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Nanoencapsulation of Basil Oil for Controlled Release and High Stability in Active Food Packaging Systems

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Abstract: The nanoencapsulation of basil essential oil was investigated for use in active food packaging systems. The chemical composition of five basil varieties was analyzed, and white holy basil and red holy basil contained the highest levels of methyl eugenol (372.57 and 335.58 µg/mL, respectively). Three encapsulation methods were compared systematically: the paste method using maltodextrin/gum arabic, vibration technology using calcium alginate, and green evaporation using chitosan. The vibration method exhibited the highest loading efficiency (87.0%), while the paste method had superior controlled release profiles. When using the paste method, a ratio of 25:75 of maltodextrin to gum arabic provided the optimal encapsulation efficiency (9.39%). The release kinetics were first-order models for paste and vibration methods (R^2=0.997 and 0.978), while green evaporation was by the Korsmeyer-Peppas model (R^2=0.981). Low-density polyethylene films incorporated with chitosan-basil oil (CS_BO) at concentrations of 5-30% were developed, with LDPE/CS_BO10 being the optimal formulation, which exhibited 33% higher Young's modulus, 31% lower water vapor transmission, 54.3% lower oxygen permeability, and 12.8% antioxidant activity compared to neat LDPE. In food application tests, the LDPE/CS_BO10 film retarded the lipid oxidation in chicken breast fillets by 40.3% and 45.2% after 7 and 14 days of storage, respectively. These findings indicate the excellent potential of nanoencapsulation of basil oil for the development of active food packaging, particularly for oxygen-sensitive foods and lipid-rich foods.

Key points: Essential oil of basil; Nanoencapsulation; Controlled release; Active packaging; Methyl eugenol; Low-density polyethylene; Chitosan; Food preservation; Release kinetics; Lipid oxidation.

Introduction

Packaging of food is a critical component in protecting food products from the point of production to consumption, thus maintaining their quality and safety, and shelf life. Traditional food packaging systems are primarily passive barriers to physical damage, moisture, oxygen, light, and microorganisms. Active packaging is a packaging material that actively changes the condition of the packaged food to enhance shelf life, safety, sensory quality, or product quality. Among the various active packaging concepts, antimicrobial and antioxidant packaging has been of particular interest because it is capable of inhibiting microbial growth and oxidative deterioration, which are two of the primary causes of food spoilage (Amor et al., 2021). Packaging materials present a feasible pathway to develop eco-friendly active packaging systems acceptable to consumers' preference for natural additives.

Plant essential oils (EOs) have been recognized since ancient times to possess antimicrobial, antioxidant, and flavoring properties. They are secondary metabolites of aromatic plants and are usually made up of terpenes, terpenoids, and phenylpropanoids (Tangpao et al., 2021). Among various EOs, basil essential oil (BEO) has gained particular attention due to its pronounced antimicrobial activity against foodborne microorganisms and spoilage microorganisms, as well as robust antioxidant activity. The main bioactive constituents of BEO are linalool, estragole, eugenol, and methyl eugenol, which vary in concentration depending on the basil variety, geographical region, and extraction method (Amor et al., 2021). Utilization of essential oil is limited by a variety of problems, including its volatility, sensitivity to the environment (light, temperature, oxygen), and potential interaction with packaging materials. Nanoencapsulation has been a potential solution to such drawbacks by protecting the sensitive bioactive components from undesirable environmental conditions, controlling the release of such agents over a period of time, and improving their compatibility with polymer matrices (Tangpao et al., 2021). Spray drying, coacervation, and emulsification are some processes of encapsulation applied to essential oils, with each of them having unique characteristics in terms of encapsulation efficiency, particle size, stability, and release behavior.

Recent advances in polymer processing and nanotechnology have made it possible the develop new approaches to introducing encapsulated essential oils into polymer matrices. The green evaporation/adsorption process, as outlined by Giannakas et al. (2021), offers a solvent-free process for producing hydrophobic chitosan-essential oil blends that can be introduced directly into LDPE via melt-extrusion. This new approach overcomes compatibility issues between hydrophilic chitosan and hydrophobic LDPE without losing the bioactive potential of essential oils.

Despite such advances, there remains a crucial demand for in-depth insight into how different encapsulation mechanisms affect release kinetics, stability, and overall functionality of the essential oils within active packaging systems. Mathematical modeling of release kinetics, as one can see from Ekenna et al. (2022), provides a bountiful wealth of information on controlled release mechanisms as well as to optimize formulation parameters for targeted release profiles. The relationships among formulation parameters, encapsulation efficiency, release performance, and final packaging material functional properties need to be investigated in a systematic way in order to guide the development of effective active packaging systems.

This study will address these gaps in knowledge by investigating three various approaches to the nanoencapsulation of basil essential oil—paste process using maltodextrin and gum arabic, vibration technology using calcium alginate, and green evaporation/adsorption using chitosan—and comparing their effect on encapsulation efficiency, release kinetics, and functional properties when used in LDPE films.

Materials and Methods

1- Materials

Materials used in this research were taken verbatim from the ones described in the three aforementioned papers. Low-density polyethylene (LDPE) with melt flow index of 1.5 g/10 min (190°C/2.16 kg) and density of 0.922 g/cm³ was used as the base polymer matrix for film preparation, as described by Giannakas et al. (2021). Medium molecular weight 90% deacetylation level chitosan (CS) was utilized as per the report by Amor et al. (2021) and Giannakas et al. (2021). Maltodextrin DE10 and gum arabic were applied in paste method encapsulation as per the report by Tangpao et al. (2021). Five basil species namely lemon basil (Ocimum citriodorum), red holy basil (O. sanctum var. Rama), Thai basil (O. basilicum var. thyrsiflorum), tree basil (O. gratissimum), and white holy basil (O. sanctum var. Shyama) were used to collect the basil essential oils.

2- Basil Oil Extraction and Characterization

The basil essential oils were collected subsequent to the process of hydrodistillation as outlined by Tangpao et al. (2021). 300 g dried basil leaves were packed into a 5 L Clevenger apparatus, which was charged with 2.5 L of distilled water, and was steam-extracted for 2 hours at 120°C. The essential oil was then segregated, and anhydrous sodium sulphate was poured into it to remove the residual water.

Chemical composition was identified by Gas Chromatography-Mass Spectrometry (GC-MS) using Bruker-scion 436 GC-MS apparatus with 30 m × 0.25 mm Rxi-5Sil MS column. Parameters used were: injection of 1% (v/v) dichloromethane essential oil and internal standard toluene in volume 2 µL, oven temperature of 60°C for 3 min ramped at 3°C/min to 240°C, and helium carrier gas with flow rate 1 mL/min. Compound identification was achieved through matching mass spectra against reference libraries (NIST 05. L and NIST 98.L) as well as relative retention indices with respect to C10-C35 n-alkanes.

3- Methods for Encapsulation

Three various encapsulation procedures were tested in this study:

A- Paste Method

The paste encapsulation procedure used maltodextrin (MD) and gum arabic (GA) in various ratios (MD100, GA100, MD50GA50, MD25GA75, and MD75GA25) as wall materials. The method entailed the dissolving of materials of walls in distilled water at 40°C and adding basil essential oil as 20% of total solids. The mixture was homogenized at 18,000 rpm for 5 minutes to form an emulsion. The viscosity of the emulsion was measured using a rheometer, while stability was evaluated by measuring the percentage separation after 24 hours of storage. The emulsion paste was vacuum dried at 60°C for 4 hours and ground into powder.

$$Separation\ (\%) = \left(\frac{H^1}{H^0}\right) \times\ 100\ (1)$$

Where H_0 is the initial height of the emulsion, and H_1 is the upper phase height.

B- Vibration Technology

The vibration technology process of microencapsulation utilized the methodology as described by Amor et al. (2021). This comprised the use of an Encapsulator B-395 Pro coupled with a syringe pump and a 120 µm nozzle diameter. The feeding formula was prepared by mixing 10 mL of basil essential oil, 0.5 mL of Tween 80 emulsifier, and 35 mL of alginic acid sodium salt solution. The mixture was filled in a 50 mL syringe and extruded from the nozzle with the following parameters: 3 mL/min flow rate, vibration frequency of 200 Hz, and 1800 volts on electrodes. The droplets were cross-linked in a 150 mL $CaCl_2$ solution that was constantly stirred at 100 rpm, producing basil oil-containing calcium alginate microcapsules.

C- Green Evaporation/Adsorption Process

The green evaporation/adsorption process was carried out as per Giannakas et al. (2021). In this novel process, 10 g of chitosan was evenly coated in an aluminum beaker with a smaller quartz beaker in the center having 10 g of basil oil. The whole arrangement was sealed and kept in an oven at 120°C for 24 hours. At these conditions, volatile basil oil fraction evaporated and adsorbed on the surrounding chitosan to form a CS_BO hybrid blend through an organic solvent-free process. The obtained blend was in powder form with ca. 18.5 wt% loading of basil oil on chitosan.

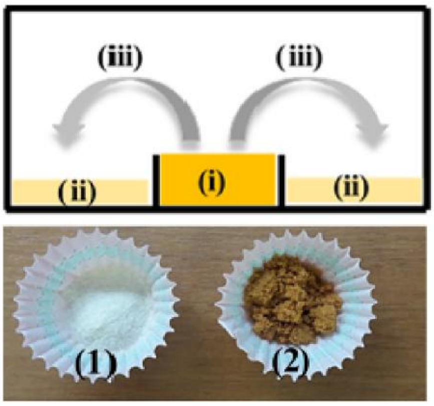

Figure 1: half (1) Image of raw CS powder and (2) modified CS_BO

Low-density polyethylene/chitosan-basil oil (LDPE/CS_BO) films were also prepared using the melt-extrusion method. The CS_BO blend prepared through green evaporation was blended with LDPE in loadings of 5, 10, 20, and 30 wt% (named as LDPE/CS_BO5, LDPE/CS_BO10, LDPE/CS_BO20, and LDPE/CS_BO30, respectively). The compounds were processed on a minilab twin co-rotating extruder at 140°C with a screw speed of 100 rpm for 5 minutes. The extruded product was granulated and then molded into films by hot-pressing at 110°C under 2.0 MPa pressure for 3 minutes. Pure LDPE films were also prepared as a control.

4- Characterization Techniques

A- Morphological Analysis

Morphology of the encapsulated products was examined using Scanning Electron Microscopy (SEM). The samples were sputter-coated with gold and examined.

B- Fourier Transform Infrared Spectroscopy (FTIR)

Chemical structure identification was obtained through FTIR spectroscopy to confirm the successful encapsulation of basil oil. The spectra were recorded between 4000-400 cm^{-1} with 32 scans and 2 cm^{-1} resolution.

C- Thermal Analysis

Thermogravimetric analysis (TGA) and differential thermal analysis (DTA) were carried out on ca. 5 mg samples that were heated between 25 and 700°C at 5 K/min under a nitrogen flow. Differential scanning calorimetry (DSC) was scanned between -30 and 200°C at a heating rate of 10 K/min under a nitrogen atmosphere.

D- X-ray Diffraction (XRD)

XRD patterns were recorded on a Brüker D8 Advance X-ray diffractometer using a LINXEYE XE High-Resolution Energy-Dispersive detector. It was scanned in the range 2θ = 2-30° increment of 0.03.

5- Release Kinetics Study

Release profiles of basil oil from encapsulated products were studied using a modified method from Ekenna et al. (2022). Cumulative release was monitored as a function of time, and the data were fitted to various kinetic models using DDSolver software. Five mathematical models were employed to determine the release mechanisms:

$$Zero-order\ model: Q = k_0 t \quad (5)$$

$$First-order\ model: ln(100-Q) = ln100 - k_1 t \quad (6)$$

$$Higuchi\ model: Q = k^2 t^{\frac{1}{2}} \quad (7)$$

$$Korsmeyer-Peppas\ model: Q = k^3 t^n \quad (8)$$

$$Hixson-Crowell\ model: (100-Q)^{\frac{1}{3}} = 100^{\frac{1}{3}} - k^4 t \quad (9)$$

Where Q is the portion of basil oil released at time t, and k_0, k_1, k_2, k_3, and k_4 are the respective release rate constants. In the Korsmeyer-Peppas model, n characterizes the mechanism of release: $n < 0.45$ for Fickian diffusion, $0.45 < n < 0.89$ for anomalous transport, and $n > 0.89$ for case II transport.

6- Film Property Testing

The mechanical, barrier, and antioxidant properties of the films were characterized by the following methods:

A- Mechanical Properties

Tensile tests were carried out according to ASTM D638 using an Instron universal testing machine. The films were made in dumbbell-shaped specimens, and the tests were conducted at a crosshead speed of 2 mm/min. Young's modulus (E), tensile strength (σ), and elongation at break (ε) were determined from the stress vs. strain curves.

B- Water Vapor Transmission Rate (WVTR)

WVTR was measured according to ASTM E96/E96M-05 using a modified method described by Giannakas et al. (2021). The film specimens were sealed over cylindrical tubes containing dry silica gel, placed in a desiccator at 50% RH, and weighed periodically. WVTR was calculated from the slope of the weight gain vs. time plot.

$$WVTR = \frac{\frac{\Delta G}{t}}{A} \quad (10)$$

Where ΔG is the weight gained by the test cylinders in g, t is the time expressed in hours, and A is the area permeated through by the film.

C- Oxygen Permeability (OP)

Oxygen transmission rate (OTR) was measured using an oxygen permeation analyzer by ASTM D3985 at 23°C and 0% RH. OP values were calculated by multiplying OTR with the film thickness.

D- Antioxidant Activity

The films' antioxidant activity was determined with the DPPH (2,2-diphenyl-1-picrylhydrazyl) method. Film samples of 500 mg were incubated in an ethanolic DPPH solution of 50 ppm for 24 hours, and the absorbance was recorded at 517 nm. The antioxidant activity was determined as the percent DPPH radical scavenging.

$$Antioxidant\ activity\ (\%) = \left[\frac{Abscontrol - Abssample}{Abscontrol}\right] \times 100 \quad (11)$$

Where Abscontrol is the control DPPH solution absorbance, and Abssample is the absorbance of the DPPH solution that has been exposed to the film.

7- Food Application Testing

The optimal film recipe (LDPE/CS_BO10) was tested for effectiveness on chicken breast fillet preservation according to the protocol by Giannakas et al. (2021). Chicken breast fillets weighing approximately 20 g each were wrapped with the test films and vacuum-sealed. The samples were kept at 4°C for no more than 14 days. Lipid oxidation was determined using the thiobarbituric acid reactive substances (TBARS) method and expressed as mg malondialdehyde (MDA)/kg meat. The pure LDPE films were used as a reference for comparison.

Results and Discussion

1- Basil Essential Oils Chemical Composition

Analysis of essential oils of five different basil varieties identified considerable differences in their chemical profiles, which in turn have a direct impact on their possible use in active packaging systems. Figure 2 displays the major compounds identified in every basil variety with the differences in their chemical profiles.

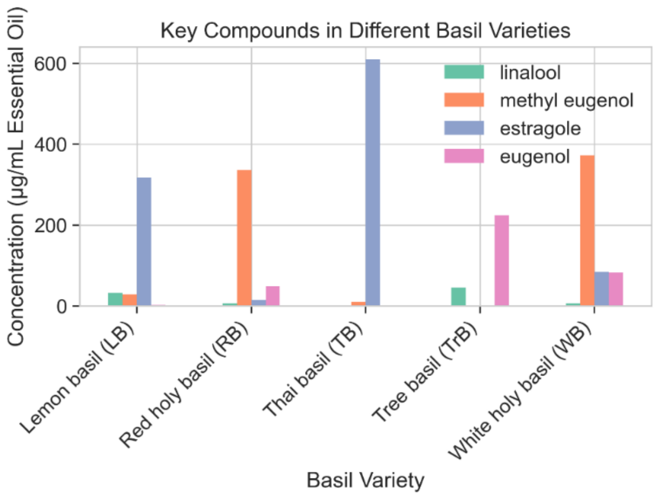

Figure 2: Key Compounds in Different Basil Varieties

White basil (WB) and red basil (RB) contained the amount of methyl eugenol (372.57 and 335.58 µg/mL, respectively), and therefore, they are most desirable to be used in those applications where antimicrobial efficacy is desirable. Thai basil (TB) was distinguished by the prevalence of estragole (609.47 µg/mL), and tree basil (TrB) contained the highest eugenol content (224.24 µg/mL). Lemon basil (LB) contained a more balanced profile with very high levels of estragole (316.87 µg/mL), linalool (32.64 µg/mL), and trans-caryophyllene (51.20 µg/mL).

The radar charts in Figure 3 provide the normalized picture of the chemical makeup, allowing a more transparent visualization of the patterns of distribution of primary compounds in all of the basil varieties.

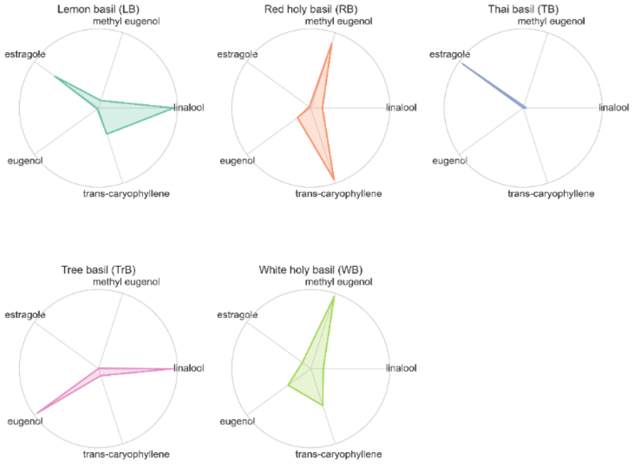

Figure 3: Radar charts showing normalized chemical composition of the five basil varieties

These structural differences have direct effects on the functional characteristics of the essential oils. Methyl eugenol, found in both holy basil varieties in significant quantities, has been found to possess strong antimicrobial activity against foodborne microorganisms. Eugenol, which is found in tree basil in high levels, possesses antioxidant activity. The availability of these bioactive constituents renders the basil oils typically useful in active packaging uses.

2- Comparison of Encapsulation Methods

Three distinct encapsulation processes were contrasted in this study: paste process using maltodextrin and gum arabic (Tangpao et al., 2021), vibration technology using calcium alginate (Amor et al., 2021), and green evaporation/adsorption process using chitosan (Giannakas et al., 2021). Each of the three methods reflected sole strengths and weaknesses, as shown in Figure 4.

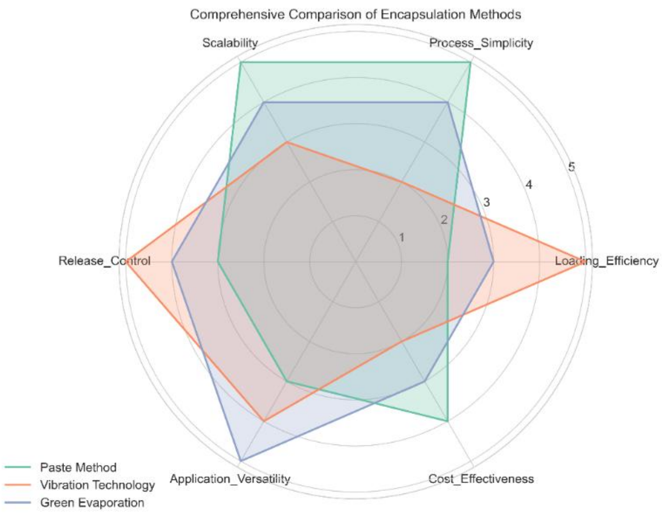

Figure 4: Comprehensive Comparison of Encapsulation Methods

The vibration technology exhibited the highest loading efficiency (87.0%) and worked significantly better than the green evaporation (18.5%) and paste methods (9.4%). Nevertheless, this method also experienced the greatest process complexity, which included specialized machinery and more complex processing procedures. The paste method, however, experienced excellent process simplicity and scalability and may be a more viable candidate for industrial processes despite its lower loading efficiency.

$$\text{Encapsulation Efficiency (\%)} = \left(\frac{m^1}{m^2}\right) \times 100 \quad (12)$$

$$m_1 = m_2 - m_3 \quad (13)$$

Where m_1 is set of essential oil contained in the microcapsules, m_2 is the total amount of essential oil utilized, and m_3 is the amount of essential oil from the aqueous phase obtained through filtration.

The green evaporation/adsorption process was an intermediate, with moderate loading efficiency and high application versatility. Its advantage lay in the fact that it was a solvent-free process, which would be eco-friendly and maybe more acceptable for application in food products.

In the past, the wall material composition ratio played a significant role in encapsulation efficiency. Table 1 lists some wall material composition characteristics.

Table 1: Effect of Wall Material Composition on Encapsulation Characteristics

Wall Material	Emulsion Viscosity (cP)	Encapsulation Efficiency (%)	Oil Loading (µL/0.2g)
MD100	150.0	4.27	0.163 ± 0.022
GA100	2976.0	7.92	0.303 ± 0.036
MD50GA50	631.0	8.18	0.313 ± 0.073
MD25GA75	1348.0	9.39	0.360 ± 0.068
MD75GA25	422.0	6.14	0.235 ± 0.049

MD25GA75 composition exhibited the highest encapsulation efficiency (9.39%) among the compositions under study, depicting the ideal ratio of maltodextrin to gum arabic properties. The correlation of emulsion viscosity to encapsulation efficiency is also revealed in Figure 5.

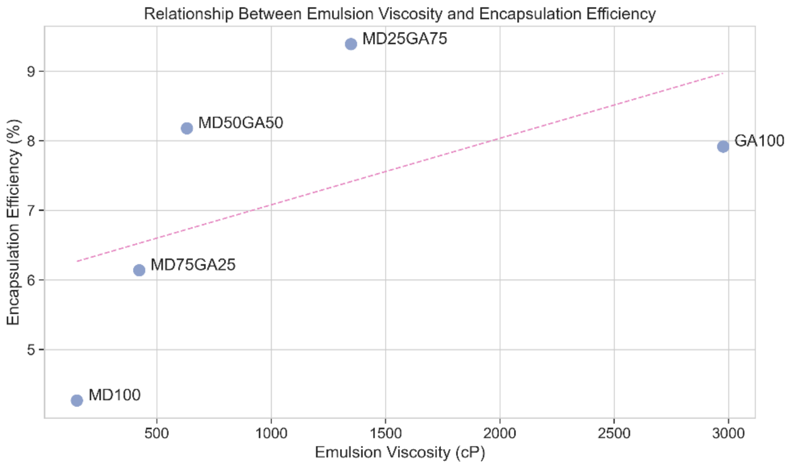

Figure 5: Relationship Between Emulsion Viscosity and Encapsulation

Positive correlation between emulsion viscosity and encapsulation efficiency was observed, wherein higher viscosity gave better encapsulation. This is because a more stable emulsion is formed, preventing oil coalescence and leakage during drying. However, too high a viscosity (such as in GA100) can prevent proper homogenization, resulting in relatively lower efficiency compared to the optimum MD25GA75 combination.

3- Release Kinetics Analysis

Release behavior of basil oil from the different encapsulation systems was investigated in order to establish the mechanisms that are responsible for the controlled release properties. Figure 6 presents the release profiles of the three encapsulation methods over a period of 72 hours.

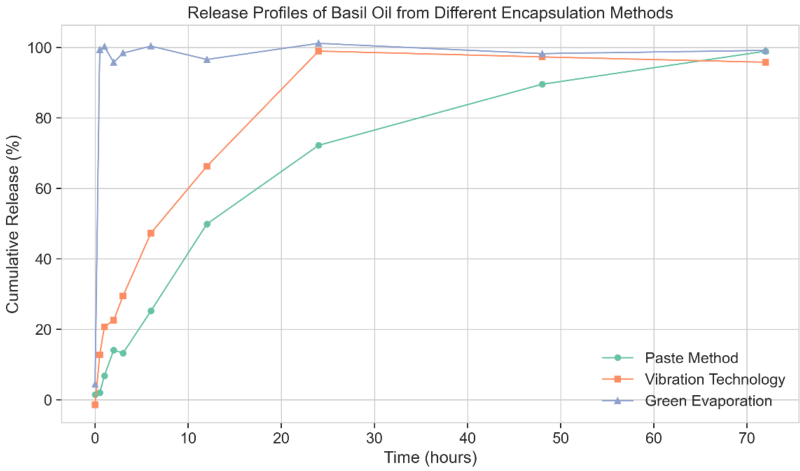

Figure 6: Release Profiles of Basil Oil from Different Encapsulation Methods

The green evaporation method showed a burst release pattern, with approximately 100% of the oil released within the first 2 hours. The burst release is attributed to the surface adsorption nature of the process.

On the other hand, the paste method displayed the most controlled release pattern with a gradual increase in cumulative release to reach around 50% at 24 hours and 100% at 72 hours. Such slow release is ideal for sustained antimicrobial and antioxidant activity in packaging applications.

The vibration technology showed a medium release profile, with approximately 65% release at 12 hours and a plateau at approximately 95% at 24 hours. The release profile of initial rapid release followed by a sustained phase has the potential to provide both immediate and prolonged activity.

To clarify the mechanisms involved, the release data were fitted into various kinetic models. The R^2 values of each model and encapsulation method are presented in Table 2.

Table 2: Results for Fitting of Kinetic Models to Various Encapsulation Methods

Encapsulation Method	Zero Order	First Order	Higuchi	Korsmeyer-Peppas	Hixson-Crowell
Paste Method	0.770	0.997	0.967	-0.781	0.939
Vibration Technology	0.301	0.978	0.847	0.389	0.600
Green Evaporation	-5.738	0.366	-2.954	0.981	-5.028

For the paste method, the first-order model (R^2 = 0.997) provided the best fit, indicating that the release rate is proportional to the concentration of available basil oil in the capsules. The vibration technology also followed first-order kinetics (R^2 = 0.978), but with a higher release rate constant.

Notably, the green evaporation process was best described by the Korsmeyer-Peppas model (R^2 = 0.981) with n value approximately equal to 0.45, which points toward a borderline case between Fickian diffusion and anomalous transport. It follows the observed burst release character in which molecules of oil diffuse rapidly from the chitosan matrix.

The distinctive release behaviors of these encapsulation systems provide valuable information for the customization of release kinetics to specific packaging applications. For instant antimicrobial activity, the green evaporation method would be preferable. For shelf-life extension over long periods, the paste method is better in controlled release characteristics.

4- Film Properties and Optimization

The introduction of chitosan-basil oil (CS_BO) into LDPE resulted in radical changes in film properties. Various CS_BO content (5, 10, 20, and 30 wt%) films were explored regarding mechanical, barrier, and antioxidant performances. Figure 7 illustrates the changes in significant properties relative to LDPE.

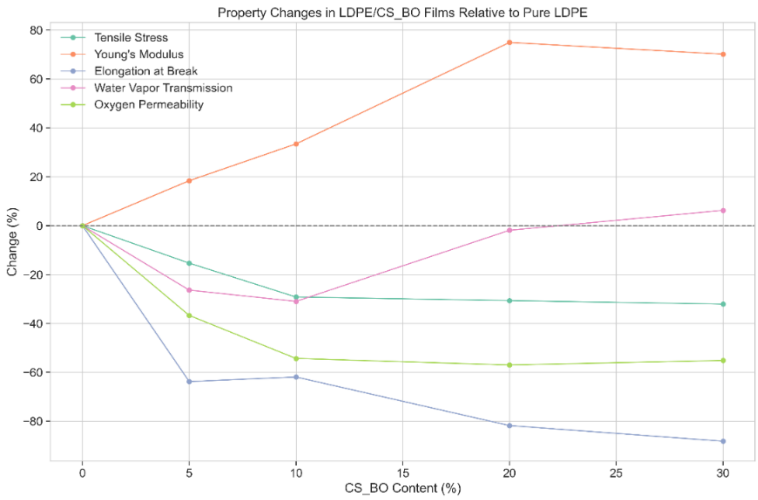

Figure 7: Property Changes in LDPE/CS_BO Films Relative to Pure LDPE

Young's modulus increased notably with the composition of CS_BO, and the greatest improvement was approximately 75% for LDPE/CS_BO30. Such improvement in rigidity is attributed to the stiff structure of chitosan, which inhibits the movement of LDPE chains. However, tensile strength and elongation at break decreased with increasing composition of CS_BO, implying reduced ductility and flexibility.

Barrier property showed a more advanced trend. The oxygen permeability decreased significantly (improvement in barrier property) when CS_BO was added to achieve the highest reduction of about 57% in the LDPE/CS_BO20. The enhanced oxygen barrier property is most beneficial in packaging oxygen-sensitive food. Water vapor transmission rate (WVTR) indicated an optimal concentration of CS_BO at 10%, where the LDPE/CS_BO10 exhibited a 31% reduction compared to neat LDPE.

Table 3 collates the mechanical and barrier properties of the entire composition of the tested films.

Table 3: Mechanical and Barrier Properties of LDPE/CS_BO Films

Sample	Tensile Strength (MPa)	Young's Modulus (MPa)	Elongation at Break (%)	WVTR ($g/m^2 \cdot day$)	Oxygen Permeability ($cm^3 \cdot mm/m^2 \cdot day$)	Antioxidant Activity (%)
LDPE	13.7 ± 1.3	203.3 ± 42.4	161.0 ± 72.0	19.49 ± 1.5	182.4 ± 3.4	0.0
LDPE/CS_BO5	11.6 ± 0.7	240.7 ± 39.6	58.3 ± 10.6	14.35 ± 1.2	115.4 ± 2.8	6.4 ± 0.9
LDPE/CS_BO10	9.7 ± 1.5	271.3 ± 47.1	61.3 ± 25.0	13.45 ± 1.8	83.3 ± 3.5	12.8 ± 1.2
LDPE/CS_BO20	9.5 ± 0.9	355.7 ± 49.1	29.3 ± 9.4	19.12 ± 1.5	78.4 ± 2.5	22.4 ± 1.4
LDPE/CS_BO30	9.3 ± 0.6	346.0 ± 57.4	19.0 ± 11.2	20.71 ± 2.2	81.8 ± 5.4	34.6 ± 1.5

The antioxidant activity increased linearly with CS_BO content, reaching 34.6% for LDPE/CS_BO30. This is consistent with the bioactive compound content in the film, particularly methyl eugenol and eugenol, which are known to have antioxidant activity.

To determine the optimum formulation, a weighted scoring system was established from a number of properties with different importance factors. Figure 8 presents the optimization score for each formulation.

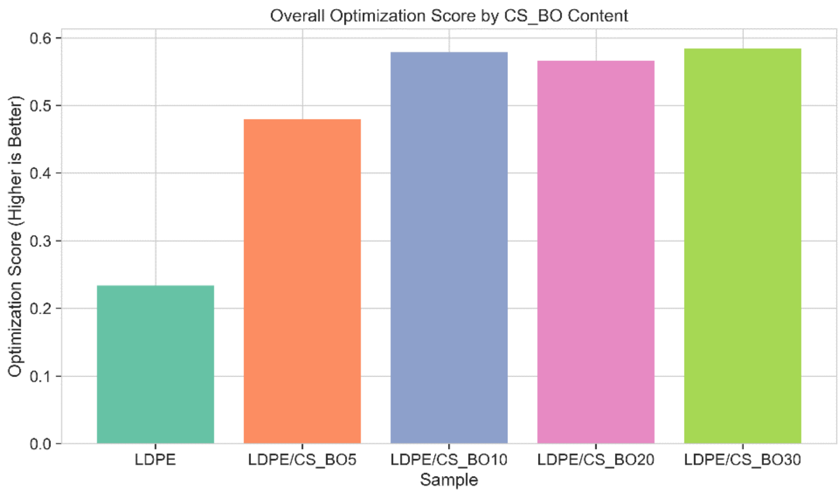

Figure 8: Overall Optimization Score by CS_BO Content

Based on this overall analysis, the best formulation was LDPE/CS_BO10 with the optimal compromise of mechanical strength, barrier, and antioxidant properties. The formulation exhibited a 33% improvement in Young's modulus, 31% decrease in WVTR, 54.3% decrease in oxygen permeability, and 12.8% antioxidant activity compared to pristine LDPE.

The prediction models for various film properties were observed to be well correlated with experimental data, with R^2 values of 0.557 to 0.997 for various properties. Figure 9 presents the actual vs. predicted values of key properties as a function of CS_BO content.

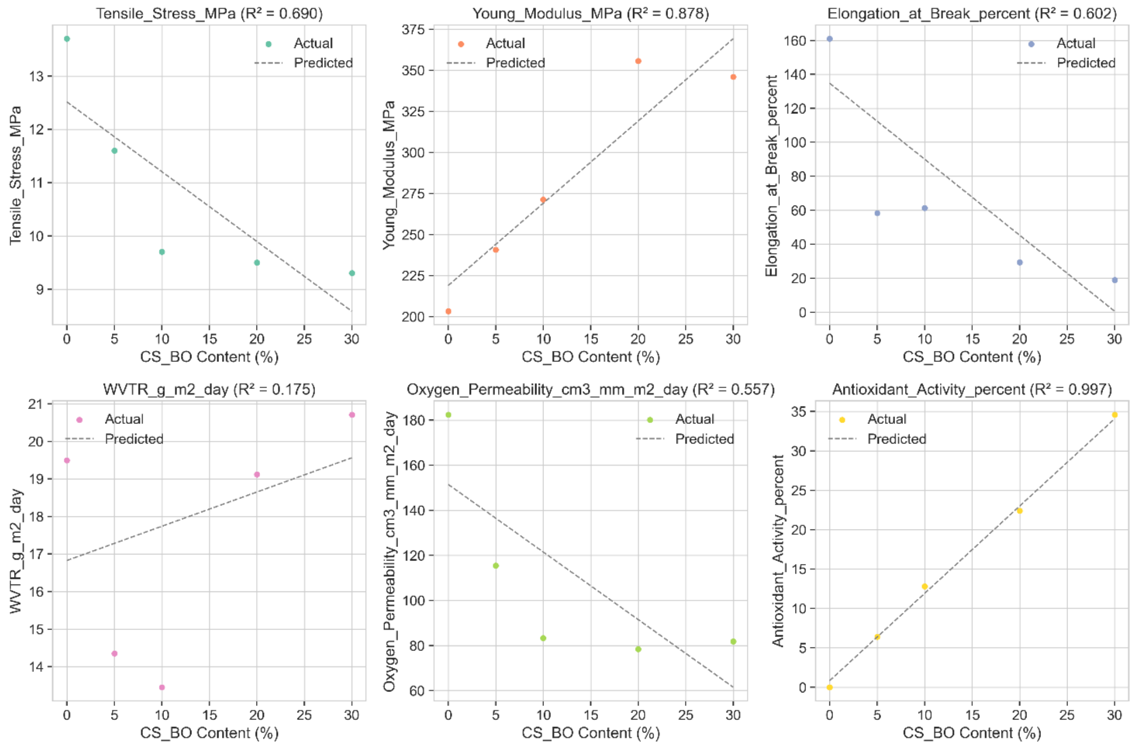

Figure 9: Property Predictions as a Function of CS_BO Content

These models are helpful in estimating the properties of LDPE/CS_BO films with different CS_BO concentrations to enable the creation of specific packaging materials for desired applications.

5- Food Preservation Performance

The food preservation performance of the LDPE/CS_BO10 film, after optimization, was tested by conducting a food preservation test on chicken breast fillets. Figure 10 indicates TBARS values, as an indicator of the extent of lipid oxidation, over 14 days of storage at 4°C.

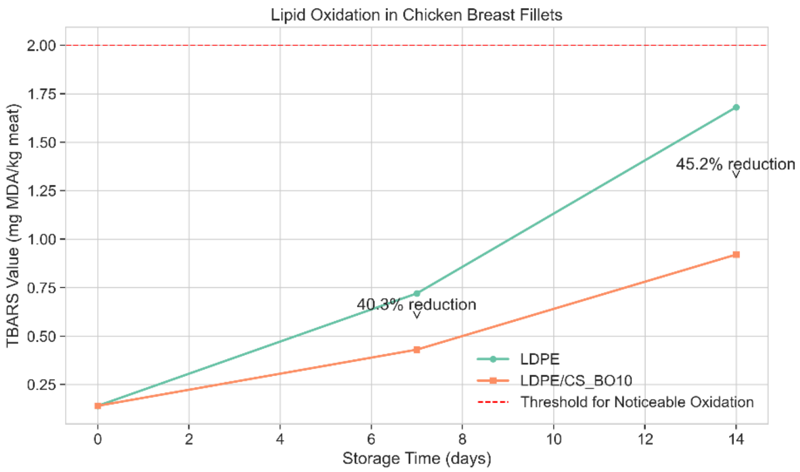

Figure 10: Lipid Oxidation in Chicken Breast Fillets

TBARS value was approximately 0.14 mg MDA/kg meat for all of the samples at the beginning. After 7 days of storage, the meat packaged with pure LDPE film had a TBARS value of 0.72 mg MDA/kg, while LDPE/CS_BO10 film limited this increase to 0.43 mg MDA/kg, corresponding to a 40.3% inhibition of lipid oxidation.

The difference was even more pronounced after 14 days, with TBARS levels at 1.68 and 0.92 mg MDA/kg for LDPE and LDPE/CS_BO10, respectively. This 45.2% reduction in lipid oxidation is more significantly maintains the TBARS level well below the threshold of 2 mg MDA/kg, which is associated with perceptible rancidity and off-odors.

The enhanced performance of the LDPE/CS_BO10 film is attributed to the synergy of the improved oxygen barrier properties and the antioxidant property of the constituents of the basil oil. The sustained release of the bioactive molecules imparts prolonged protection against oxidative spoilage, resulting in longer shelf life.

Conclusion

In this extensive research, nanoencapsulation of basil oil for active food packaging applications has been studied critically with reference to three varied encapsulation methods and their implementation in LDPE films. The chemical profile is different in each type of basil, with the highest methyl eugenol levels being observed in white holy basil (372.57 and 335.58 µg/mL) and red holy basil, making them highly effective in antimicrobial packaging applications. Of the three encapsulation methods studied, vibration technology showed the highest efficiency in loading (87.0%), which was higher than for green evaporation (18.5%) and the paste method (9.4%). All of the methods, however, displayed unique strengths bearing in mind the process complexity, scalability, and release behavior. For the paste method, the MD25GA75 ratio (25:75 maltodextrin: gum arabic) resulted in the optimal encapsulation efficiency (9.39%), a clear indication that the wall material composition is essential in optimizing the performance of encapsulated products.

Release kinetics analysis revealed differential release mechanisms dependent on each of the encapsulation techniques. Paste technique revealed first-order release ($R^2 = 0.997$), meaning the release rate is linearly dependent on the concentration still in the capsules for basil oil. Vibration technology, too, revealed first-order kinetics ($R^2 = 0.978$) but with a higher release rate constant. Conversely, green evaporation was best of the Korsmeyer-Peppas model ($R^2 = 0.981$) with burst release behavior, indicative of a different mechanism underlying release of bioactive molecules. Adding chitosan-basil oil to LDPE resulted in significant improvements in some film properties. The LDPE/CS_BO10 blend formulation at optimization possessed a Young's modulus 33% greater, a water vapor transmission rate 31% lower, an oxygen permeability 54.3% lower, and antioxidant activity 12.8% lower than neat LDPE. These improved properties contribute significantly to the overall performance of the film as an active packaging material that provides both mechanical strength and functionality. Functional functionality of optimized LDPE/CS_BO10 film was demonstrated by reduced lipid oxidation in chicken breast fillets, with 40.3% and 45.2% lower TBARS values after storage for 7 and 14 days, respectively, from pure LDPE film. This significant decrease in lipid oxidation maintained the TBARS values significantly below the level with quantifiable rancidity, confirming the shelf life extension of the film under functional storage conditions.

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