A DUAL-FEATURE ACTIVE PACKAGING: ANTIMICROBIAL RELEASE AND CO_2 SCAVENGING FOR FRESH PRODUCE PRESERVATION

NAFEESA BINTI MOHAMAD JILANI

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by

NAFEESA BINTI MOHAMAD JILANI

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LIST OF SYMBOLS

%	Percentage
° C	Celsius
$<$	Less than
$\leq$	Less than or equal to

LIST OF ABBREVIATIONS

CO_2	Carbon dioxide
βCD	B-cyclodextrin
O_2	Oxygen
PLA	Polylactic acid
PCL	Polycaprolactone
PVA	Polyvinyl alcohol
PVDF	Polyvinylidene fluoride
PBAT	Polybutylene Adipate-Co-Terephthalate
ZnO	Zinc oxide
Ag	Silver
PBS	Polybutylene succinate
MAP	Modified active packaging
LBSC	Liquefied ball-milled shrimp shell chitin
PPC	Popping candy
FA	Ferulic acid
TPCA	5-oxo-3,5-dihydro-2H-thiazolo [3,2-a] pyridine-7-carboxylic acid
MgO	Magnesium oxide
GP	G-polymer
aHal	Alkaline treated halloysite nanotubes
WVTR	Water vapor transmission rate
1-MCP	1-Methylcyclopropene
TiO_2	Titanium dioxide
CEO	Cumin essential oil
NATA	Natamycin
EGCG	Epigallocatechin gallate
PP	Polypropylene
PS	Polystyrene
GCD	Glucose derived carbon dots
NGCD	Nitrogen functionalized glucose derived carbon dots
Pb	Polyaminopropyl biguanide
CuO	Copper oxide

PEI	Branched polyethyleneimine
SD	Standard deviation
EE	Encapsulation efficiency
CoPcTs-P25	Cobalt sulfonated phthalocyanine/titanium dioxide
hBN	Hexagonal boron nitride
FTIR	Fourier Transform Infrared Spectroscopy
DSC	Differential Scanning Calorimetry
TGA	Thermogravimetric Analysis
TSS	Total soluble solids

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PEMBUNGKUSAN AKTIF DWI-CIRI: PELEPASAN ANTIMIKROB DAN PENGHAPUSAN GAS CO_2 UNTUK PENGAWETAN HASIL SEGAR

ABSTRAK

Kajian ini memberi tumpuan kepada penghasilan dan penilaian bahan tambahan aktif dengan dwi-ciri—pembebasan antimikrob dan keupayaan menangkap CO_2—untuk pemeliharaan hasil segar. Dalam Fasa 1, kompleks β-siklodekstrin (βCD) telah disintesis menggunakan linalool dan eugenyl acetate melalui kaedah pemendakan bersama dan mengaduk. Pencirian dilakukan menggunakan analisis konformasi, termasuk Fourier Transform Infrared Spectroscopy (FTIR), Differential Scanning Calorimetry (DSC), dan Thermogravimetric Analysis (TGA). Selain itu, pengukuran kuantitatif mengenai kecekapan enkapsulasi dan kinetik pelepasan turut disertakan. Hasil dapatan kajian menunujukkan kaedah pemendakan bersama amat berfaedah untuk meningkatkan kestabilan terma eugenyl acetate (enkapsulasi lengkap sebatian tetamu) dan meningkatkan kecekapan enkapsulasi linalool sebanyak 24.2%. Pemendakan bersama juga memudahkan pembebasan antimikrob terkawal dan berterusan, yang penting untuk aktiviti yang berpanjangan tanpa fitotoksisiti yang cepat. Berdasarkan keputusan ini, pemendakan bersama telah dipilih untuk Fasa 2, di mana linalool dan eugenyl acetate digunakan sebagai agen antimikrob. Fasa 2 memfokuskan pada kesan aditif aktif dwi-ciri terpilih dalam memanjangkan jangka hayat tomato ceri sebagai model hasil segar. Hasil kajian ini memerhatikan penurunan berat produk kumulatif minimum ($<2\%$) semasa penyimpanan, dengan kombinasi EA-PEI menunjukkan prestasi unggul dengan menstabilkan penurunan berat dari hari ke-25 hingga hari ke-40 berbanding rawatan lain. Dari segi kekentalan, sampel yang mengandungi linalool adalah optimum untuk penyimpanan jangka pendek, manakala

eugenyl acetate yang digabungkan dengan PEI terbukti lebih berkesan untuk penyimpanan jangka panjang. PEI membantu menampan terhadap kehilangan ketegasan secara tiba-tiba yang biasanya dilihat dalam rawatan EA dan mengurangkan kesan buruk pengumpulan CO_2. Perhubungan negatif antara tahap CO_2 dan ketegasan telah dikenal pasti, dengan ambang CO_2 yang disyorkan sebanyak ≤ 0.17 g untuk mengekalkan ketegasan. Selain itu, rawatan aktif dengan ketara melambatkan kerosakan kulat, memanjangkan hayat penyimpanan sehingga 15 hari berbanding kumpulan kawalan, dengan EA-PEI adalah yang paling berkesan dalam mencegah aktiviti kulat sepanjang tempoh penyimpanan. Penemuan ini menggariskan potensi bahan tambahan aktif dwi-ciri yang dibangunkan untuk meningkatkan pemeliharaan dan jangka hayat hasil segar, menunjukkan kebolehgunaan dan keberkesanannya dalam mengurangkan kerosakan dan mengekalkan kesegaran.

A DUAL-FEATURE ACTIVE PACKAGING: ANTIMICROBIAL RELEASE AND CO_2 SCAVENGING FOR FRESH PRODUCE PRESERVATION

ABSTRACT

This study focuses on the development and evaluation of active additives with dual-feature: antimicrobial release and CO_2 scavenging capabilities—for the preservation of fresh produce. In Phase 1, β-cyclodextrin (βCD) inclusion complexes were synthesized using linalool and eugenyl acetate through co-precipitation and kneading methods. Characterization was performed using conformational analysis such as Fourier transform infrared spectroscopy (FTIR), differential scanning calorimetry (DSC), and thermogravimetric analysis (TGA). Additionally, quantitative measures of encapsulation efficiency (EE) and release kinetics were included. The results indicated co-precipitation method is particularly advantageous for improving the thermal stability of eugenyl acetate (complete encapsulation of guest compound) and enhancing the EE of linalool by 24.2 %. Co-precipitation also facilitated controlled and sustained antimicrobial release, which is crucial for prolonged activity without rapid phytotoxicity. Based on these results, co-precipitation was selected for Phase 2, where linalool and eugenyl acetate were utilized as antimicrobial compounds. Phase 2 focuses on the effect of selected dual-feature active additive in prolonging the shelf life of cherry tomatoes as a fresh produce model. The study observed minimal cumulative weight loss (< 2%) during storage, with the EA-PEI combination demonstrating superior performance by stabilizing weight loss from day 25 to day 40 compared to other treatments. In terms of firmness, linalool-containing samples were optimal for short-term storage, while eugenyl acetate combined with PEI proved more effective for long-term storage. PEI helped buffer against abrupt firmness loss

typically seen in EA treatments and mitigated the adverse effects of CO_2 accumulation. An inverse relationship between CO_2 levels and firmness was identified, with a recommended CO_2 threshold of ≤ 0.17 g to maintain firmness. Additionally, the active treatments significantly delayed fungal spoilage, extending storage life by up to 15 days compared to the control group, with EA-PEI being the most effective in preventing fungal activity throughout the storage period. These findings highlight the potential of the developed dual-feature active additives to enhance the preservation and shelf life of fresh produce, demonstrating their applicability and effectiveness in reducing spoilage and maintaining freshness.

CHAPTER 1

INTRODUCTION

1.1 Introduction

1.1.1 Overview

The loss of fresh produce in the post-harvest system represents a multifaceted problem, particularly in developing countries where resource allocations are limited (Arah et al., 2016; Verma et al., 2019; Volpe et al., 2023). Not only does fresh produce loss perpetuate food loss, food waste, food insecurity by reducing the availability of nutritious food options, but it also represents a significant economic loss for agriculture stakeholders (Buzby et al., 2014; Hossain et al., 2020; Nair et al., 2023; Sousa et al., 2017). Therefore, it is urgent to find sustainable solutions to mitigate produce loss. To address this pressing issue, deteriorating factors that contribute to such losses in fresh produce are investigated.

1.1.2 Problem Statement

Fresh produce is inherently susceptible to various deterioration factors that compromise its quality and shelf life after harvest. Key factors that internally stem from fresh produce include biochemical processes such as respiration, transpiration, and ethylene production (Abreu et al., 2012; Yahia, 2018). Firstly, respiration breaks down stored carbohydrates into simple sugars, leading to deterioration in internal composition and spoilage in the commodity (Sousa et al., 2017). Moreover, the accumulation of carbon dioxide (CO_2) from respiration can disrupt aerobic process and accelerate senescence in fresh produce (Krupa & Tomala, 2021; D. Wang et al., 2020). This fermentative metabolic activity can lead to off-flavors and physiological disorders (Boeckx et al., 2019; Lee, 2016). This justifies the reason respiration rate is commonly associated with the deterioration rate of highly respiring fresh produce such as strawberry, avocados and broccoli (Alegbeleye et al., 2022; Kandasamy, 2022). Secondly, spike in ethylene production during ripening stages in climacteric fruits can lead to accelerated ripening, chlorophyll degradation in leafy vegetables, enhanced fruit softening (Flores-Cortez et al., 2018; Nayik & Muzaffar, 2014; Nimitkeatkai et al., 2022). Lastly, excessive transpiration, especially in small fleshy fruits can cause excessive water loss and negatively impact weight, texture, and overall quality of fresh produce (Damas-Job et al., 2023; Lufu et al., 2020; Youssef & El-Sayed, 2018).

Additionally, environmental conditions such as changes in holding/handling temperatures, high humidity levels, excessive exposure to light, mechanical damage from improper handling promote microbial proliferation (Brecht et al., 2008; Fonseca et al., 2002). This spoilage causes breakdown of organic matter, degradation, and decline in quality and nutritional content of produce (Álvarez-Hernández et al., 2021; L. Z. Deng et al., 2020). Thus, addressing these factors effectively is pivotal in tackling losses in fresh produce.

Despite existing literature offering insights into various preservation methods for fresh produce, a notable gap persists in research focusing on integrated active systems that can simultaneously address two multiple deterioration factors, specifically, microbial proliferation and CO_2 accumulation.

1.1.3 Aim

This study seeks to investigate the feasibility and efficacy of an active system designed to combat spoilage in fresh produce, focusing on mitigating spoilage caused by microbial contamination and excessive exposure to CO_2. Thus, the aim of this study was to develop active additives that integrate controlled antimicrobial release with CO_2 scavenging capabilities, thereby enhancing the preservation of fresh produce.

The broader implications of this research extend beyond cherry tomatoes. Our integrated approach addresses key areas that can contribute to reducing post-harvest losses in various types of fresh produce. This research has the potential to benefit developing countries, where food security is paramount, by promoting sustainable packaging technologies that prolong the freshness of fruits and vegetables.

1.1.4 Objectives

The specific objectives of this study were:

i. To synthesize active additives with dual features, a combination of controlled antimicrobial release and CO_2 scavenging capabilities.

ii. To assess the effectiveness of synthesized dual-feature active additive in a model packaging system for prolonging the shelf life of fresh produce, namely cherry tomatoes as a model.

1.2 Thesis Organization

Chapter 1 provides a general background on the impact of fresh produce loss and the factors contributing to their deterioration. This chapter identifies research gaps, highlighting the limitations of current integrated active systems with multiple functionalities. It also proposes strategies to address these gaps through the objectives of the project.

Chapter 2 focuses on the current literature regarding various active systems, with particular emphasis on multi-functional systems and active systems employed in fresh produce preservation. The gaps identified in the literature and potential approaches to address them are outlined.

Chapter 3 is dedicated to the first phase of the study, which involves the synthesis of inclusion complexes using two complexation methods (*i.e.,* co-precipitation and kneading) and two antimicrobial compounds (*i.e.,* linalool and eugenyl acetate). The characterization of the formed inclusion complexes is performed using confirmatory analyses such as Fourier transform infrared spectroscopy (FTIR), differential scanning calorimetry (DSC), and thermogravimetric analysis (TGA) along with encapsulation efficiency (EE), and release kinetics. The most suitable inclusion complex was selected as an antimicrobial additive for the integrated system.

Chapter 4 presents the development of the integrated system—a dual-feature active system with antimicrobial and CO_2 scavenging capabilities. The potential of polyethyleneimine (PEI) as a CO_2 scavenger is demonstrated through FTIR analysis, which reveals characteristic peaks indicating the presence of amine groups that provide high selectivity for CO_2 capture. The two active additives are combined using simple blending techniques. The effectiveness of the active treatments in preserving key quality parameters (i.e., weight loss, firmness, CO_2 accumulation, fungal proliferation, total soluble solids (TSS), and pH) in a model fruit system (i.e., cherry tomatoes) is thoroughly assessed.

Chapter 5 summarizes the overall conclusions from both phases of the project. This chapter highlights the capabilities and advantages of each active treatment, their potential applications in preserving cherry tomatoes, and the versatility of these treatments to be applied in other packaged fresh produce. Finally, it outlines possible future enhancements and directions for further research.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview of Active Systems

The primary role of packaging in terms of protection conventionally focused on passive roles, providing a passive barrier between the external environment and food product. However, the present needs of consumers to be provided with safe, minimally processed and preserved food in environmentally responsible packaging has extended the need for packaging with enhanced protective functions (Fadiji et al., 2023). In response, the proactive functionality of active packaging can be an innovative approach to meet needed packaging development. Active packaging technology technically involves incorporation of absorbing or releasing additives to alter the native environment of packaged food to minimize undesirable changes, improve product quality and maximize product shelf life (Almenar, 2020; Yildirim & Röcker, 2018). To achieve intended effects, active additives must contribute through the means of delaying oxidation, controlling respiration rate, inhibiting microbial growth, and/or retaining sensorial characteristics such as flavor, aroma and texture (Vasile & Baican, 2021). According to the U.S. Food and Drug Administration (FDA), food additives are defined as any substance the intended use of which results, or may reasonably be expected to result, directly or indirectly, in becoming a component of food or otherwise affecting its characteristics (21 CFR 184.1061).

2.2 Key Additives in Active Systems

The development of active systems hinges on the capacity of active additives in performing targeted functions, in mitigating spoilage and maintaining quality attributes of food products. Table 2.1 summarizes key additives in various active food systems and highlights some current published works on these systems from 2020 to 2024.

Table 2.1: Active food systems and corresponding additives with recent research trends (2020-2024).

Active System	Active additive		Findings	Reference
	Type	Compound		
		Antimicrobial Compounds		
Antimicrobial	Essential Oil/ Active compound	Oregano essential oil	Oregano/βCD incorporated into polylactic acid /polycaprolactone (PLA/PCL) electrospun nanofibers demonstrated effective antimicrobial activity in packaged blackberry, validating its potential as an active packaging material.	(C. Shi et al., 2022)
		Cinnamaldehyde	Cinnamaldehyde/βCD added to chitin/polyvinyl alcohol (PVA) blends successfully formed antimicrobial packaging films, effectively preserving cherry tomato quality during storage.	(Qian et al., 2022)
		p-Anisaldehyde	p-Anisaldehyde/βCD inclusion complexes exhibited sustained release behavior and effectively inhibited *Escherichia coli (E.coli)* and *Staphylococcus aureus (S.aureus)*, confirming their antimicrobial potential.	(Lin et al., 2022)

	Thyme essential oil	Electrospun thyme oil-zein fibres showed significant antimicrobial effects in packaged meat, validating their use as an active packaging component.	(Peixoto et al., 2023)
	Thymol or clove oil	Thymol-agave and clove oil-agave fibres demonstrated strong antimicrobial activity against *S. aureus* and *E. coli* in ex situ studies, indicating their potential as antimicrobial composites.	(Turki et al., 2023)
	Oregano essential oil	Among oregano essential oil, cinnamaldehyde, and 2-nonanone, cinnamaldehyde exhibited the highest antifungal activity against *Botrytis cinerea.* Also, oregano essential oil effectively extended the shelf life of gooseberries in modified atmosphere packaging (MAP).	(Cortés et al., 2023)
	Cinnamon essential oil	Cinnamon oil/βCD incorporated into polyvinylidene difluoride (PVDF) electrospun nanofibers provided strong antimicrobial protection for griskin, validating its efficacy as an active packaging material.	(Guan et al., 2024)
Bacteriocins	Bacteriocins derived from *Lactococcus lactis spp.* (Nisin)	Nisin, combined with Ethylenediaminetetraacetic acid, effectively inhibited microbial growth in packaged pork when incorporated into	(Leelaphiwat et al., 2022)

		Polybutylene adipate terephthalate (PBAT) or TPS/PLA polymer blends.	
	Bacteriocins derived from lactic-acid bacteria	Cell-free supernatants containing multiple bacteriocins effectively reduced biogenic amine-producing lactic acid bacteria in cheese, confirming their antimicrobial potential.	(Villarreal et al., 2024)
	Bacteriocins derived from *Lactobacillus sakei* (sakacin)	Sakacin-zein electrospun nanofibers showed strong antimicrobial activity, effectively preserving the quality of quail breast during storage.	(Heydari-Majd et al., 2023)
Lysozyme	Lysozymes derived from egg white	Lysozyme grafted onto polydopamine successfully inhibited microbial growth in packaged fresh pork, demonstrating its potential as an antimicrobial film component.	(Lv et al., 2024)
Organic acid	Multiple organic acid	A blend of organic acids effectively inhibited *E. coli* K88 virulence genes, validating their potential as antimicrobial compound.	(Bonetti et al., 2020)
Biopolymer	Chitosan, guar gum, watermelon rind extract	Chitosan/guar gum films enhanced with watermelon rind extract exhibited improved physicochemical properties and effectively preserved fresh-cut bananas during storage.	(F. Wang et al., 2023)

	Chitosan nanoparticles	Chitosan nanoparticles added to starch films showed strong antimicrobial activity, effectively reducing bacterial counts.	(Shapi'i et al., 2020)
Biocontrol	*Debaryomyces hansenii*	*Debaryomyces hansenii* effectively controlled spoilage in strawberries, confirming its potential as a biocontrol agent.	(L. Zhao et al., 2023)
	Wickerhamomyces anomalus	*Wickerhamomyces anomalus* effectively controlled spoilage in kiwi, confirming its potential as a biocontrol agent.	(Q. Zhao et al., 2023)
	Aureobasidium pullulans S-2	*Aureobasidium pullulans* S-2 effectively controlled spoilage in tomato, confirming its potential as a biocontrol agent.	(Y. Shi et al., 2022)
Carbon dots	Bacterial derived carbon dots doped with sulphur	Sulphur-doped carbon dots incorporated into PVA films effectively inhibited microbial growth in pork meat, confirming their antimicrobial potential.	(Hong et al., 2024)
	Green tea derived carbon dots doped with nitrogen & phosphorus	Nitrogen and phosphorus-doped carbon dots in chitosan/starch films showed significant antimicrobial activity against *Listeria monocytogenes* (*L.monocytogenes*), *E. coli*, and *S. aureus* in packaged meat.	(Khan et al., 2023)

		Kohlrabi peel derived carbon dots doped with zinc oxide (ZnO)	ZnO-doped carbon dots in carrageenan films provided effective antimicrobial protection for packaged shrimp.	(Khan et al., 2024)
		Bacterial derived carbon dots	Carbon dots in nanocellulose nanopaper exhibited antimicrobial and ultraviolet protection, validating their potential as multifunctional packaging material.	(Kousheh et al., 2020)
	Silver (Ag)	Ag-metal organic framework	A modified Ag-metal organic framework with sodium alginate effectively reduced spoilage and toxicity in packaged fresh-cut white radish.	(M. Xu et al., 2024)
		Oxygen Scavengers		
Oxygen (O_2) scavenger	Enzyme-based	Glucose oxidase	Immobilized glucose oxidase on ZnO nanoparticles exhibited enhanced O_2 scavenging capabilities.	(Batool et al., 2022)
		Bilirubin oxidase	Bilirubin oxidase functioned effectively as an O_2 scavenger without producing hydrogen peroxide as a by-product.	(Monteiro et al., 2022)

	Biopolymers	Natural latex	Natural rubber latex with acetophenone and manganese chloride as catalyst were developed.	(Ramakanth et al., 2022)
			Extruded low-density-polyethylene (LDPE) with 5 % natural rubber films extended shelf life of bread and khoa.	(Pawde et al., 2023)
		β-mycerene	β-Myrcene demonstrated effective O_2 scavenging properties.	(Ramakanth et al., 2023)
	Organic	Catechin	Catechin effectively scavenged O_2 in foods with moderate to high susceptibility to oxidation.	(Jain et al., 2024)
		Gallic acid	Gallic acid/sodium carbonate in chitosan matrix functioned as O_2 scavenging material, triggered by moisture.	(G. Singh et al., 2021)
			Prospect of gallic acid/sodium carbonate in thermoplastic agar-PBAT blends functioned as O_2 scavenging material, triggered by moisture.	(Iribarren et al., 2023)
			Gallic acid in polybutylene succinate/ polybutylene adipate-coterephthalate (PBS/PBAT) functioned as O_2 scavenging material	(Sonchaeng et al., 2022)

		Resorcinol	Resorcinol/potassium carbonate functioned effectively as an O_2 scavenging material with a moisture-triggered mechanism.	(B. P. Kumar et al., 2023)
	Metallic	Iron	Iron-based scavengers effectively reduced O_2 levels, inhibiting spoilage microbes.	(Escobar et al., 2023)
		Palladium	Palladium-based scavengers effectively prevented oxidation in linseed oil.	(Faas et al., 2020)
		Sodium	Sodium-based scavengers effectively reduced decay incidence in packaged barberries.	(Niazmand & Yeganehzad, 2020)
		Moisture Scavengers		
Moisture scavenger	Hydrogels	Chitin, fish gelatine	Hydrogels from chitin and fish gelatine effectively scavenged moisture while serving as carriers for bioactive compounds.	(Uranga et al., 2020)
		Gelatine, microcrystalline cellulose (MCC),	Hydrogels from gelatine, microcrystalline cellulose, and nanocrystalline cellulose effectively scavenged moisture in packaged chicken breast.	(Acevedo-Puello et al., 2023)

	nanocrystalline cellulose (NCC)		
Cellulose-based material	Wood fibres	Wood fibre-based absorbent pads effectively absorbed moisture, improving the quality of fresh and cold pork, with or without clove oil inclusion.	(C. Jiang et al., 2024)
Deep eutectic solvent	Choline chloride or betaine	Deep eutectic solvents in a gelatine matrix effectively scavenged moisture in packaged fresh produce.	(Wan et al., 2024)
Aerogels	Germinated wheat starch	Aerogels from germinated wheat starch, with grape skin extract, effectively scavenged moisture and exhibited antioxidant activity.	(Silva et al., 2023)
	Chitosan, residual lignin	Aerogels from chitosan, reinforced with residual lignin and bay leaf extract, effectively scavenged moisture and exhibited antioxidant activity in packaged fresh meat.	(Rincón et al., 2023)
Polymeric	Polyacrylic acid, cotton	The presence of a polyacrylic acid-cotton adsorber effectively prevented condensation in packaged fresh tomato.	(Agudelo-Rodríguez et al., 2020)

		Sodium polyacrylate	Equilibrium Modified Atmosphere Packaging systems with sodium polyacrylate effectively controlled moisture, improving the quality of packaged gooseberry fruit.	(Garavito et al., 2022)
		Waterborne polyurethane, halloysite nanotube	Waterborne polyurethane/halloysite nanotube composites functioned with moisture and ethylene absorbing properties.	(Kolgesiz et al., 2023)
			Carbon Dioxide Emitters/ Scavengers	
Carbon dioxide (CO_2) emitter/ scavenger	Controlled air systems	15 % CO_2 (with 35 % O_2 + 50 % N_2) or 20 % CO_2 (with 30 % O_2 + 50 % N_2)	A 20 % CO_2 atmosphere maintained better retention of bioactive compounds, soluble sugars, antioxidant activity, and phenolic compounds compared to a 15 % CO_2 atmosphere in packaged onion.	(Gouda et al., 2023)
		20 kPa CO_2 (with 20 kPa O_2 + 60 kPa N_2)	Short-term CO_2 exposure (20 kPa, 3 days) effectively prevented structural damage and metabolic dysfunction in table grapes.	(Vazquez-Hernandez et al., 2020)
		21 % CO_2 (with 5 % O_2)	CO_2 exposure caused injury and off-flavors due to the accumulation of ethanol, volatile compounds, aldehydes and esters from anaerobic	(J. Chen et al., 2019)

		metabolism, with ethanol levels 5.9 times higher than in control systems (air).	
	3 % or 5 % CO_2	A 5 % CO_2 atmosphere retained better vitamin C content, color, lycopene content, weight, firmness, and pectin content compared to a 3 % CO_2 atmosphere in cherry tomato fruit.	(Taye et al., 2017)
MAP	CO_2/O_2	High CO_2 concentrations (20, 40 or 60 %) supressed bacterial growth and total volatile basic nitrogen production. However, increased CO_2 conditions promoted lipid oxidation on pork patties.	(Liang et al., 2024)
	CO_2/N_2	CO_2 (0, 20, 60 or 100 %) in MAP systems inhibited *Shewanella putrefaciens* in yellow croaker, with higher CO_2 concentrations providing greater inhibition, particularly at 100 % CO_2.	(P. Li et al., 2023)
Synthetic compound	Popping candy (PPC)	PPC incorporated release CO_2 once in contact with moisture. Inhibition of mold growth and reduced respiration rates in packaged strawberry.	(S. Li et al., 2022)
	Sodium bicarbonate	Sodium bicarbonate impregnated in mesoporous media significantly removed accumulated CO_2 in packaged kimchi.	(Jeong et al., 2024)

Antioxidant Compounds				
Antioxidant	Natural (organic) + synthetic	Ferulic acid (FA)-antioxidant, 5-oxo-3,5-dihydro-2H-thiazolo [3,2-a] pyridine-7-carboxylic acid (TPCA).	FA-TPCA-loaded chitosan/PVA blended film exhibited high antioxidant and UV absorbing properties prevented oxidative spoilage in peanut butter.	(H. Chen et al., 2024)
	Natural (inorganic)	Magnesium oxide (MgO), ZnO,	ZnO/PLA films exhibited UV absorption with decreased surface hydrophilicity. MgO/ZnO/NCC/PLA films had UV absorption with improved mechanical strength, antimicrobial activity, lower O_2 and water vapor permeability.	(Li et al., 2023)
	Natural (organic)	Lemon extract (hesperidin, eriocitrin) or tomato extract (protocatechuic acid, chlorogenic acid)	The active PLA and GP (G-polymers) incorporated with lemon and tomato extract release high number of phenolic compounds, suiting potential as antioxidant packaging in high fat foods.	(Mariño-Cortegoso et al., 2022)
		Carvacrol, eugenol	Controlled release of encapsulated carvacrol and eugenol in βCD activated antioxidant defence systems of lemon flavedo tissue, prompting lower decay incidences.	(López-Gómez et al., 2023)

		Ethylene Scavenger		
Ethylene scavenger	Natural (inorganic)	Alkaline treated halloysite nanotubes (aHal)	aHal-reinforced PBS films exhibited strong ethylene absorption, effectively extending the shelf life of cut apples and tomatoes.	(Ucpinar Durmaz et al., 2024)
		Sillimanite (Al_2SiO_5) or bentonite (Al_2H2O_6Si)	The mineral clay-based material demonstrated effective ethylene absorption, making it a suitable choice for use in fresh produce packaging.	(P. Kumar et al., 2024)
	Natural (organic)	Activated carbon	Activated carbon derived from walnut shells and oak wood chips, incorporated into PP composites, effectively absorbed ethylene, enhancing produce longevity.	(Yurtay et al., 2024)
		Zein	Zein-reinforced polyurethane foam created a bio-based packaging material with dual ethylene-adsorbing and cushioning properties, suitable for fresh produce.	(Fan et al., 2024)
	Synthetic	1-Methylcyclopropene (1-MCP), ethylene scavenger	Combined 1-MCP and ethylene scavenger system significantly reduced ethylene accumulation and respiration rate in peaches, optimizing freshness during E-commerce logistics.	(C. Cheng et al., 2024)

			Odor Scavengers	
Odor scavenger	Natural (inorganic)	ZnO celite	Effective as bottle cap liner films in plastic kimchi packaging, efficiently absorbing volatile sulphur compounds and reducing odor.	(N. Kim et al., 2024)
		Citric acid	Successfully eliminated amines produced during protein degradation in fish packaging, enhancing odor control.	(Akbar & Mustari, 2024)
	Natural (organic)	Coffee grounds	Coffee ground-natural rubber composites enhanced material hardness, CO_2 adsorption, and significantly improved odor absorption capabilities.	(Somdee et al., 2024)

2.2.1 Antimicrobial Compounds

Given the rising consumer preference for natural and safe products, natural antimicrobial compound, particularly essential oils, have gained widespread attention. These compounds are generally recognized as safe (GRAS) and enjoy better consumer acceptance (Westlake et al., 2022). However, the direct incorporation of essential oils into polymeric packaging materials presents challenges. These challenges include low solubility in water, high volatility due to the low molecular weight aromatic constituents, potential alterations to the barrier properties of polymer films, and uncontrolled release of active compounds (Fadiji et al., 2023; Huang et al., 2019; Jamróz & Kopel, 2020; Luo et al., 2022). Additionally, the strong aroma of essential oils can cause undesirable sensory changes in the food product (Rodrigues Arruda et al., 2022).

To address these challenges, encapsulation techniques have been explored to enhance the solubility, stability and controlled release of essential oils in packaging systems (Peixoto et al., 2023; Qian et al., 2022; C. Shi et al., 2022; Turki et al., 2023). By entrapping essential oils within carrier matrices, encapsulation enhances solubility, creates a protective barrier against volatilization, and enable sustained-release properties, thereby expanding applicability while preserving antimicrobial efficacy. Various encapsulants, such as cyclodextrins, liposomes, silicon dioxide, and electrospun fibres have been employed (Cortés et al., 2023; Guan et al., 2024; Lin et al., 2022).

Cyclodextrins and their derivatives, recognized for their low toxicity and high biocompatibility, have become prominent encapsulating agents in green chemistry (C. Deng et al., 2022; S. Li et al., 2022; Luo et al., 2022). Structurally, cyclodextrins are cyclic compounds with a truncated cone shape, where the exterior is formed by hydrophilic groups, and the interior features a hydrophobic cavity. This unique structure enables cyclodextrins to form stable inclusion complexes by hosting hydrophobic guest molecules, such as essential oils, within their cavities (Pante et al., 2024). Among cyclodextrins, βCD is particularly favoured due to its affordability and moderate cavity size, suitable for accommodating compounds with molecular masses ranging from 100-400 g/mol, which includes most essential oils (Castro et al., 2022; C. Deng et al., 2022). The resulting inclusion complexes are water-soluble, withstand processing temperatures, and offer sustained-release properties.

Recent studies have made significant strides in exploring the potential of βCD inclusion complexes across various applications. One key area of focus has been the encapsulation of underutilized essential oils or their active components to form stable inclusion complexes (S. Li et al., 2022; Luo et al., 2022). These studies have shown that inclusion complexes can effectively enhance the solubility, stability, and controlled release of essential oils, thereby extending their applicability in food packaging.

In addition to forming inclusion complexes with essential oils, recent research has increasingly focused on the development of antimicrobial films incorporating βCD, particularly through the use of natural polymeric materials and nanofibers produced via electrospinning techniques (Guan et al., 2024; Qian et al., 2022; C. Shi et al., 2022). A notable study by Guan et al. (2024) explored a double encapsulation method, in which cinnamon essential oil was first encapsulated within βCD before being integrated into PVDF nanofibers through electrospinning. This innovative approach effectively reduced the agglomeration of nanoparticles and mitigated the rapid evaporation of cinnamon essential oil. The resulting antimicrobial film demonstrated a controlled release profile, providing a promising solution for extending the shelf life of griskin.

Furthermore, a critical aspect of recent research has been the effort to understand the complexation mechanisms involved in the formation of βCD inclusion complexes. Various studies have employed different complexation methods and explored the interactions between βCD and a range of guest compounds (Castro et al., 2022; H. Chen et al., 2024). For instance, H. Chen et al. (2024) conducted a detailed investigation into the inclusion complexes formed using ester aroma compounds with varying chain lengths and functional group positions, offering valuable insights into how these molecular characteristics influence complexation. Moreover, computational approaches, such as response surface methodology (RSM) and molecular docking, have been instrumental in providing insights into these mechanisms (C. Deng et al., 2022; Sakai et al., 2023; Yan et al., 2022).

Despite these advancements, there are still significant gaps in the current body of research on βCD inclusion complexes. One notable gap is the limited number of studies that compare the differences between various inclusion complexes formed under different conditions. While much of the research has focused on the changes in active compounds before and after encapsulation, comparative analyses of the complexes themselves remain underexplored. Additionally, although advanced techniques like molecular docking are frequently used to study the formation and stability of βCD inclusion complexes, there is a lack of research employing more accessible confirmational analyses such as FTIR, DSC and TGA. These techniques, while less complex than molecular docking, can still provide valuable insights into the structural and thermal properties of the inclusion complexes, and their limited use represents a missed opportunity for deeper understanding and broader applicability.

Beyond essential oils, research is increasingly focused on discovering alternative natural antimicrobial compounds. Bacteriocins, for instance, exhibit broadspectrum antimicrobial properties and are compatible with various polymeric films, often enhancing their mechanical properties (Leelaphiwat et al., 2022; Villarreal et al., 2024). Recent studies have also explored the encapsulation of bacteriocins to enhance their stability and bioavailability. Heydari-Majd et al. (2023) demonstrated the controlled release of sakacin, a bacteriocin, through encapsulation in biodegradable zein nanofibers via electrospinning.

Chitosan, a biopolymer with inherent antimicrobial properties, is another focus of current research. Its inhibitory activity against gram-positive bacteria makes it a promising candidate for food packaging films and coatings. Efforts to improve the physicochemical properties of chitosan films often involve the addition of cross-linkers or blending with starch-based polymers (Shapi'i et al., 2020; F. Wang et al., 2023). Moreover, biocontrol agents, particularly yeast and yeast-like fungi, are being investigated as natural alternatives to chemical fungicides for postharvest disease control in fresh produce. These agents function through mechanisms such as competition for nutrients, induction of plant resistance, and secretion of antimicrobial substances (Y. Shi et al., 2022; X. Zhang et al., 2020; L. Zhao et al., 2023).

While natural antimicrobials are increasingly favoured, synthetic antimicrobials still play a vital role due to their potent antimicrobial activity. However, concerns about toxicity have limited their application. Recent studies are exploring ways to mitigate these concerns. For instance, Xu et al. (2024) investigated a modified Ag metal-organic framework (MOF) coated with sodium alginate to reduce the toxicity of Ag while maintaining its antimicrobial efficacy.

Additionally, there is growing interest in carbon dots as potential antimicrobial compounds due to their low toxicity, environmental sustainability, and compatibility with various materials. Current research is focused on sourcing carbon dots from natural compounds such as green tea, fruit peels, and bacteria (Khan et al., 2023; Kousheh et al., 2020; Lv et al., 2024).

In short, recent studies on antimicrobial packaging systems have investigated various aspects, including the selection of effective antimicrobial compounds, optimization of incorporation techniques, ensuring compatibility with packaging materials, and evaluating efficacy of antimicrobials. These advancements aim to enhance food safety and extend shelf life by effectively inhibiting spoilage and pathogenic microorganisms.

2.2.2 Oxygen Scavengers

Oxidative degeneration in foods can lead to the loss of color, odor, texture and nutritional value (Jain et al., 2024; Pawde et al., 2023). This includes the production of off-flavors in fatty foods, stale odors in bakery products, and browning in fresh produce (Cichello, 2014). To mitigate these effects, O_2 scavengers are used in various food systems.

Maintaining an optimal concentration of O_2 is crucial to maintain quality of fresh produce. In packaged fresh produce, O_2 levels tend to deplete, due to respiration. Over time, O_2 depletion may fall below tolerance levels, triggering anaerobic conditions. This results in irreversible physiological damages including browning, generation of off-odors and accumulation of ethanol and acetaldehyde from fruit fermentation (Matityahu et al., 2016; Perumal et al., 2022; Schlie et al., 2023). While MAP systems are commonly employed, they have inherent limitations. Perforations in the packaging can delay the time it takes to reach equilibrium, and to prevent excess O_2 buildup, packaging materials must have higher O_2 permeability than carbon dioxide. These constrains often result in uncontrolled O_2 transfer and potential anaerobic conditions (Escobar et al., 2023; Pawde et al., 2023). Additionally, vacuum packaging