA is a method of statistics for examining the means of several groups to find notable variations among categories. It offers methods for measuring permeability, mechanical characteristics, and antioxidant activity in biodegradable films containing essential oils. This method aids in establishing if essential oils significantly enhance the quality of food preservation.

Table 1. Findings of biodegradable films using essential oils on food quality criteria

Factors	**sum of Square**	**Mean Square**	**Degrees of Freedom**	**F-Value**	**P-Value**	**Interpretation**
DPPH	12.45	4.15	3	9.32	0.004	Significant
TBARS	15.78	5.26	3	10.21	0.002	Significant
TS	8.32	2.77	3	6.89	0.015	Significant
EB	7.9	2.63	3	5.47	0.023	Significant
Permeation	2.45	0.82	3	1.32	0.289	Not Significant
Migration	3.21	1.07	3	1.89	0.198	Not Significant

A comprehensive conclusion on the efficacy of biodegradable films enhanced with essential oils as food quality enhancers and preservation solutions is established in Table 1. The DPPH and the TBARS test results presented statistically substantial changes ($p < 0.05$) in the essential oils' ability to effectively reduce oxidation. The essential oils applied to the film had significant effects on EB and TS, thus affecting its flexibility and durability. The essential oils never affect the barrier qualities based on the penetration and migration values because no significant differences were observed ($p > 0.05$). The results show that these films effectively preserve information based on the examination.

Assessment of Essential Oil-Based Biodegradable Films

The t-test serves as a statistical procedure that checks for value differences between two groups and determines whether such differences are significant. The experiment evaluates the food preservation effects of essential oil-enriched biodegradable films by performing t-tests. The testing method explores three aspects: film mechanical properties in addition to antioxidant capabilities and barrier functionality.

Table 2. T-test evaluation of biodegradable films for food preservation and quality

Factors	DF	T Value	P Value	Interpretation
DPPH	30	3.56	0.01	Significant
TBARS	30	4.2	0.03	Significant
TS	30	-2.18	0.02	Significant
EB	30	-2.15	0.04	Significant
Permeation	30	0.01	0.98	Not Significant
Migration	30	0.02	0.99	Not Significant

Food quality is maintained during preservation by biodegradable films impregnated with essential oils, as shown in Table 2 with t-test results. The DPPH and TBARS evaluation results confirmed the antioxidant properties of the films through their protective food oxidation effect at p-values lower than 0.05. The EB and TS test results decreased significantly ($p < 0.05$), indicating minor mechanical issues in the films, although remaining flexible. The penetration and migration tests verify that essential oil incorporation produces no substantial impact on the barrier quality of the sample material ($p > 0.05$). Food preservation methods show effectiveness through biodegradable films that contain essential oils because these oils function as antioxidants, which increase preservation time without affecting packaging characteristics suitable for sustainable reuse.

The Influence of Essential Oils on Biodegradable Films

To make it feasible to quantify the correlation between three crucial elements that influence the performance of essential oils in biodegradable films. Linear regression is one of the primary statistical methods that offers a model for the dependent variable with one or more independent variables. The assessment establishes which factors, while maintaining their quality criteria, have the most effects on food conservation.

Table 3. Regression evaluation of essential oils in biodegradable films

Factors	Regression Coefficient (β)	Standard Error (SE)	T-Value	P-Value	R^2 Value	Interpretation
DPPH	0.75	0.1	7.5	0.0005	0.88	Significant
TBARS	0.85	0.09	9.44	0.0002	0.91	Significant
TS	-0.5	0.12	-4.17	0.003	0.75	Significant
EB	-0.4	0.11	-3.64	0.005	0.72	Significant
Permeation	0.15	0.08	1.87	0.07	0.23	Not Significant
Migration	0.1	0.07	1.43	0.16	0.16	Not Significant

A regression analysis of several characteristics of biodegradable films with essential oils and their impact on food preservation is presented in Table 3. The strength of the relationship and the direction in which these factors affect the outcomes are shown by the regression coefficients. According to the data analysis, DPPH, TBARS, TS, and EB, all provide statistically significant results (p-value < 0.05), indicating that essential oils improve material resilience and antioxidant capacity, strengthening food preservation techniques. Since the p-values for the permeability and migration results were more than 0.05, no significant statistical relationships were found, indicating that essential oils had little effect on these two characteristics. Based on their R^2 values, the important components in the films show a strong to moderate fit, confirming their capacity to sustainably protect food quality.

Using a data table that demonstrates the outcomes of the motorized assets TS and EB, barrier effects permeation and migration, and antioxidant activities DPPH and TBARS of biodegradable films containing EOs for food preservation. Figure 2 illustrates how essential oils improve food quality standards and product shelf life using percentage values.

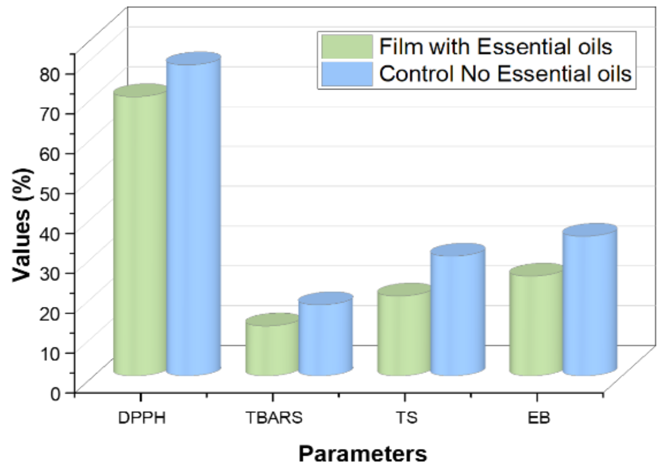

Figure 2. Comparing the food preservation properties of biodegradable films with and without essential oils

The results of the DPPH and TBARS tests for antioxidant activity demonstrate that introducing essential oil to films considerably slows down the rate of oxidative degradation. Essential oils reduce the films' flexibility and durability by increasing their EB and slightly decreasing the TS.

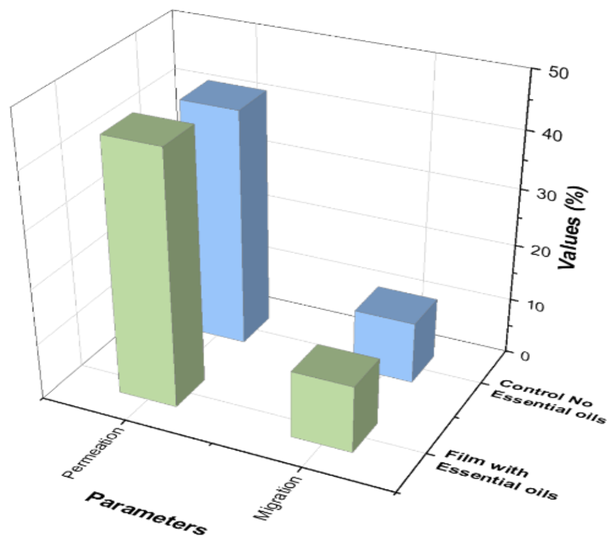

Figure 3. Analysis of permeation and migration in biodegradable films containing essential oils and controls

Essential oils seem to provide a solution that reduces film strength while maintaining penetration rates, as shown in Figure 3. Data points that demonstrate comparable outcomes across essential-oil and essential-oil-free films indicate that the required oils maintain constant migration and penetration rates. Even though essential oils cause a minor decrease in mechanical qualities, which are necessary for food preservation, barrier qualities remain unaffected.

Discussion

The effectiveness of biodegradable packaging, including essential oils for improving food preservation techniques while upholding criteria for product quality, was assessed. According to statistical studies using

ANOVA, t-tests, and linear regression, the essential oil-treated packaging films increased the antioxidant characteristics of DPPH and TBARS; however, significant decreases in TS and elongation at break were also observed. The assessment of basic effects on migration or permeation showed that no significant adverse effects influenced the results of food safety. This model provided vital information regarding biodegradable packaging while analyzing the effects of essential oils using robust statistical techniques. Experiments confirm that sustainable biopolymer films operate as eco-friendly alternatives to plastic, safeguarding food quality standards.

Conclusion

To demonstrate the several benefits that biodegradable films containing essential oils offer for both food preservation and quality control. During antioxidant tests, the essential oil-containing films successfully defend against free radicals, extending product shelf life while preserving food safety and food quality maintenance. The outcomes demonstrated that the film extracts had 5%–8% less antioxidant activity than pure essential oils, according to the DPPH test. The findings indicated that, with a p-value less than 0.05, the films' mechanical and antioxidant activity varied substantially from that of the control group. The films' reduced EB and TS remained within acceptable limits for practical application. Through barrier testing for migration and permeability, experiments established that the addition of essential oil to the films had no apparent effect on their protective assets. The results of the experiment show that biodegradable films enhanced with essential oils offer sustainable packaging options that preserve food and lessen dependency on non-biodegradable plastics for packaging uses. The primary results demonstrate that essential oils can be mixed with biodegradable films and used in food packaging representations.

Limitations and Future Scope

The decreased antioxidant action of the films in comparison to pure essential oils. Additionally, packing durability can be impacted by a decrease in mechanical strength. To increase economic viability and the possibility of large-scale production, future research should concentrate on improving mechanical qualities, optimizing film composition, and assessing the implications of long-term storage.

Author Contributions

All Authors contributed equally.

Conflict of Interest

The authors declared that no conflict of interest.

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