Functional Polymeric Plastic for Bakery Products

Subjects: Polymer Science

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Polymeric materials including plastic and paper are commonly used as packaging for bakery products. The incorporation of active substances produces functional polymers that can effectively retain the quality and safety of packaged products. Polymeric materials can be used to produce a variety of package forms such as film, tray, pouch, rigid container and multilayer film.

functional polymer | bakery products | antimicrobial | bakery packaging | active packaging system

1. Introduction

Polymer materials are a vital part of bakery packaging, as seen in **Table 1** and **Table 2**. They play an important role in protecting food, ensuring freshness and modifying barrier properties such as water vapor and oxygen permeability. Polymer materials also influence mechanical properties of tensile strength and elongation at break, while releasing active compounds which inhibit microorganism growth and extend bakery product shelf life. These polymeric materials can be used to make many product forms including film, tray, rigid container, multilayer film and pouch. The active packaging system can involve non-volatile compounds, volatile compounds, edible mixed polymers, coated polymers, active paper and paperboard, oxygen scavenging, and ethanol emitters (**Table 1**).

Table 1. Functional polymers and packaging technology for bakery products.

Functional Packaging	Active Agents	Packaging Form	Type of Bakery	Remarkable Results	References
Non-volatile active compounds	Zinc oxide nanoparticles	Chitosan-carboxymethyl cellulose film	Preservative-free soft sliced wheat bread	➢ Coated films had decreased water vapor permeability, maintained higher moisture content, and increased water activity than the control ➢	[1]

Functional Packaging	Active Agents	Packaging Form	Type of Bakery	Remarkable Results	References
				ZnO 1% and 2% inhibited *Aspergillus niger* and no mold growth on the bread for 15 days	
	Natamycin	Chitosan-natamycin vacuum packaged and spraying	Phyllo pastry	➢ Chitosan and natamycin preserved sensory attributes for 17 days at 4 °C storage and inhibited Enterococci and *Clostridium* spp. up to 18 days	[2]
	Sodium propionate	Polypropylene-sodium propionate film	Bread	➢ Enhanced mechanical and thermal stability, increased hydrophilicity ➢ Films showed antimicrobial activity against both Gram-negative and Gram-positive microbials, and bread showed less spoilage by mold on day 7 during storage	[3]
	Silver nanoparticles	Polyvinyl chloride film	Sliced Bread	➢ Ag-nanoparticles 1% inhibited microorganisms in bread for 15 days of storage at 26 °C ➢ Improved the properties of PVC material	[4]
	ε-poly-L-lysine (ε-PL)	Starch film	Bread	➢ Inhibition against *A. parasiticus* and *P. expansum* and diminished aflatoxin by more than 93.90% after 7 days of testing	[5]

Functional Packaging	Active Agents	Packaging Form	Type of Bakery	Remarkable Results	References
	ZnO nanoparticles	Gelatin- polyethylene film	Sponge cake	➢ Prevented fungal growth for 28 days and maintained cake chemical and organoleptic quality	[6]
	TiO_2	Potato starch film	Sliced bread	➢ 1% TiO_2 coating increased water vapor barrier properties and inhibited the growth of *Bacillus subtilis* and *Escherichia coli*	[7]
	Chitosan	Chitosan-PLA film	Sliced bread	➢ All modified chitosan nanoparticles (CSNPs) showed capacity to inhibit *S. aureus* as high as > 98%, improved elongation at break and maintained oxygen permeation ability in a standard range for food packaging	[8]
	Sulfur quantum dot	Alginate film	Bread	➢ Integrated film improved tensile strength by 18%, UV barrier by 82% and antioxidant activity, while maintaining stiffness and WVP; sulfur-based compounds had antibacterial action against *L. monocytogenes* and *E. coli*, as well as against fungi such *A. niger* and *P. chrysogenum* and delayed the appearance of mold on bread for 14 days	[9]

Functional Packaging	Active Agents	Packaging Form	Type of Bakery	Remarkable Results	References
Volatile active compounds	Sorbate anion	Polypropylene bag	White bread	➢ The coated film retained organoleptic characteristics, moisture analysis, peroxide evolution and mold count on bread for up to 12 days at ambient temperature and inhibited growth of *Escherichia coli*, *Pseudomonas aeruginosa*, *Salmonella enterica subsp*. Arizona, Staphylococcus aureus and *Campylobacter jejuni*	[10]
	Cinnamaldehyde	Gliadin films	Sliced bread	➢ Highly effective against fungal growth for both in vitro and food packing systems; cinnamaldehyde volatility from the solution forming film inhibited activity of *P. expansum* and *A. niger* over 10 days	[11]
	Oregano essential oil	Nonwoven tissue/polypropylene-based sachet	Preservative-free sliced bread	➢ Inhibited the growth of *E. coli*, *Salmonella* Enteritidis and *Penicillium* sp., bread texture increased with storage time, but sachets had no effect; higher OEO concentration imparted unpleasant sensory effects (bitter taste and strong odor)	[12]
	Apricot kernel essential oil	Chitosan film	Sliced bread	➢ The blended film decreased WVP, lower solubility and moisture content enhanced tensile strength and	[13]

Functional Packaging	Active Agents	Packaging Form	Type of Bakery	Remarkable Results	References
				scavenging activity for both H_2O_2 and DPPH ➢ Delayed bacterial growth as *Bacillus subtilis* and *Escherichia coli* protected against fungal growth of sliced bread within the packaging on day 10	
	Grapefruit seed extract/Chitosan	Poly(ε-caprolactone)/chitosan film	Preservative-free bread	➢ Grapefruit seed extract incorporation led to increased pits on the film surface but there was no mold growth on packaged bread with film containing ≥ 1.0 mL/g grapefruit seed extract after 7 days	[14]
	trans-cinnamaldehyde	PLA/PBAT film	Bread	➢ Increased *trans*-cinnamaldehyde contributed to reduced barrier properties and decreased mechanical properties due to plasticization and pores embedded in films ➢ Films with *trans*-cinnamaldehyde from 2% and above effectively inhibited the microbial growth of bacteria and fungi for more than 21 days at 30 °C	[15]
	Eugenol and citral	Corn starch microcapsule sachet	Sliced bread	➢ The EOs-containing sachets were effective in inhibiting the growth of molds and yeasts in	[16]

Functional Packaging	Active Agents	Packaging Form	Type of Bakery	Remarkable Results	References
				media and sliced bread without affecting the sensory properties of bread	
	Thymol	PLA/PBSA film	Preservative-free bread	➢ Effective against fungal growth up to 9 days and improved thermal and barrier properties as well as decreased glass transition temperature, melting temperature and crystallinity ➢ Thymol decreased the permeability of water vapor, oxygen and carbon dioxide, tensile strength and Young's modulus but increased elongation at break	[17]
	Sorbitol/Grapefruit seed extract	Corn starch-chitosan film	Bread	➢ Inhibition against *A. niger* and extended bread shelf life up to 20 days at 25 °C and 59% RH ➢ Had low moisture content, water vapor permeability, solubility, high tensile strength and high antifungal activity	[18]
	Cymbopogon citratus essential oil	Cashew gum-gelatin film	Bread	➢ The incorporated film extended shelf life to 6 days compared with the control at only 3 days	[19]
	Carvacrol	PLA/PBAT film	Preservative-free bread	➢ PLA/PBAT blend ratio controlled the strength, permeability and release behavior of carvacrol	[20]

Functional Packaging	Active Agents	Packaging Form	Type of Bakery	Remarkable Results	References
				➢ Film showed delayed fungal growth and sporulation of *Penicillium* sp. and *Rhizopus* sp. with 2.0–2.3 times increased shelf life	
	Cinnamon oil	Natural rubber pressure-sensitive adhesive patch	Banana cake	➢ NR-PSA/CO patch delayed the growth of bacterial and fungal strains as *Escherichia coli*, *Staphylococcus aureus*, *Aspergillus niger* with extension of the 4-day shelf life	[21]
	Piper betel Linn extract	Poly (vinyl alcohol) film	Sliced bread	➢ Films had high UV blocking and antimicrobial efficiency ➢ Inhibition against bacteria such as *E. coli*, *S. typhimurium*, *S. aureus* and *P. aeruginosa* with 3% of extract concentration and preserved bread quality for 45 days at room temperature	[22]
	Cinnamaldehyde Limonene Eugenol	Fish gelatin-based nanofiber mat	Bread	➢ The incorporated mat had radical scavenging activity, ferric reducing antioxidant power and better encapsulation with the electrospinning method ➢ Inhibited the growth of *E. coli*, *S. aureus* and *A. niger* ➢ There was no fungal spot on bread antimicrobial packing	[23]

Functional Packaging	Active Agents	Packaging Form	Type of Bakery	Remarkable Results	References
	Thyme essential oil	Poly (3-hydroxybutyrate-co-4-hydroxybutyrate) film	White bread	➢ Films containing 30% *v*/*w* of thyme essential oils extended the shelf life of bread up to 5 days depending on visible mold growth observation ➢ Films enhanced both water vapor permeability and elongation at break	[24]
	Schiff base	PLA film	Bread	➢ Delayed growth of fungi on bread slices to day 5 compared with the control at day 3 ➢ Films also killed the bacteria plasma membrane as an inhibition zone	[25]
Functional paper and paperboard	PLA	Coated paperboard	-	➢ PLA-coated paperboards improved water barrier properties through decreasing water vapor permeability and increase in water contact angle	[26]
	Vanillin with dimethyl sulfoxide, ethyl alcohol, and chitosan	Coated paper	-	➢ Each coating successfully inhibited growth of bacteria; however, efficiency varied depending on mixture concentration	[27]
	Wax	Coated paper	Milk cake	➢ Maintained sensory acceptability up to 21 days	[28]

Functional Packaging	Active Agents	Packaging Form	Type of Bakery	Remarkable Results	References
				because the coated paper minimized moisture loss from milk cake	
	Cinnamon essential oil	Coated paper	-	➢ Significantly reduced mold growth by direct migration in packaging and demonstrated resistance to *Rhizopusstolonifer* growth at 4% concentration	[29]
	Ag/TiO_2-SiO_2, Ag/N-TiO_2, or Au/TiO_2	Paper modification	“Pave” bread	➢ Characteristics of the paper including busting, tensile, tearing and breaking resistance decreased as the composite content increased. ➢ Increased whiteness of the paper ➢ Ag/TiO_2-SiO_2-paper and Ag/N-TiO_2-paper extended bread shelf life by more than 2 days compared to unmodified paper in both ambient and refrigeration conditions by offering an efficient control on acidity and yeast and mold growth; Au/TiO_2 had no influence on shelf-life extension indicating that nano-Ag had preservation activity and photoactivity	[30]
	Chitosan	Coating paper	-	➢ Coating increased the glossiness of paper as the chitosan filled surface porosity	[31]

Functional Packaging	Active Agents	Packaging Form	Type of Bakery	Remarkable Results	References
				and improved moisture resistance, mechanical characteristics and flexibility	
	TiO_2 Ag-TiO_2 Ag-TiO_2-zeolite	Bleached paper	Bread	➢ Improved barrier properties such as air permeability, water vapor permeability and reduced grease permeation ➢ Bread packed in Ag-TiO_2 paper had an extended shelf life for 2 more days than the control package based on yeast and mold growth	[32]
	Nano-carbon	Wrapping paper	Brownie cake	➢ Activated carbon-modified bamboo wrapping paper preserved nutrients in food and specifically reduced the level of microbial contamination on brownie cake	[33]
	Blending of alginate, carboxymethyl cellulose, carrageenan, and grapefruit seed extract	Coated paper	Mined fish cake	➢ The biopolymer coating improved water and grease resistance, surface hydrophobicity and tensile properties of paper ➢ Coated paper showed strong antimicrobial activity against *L. monocytogenes* and *E. coli*	[34]
	Chitosan/Ag/TiO_2	Coated paper	Clarified butter	➢ Coated paper had better opacity values, reduced water vapor and oxygen	[35]

Functional Packaging	Active Agents	Packaging Form	Type of Bakery	Remarkable Results	References
				permeabilities and decreased oil permeability ➢ Inhibition against E. coli at 70.36% on an agar plate and 73.28% in butter samples, as well as against yeasts and molds at 77.02% on an agar plate and 79.28% in butter samples ➢ After six months, the peroxide value increased 6.47-fold with P-CH-Ag/TiO_2 compared to uncoated at 36.71-fold	
	Starch, NaCl, Aquaseal	Paper bag	Bread	➢ Relative humidity (RH) of sandwich paper rose to 72% and enhanced bread sensory quality and freshness up to 72 h of storage, extending the shelf life	[36]
	Geraniol	Paper sachet	Sliced bread	➢ PBS/geraniol-10% exhibited inhibition against *Escherichia coli* and *Bacillus cereus* with degradation of white bread with total plate count, yeasts, and mold count on day 42 with an antimicrobial sachet, whereas no fungus was spotted on white bread surface preserved with an antimicrobial sachet for the entire 63-day test period	[37]

Functional Packaging	Active Agents	Packaging Form	Type of Bakery	Remarkable Results	References
Edible and non-edible coating	Schiff base PLA	Kraft paper coating	Bread	➢ Paper properties showed increased smoothness, maintained heat-sealing strength, decreased air porosity value and higher oil-grease resistance	[25]
	Lactobacillus acidophilus	Edible starch/probiotic coating	Bread	➢ Probiotic coating technique obtained microencapsulation of *Lactobacillus acidophilus* and starch-based material coated onto surface of baked breads resulting in better protection on bread crust and sensory acceptability	[38]
	Ag/TiO_2 nanocomposite	HDPE film	White bread	➢ Bread stored in Ag/TiO_2-based packaging inhibited proliferation of yeast/molds, *Bacillus cereus* and *Bacillus subtilis* due to scavenging more water and oxygen molecules in the packaging headspace	[39]
	Potassium sorbate and citric acid	Potato starch, inverted sugar, sucrose coating solution	Mini panettones	➢ Panettones with an edible coating containing both additives showed fungal growth from 40 days, and with 1 g/kg potassium sorbate only, yeast and mold growth were not detected until 48 days ➢ During storage, there was reduced water activity,	[40]

Functional Packaging	Active Agents	Packaging Form	Type of Bakery	Remarkable Results	References
				moisture, elasticity and cohesiveness of panettones with additives, whereas the reverse occurred in the controls	
	Triticale flour	Edible coating and spraying	Muffin	➢ Triticale film coating worked well to prolong the staling process, keeping the fresh muffins softer during 10 days of storage because of delaying crumb-firming kinetics	[41]
	Star anise essential oil and thymol	PP/SAEO/PET/TH/LDPE film	Preservative-free sliced wheat bread	➢ Insect repellent activity sustained the bread for up to 23 days and prevented antimicrobial growth for 14 days; the developed film had low tensile strength and elastic modulus	[42]
	Garlic extract and Bread aroma	Coating on PE film	Preservative-free sliced pan loaf	➢ PE film coated with zein containing 0.5% garlic extract and bread aroma maintained bread free of mold growth for 30 days	[43]
	Lactic acid bacteria	Edible lactic acid bacteria coating	Wheat bread	➢ Coating with *Streptococcus salivarius* subsp. *thermophilus, Lactobacillus delbrueckii* subsp. *Bulgaricus, Lactobacillus acidophilus,* sodium alginate, whey and glycerol had the best protective properties against microbial spoilage	[44]

Table 2. Previous recent patents related to packaging technology for bakery products.

Materials and Components	Packaging Form	Package Conversion Technology	Bakery	Key Technology	Results	References
• Rigid container • Oxygen scavenger	Oxygen detection system	Rigid container with an oxygen detection system	Bakery products	• A rigid container comprising: (a) An oxygen barrier having an	• A rigid container with oxygen	[60]

Materials and Components	Packaging Form	Package Conversion Technology	Bakery	Key Technology	Results	References
and indicator				oxygen transmission rate of no more than 100 cc/m^2/24 h at 25 °C, 0% RH, 1 atm; (b) An oxygen scavenger; (c) An oxygen indicator comprising a luminescent compound wherein the oxygen indicator and oxygen scavenger are substantially shielded by oxygen barriers from environmental air.	barrier properties • Can measure oxygen concentration within the headspace of an assembled package • Indicates oxygen level with luminescent compound	
• PET • Indium tin oxide • Aluminum • Silicone-based	Absorbent sheet	Absorbent structure compression	Bakery products	• A structure having absorbent and microwave interactive properties containing: (a) A polymer film: PET, indium tin oxide and aluminum;	• The absorbent sheet had a non-stick food-contacting surface • The absorbent sheet can be	[61]

Materials and Components	Packaging Form	Package Conversion Technology	Bakery	Key Technology	Results	References
• Chrome complex • Wax				(b) A layer of microwave energy interactive material: indium tin oxide and aluminum; (c) A liquid-absorbing layer; (d) A liquid-impervious material; (e) A release coating overlying silicone-based material, chrome complex, wax, or any combination thereof	incorporated into or used with a tray and formed into a roll of absorbent material comprising at least two overlapping absorbent sheets	
• Paper or paperboard • Polymer emulsion • Pigment	Coated paper or paperboard	Paper or paperboard is coated with a polymer emulsion in one or more coating	Bakery products	• A method of producing a coated recyclable paper or paperboard comprising: (a) Polymer emulsion (acrylic emulsion, or styrenebutadiene emulsion) 70–90% dry weight, pigment (grade clays, titanium	• Coated paper or paperboard had improved barrier properties including water resistance of less than 10 g/m^2, moisture vapor transfer	[62]

Materials and Components	Packaging Form	Package Conversion Technology	Bakery	Key Technology	Results	References
				dioxide, calcium carbonate, barium sulfate, talc, zinc sulfate, aluminum sulfate, calcium oxide, lithopone, zinc sulfide, and mixture thereof) 10–30% dry weight; (b) Applying an aqueous coating layer; (c) Drying the coating; (d) Cooling the coated paper or paperboard	rate of less than 120 g/m^2 and was heat sealable.	
• Bimodal ethylene • 1-butylene • C6–C12-alpha-olefin terpolymer • LDPE • Metallocene-produced	Multilayer film	• Polymerization • Coextruded multilayer film	Frozen food packaging Bakery product	• The multilayer film comprised a core layer and two outer layers (O-1, O-2) (a) Core layer: bimodal ethylene/1-butylene/C6-C12-alpha-olefin terpolymer (b) Outer layer (O-1): bimodal	• The Material had excellent mechanical properties, such as stiffness, toughness, and processability and was suitable for co-extrusion processes	[63]

Materials and Components	Packaging Form	Package Conversion Technology	Bakery	Key Technology	Results	References
				terpolymer, LDPE, or LLDPE, metallocene-produced (c) Outer layer (O-2): LDPE, or LLDPE, metallocene-produced		
• LDPE • EVOH • Acrylic coating • Mustard oil	Coated film	Multilayers include coating	Gluten-free bread	• Antifungal active container comprising a high-barrier co-extruded three-layer film with an outer polymeric layer of LDPE, an intermediate polymeric layer of EVOH and an inner polymeric layer of LDPE which carried or incorporated mustard oil	• Bread samples lasted for 30 days without any fungal growth visible on the surface, whereas the control samples developed a bad taste due to retrogradation of starch	[64]
• Polyolefin • LDPE • PVOH • Carvacrol	Film	Coating film	Sliced bread	• Antifungal packaging comprising a polyolefin with a water-soluble polymer coating as a synergistic mixture of volatile	• PVOH had sufficient coating functional properties, showing high uniformity and adhesion	[65]

delayed the deterioration of phyllo pastry while preserving the basic freshness, look and acceptable sensory properties of the product. Vacuum packing with chitosan and natamycin prolonged the sensory shelf life by 11 days, and microbiological data showed that mesophilic total viable counts, yeasts and molds, psychotropic bacteria, lactic acid bacteria, *Enterobacteriaceae* and enterococci of 1 to 3 log CFU/g on the last day were the most prevalent microorganisms (day 18). Kongkaoroptham et al. (2021) [8] determined that PLA packaging films containing chitosan nanoparticles with polyethylene glycol methyl ether methacrylate (PEGMA) inhibited the growth of natural microorganisms on bread slices. All modified chitosan nanoparticles (CSNPs) showed capacity to inhibit *S. aureus* as high as > 98%, improved elongation at break and oxygen permeation ability in a standard range for food

Materials and Components	Packaging Form	Package Conversion Technology	Bakery	Key Technology	Results	References
• Allyl-isothiocyanate (AITC) [9]	[66][67][68]			natural compounds selected from carvacrol and allyl-isothiocyanate for extending the shelf life of bakery products [69]	to PE, whereas the combination of carvacrol and AITC showed enhanced antifungal activity against the main fungi responsible for damage and spoilage of sliced bread: Aspergillus niger and Penicillium	[9]

alginate- of 18%, affected. nst fungi ays. The obial cell cted with lved the cellular required nery and

gradable at-sealed ean and erol and 2018) [5] investigated the effects of ε-poly-L-lysine (ε-PL) integrated with a starch-based biofilm as an antifungal agent. They found that ε-PL inhibited growth and showed antifungal efficacy against *A. parasiticus* and *P. expansum*. *A. parasiticus*, the developer of aflatoxin, was also controlled by ε-PL incorporation and diminished aflatoxin by more than 93.90% after 7 days of testing. Sliced bread was packaged in film-forming packaging that contained nanodispersed titanium dioxide (TiO_2) by Shulga et al. (2021) [7]. Results revealed that 1% TiO_2 coating increased water vapor barrier properties and inhibited the growth of *Bacillus subtilis* and *Escherichia coli*. Viscusi et al. (2021) [10] studied polypropylene film coated with dispersed anionic clay to host sorbate for white bread packaging. The coated film retained organoleptic characteristics, moisture analysis, peroxide evolution and mold count on the bread for up to 12 days at ambient temperature. Moreover, this active packaging inhibited the growth of *Escherichia coli*, *Pseudomonas aeruginosa*, *Salmonella enterica* subsp. *Arizona*, *Staphylococcus aureus*, and *Campylobacter jejuni*. Braga et al. (2018) [4] combined polyvinyl chloride (PVC) and silver nanoparticles as an active film for bread packaging. The PVC characteristics of the film were enhanced, and 1% Ag-nanoparticles suppressed the growth of microbes in bread stored at 26 °C for 15 days. Diffusion inhibited against *B. subtilis*, *A. niger*, and *F. solani* growth. However, the utilization of nanoparticles for packaging in the food industry requires safety assessments to ensure compliance with regional and global regulations [70].

3. Volatile Active Ingredients

Volatiles and essential oils are compounds that contribute to characteristic flavors and aromas of food products such as fruits, vegetables, herbs, and spices. These compounds mainly comprise terpenes, alcohols, aldehydes, ketones, terpenoids and apocarotenoids [71]. Natural and synthetic volatile compounds have been incorporated into plastic polymers and used for bakery packaging, as shown in **Table 1**. Likewise, for white pan bread and butter cake, Klinmalai et al. (2021) [20] noted how this food, when packed in blown-film extrusion of PLA/PBAT integrated with carvacrol essential oils (0, 2 and 5%), showed delayed *Penicillium* sp. and *Rhizopus* sp. growth and sporulation by film containing 2 and 5% carvacrol, with the shelf life extended by up to 4 days. PLA/PBAT blend films with plasticized carvacrol functionalization prevented growth of mold in baked products. Sharma et al. (2022) [24] studied the bacterial-based biopolymer, poly (3-hydroxybutyrate-co-4-hydroxybutyrate) or P(3HB-co-4HB) incorporating thyme essential oil as active packaging for white bread shelf life extension. Shelf life was extended up to 5 days compared with 1–4 days for the neat film, with improved film elongation at break and water vapor permeability. Passarinho et al. (2014) [12] developed an antimicrobial sachet containing oregano essential oil that acted against yeasts, mold, and *Escherichia coli, Salmonella* Enteritidis and *Penicillium* sp. on sliced bread. During storage, γ-terpenes and φ-cymene inhibited yeast and mold growth on bread slices. Ju et al. (2020) [16] discovered that a mixture of essential oils eugenol and citral (1:1) in corn starch microcapsule sachets decreased molds and yeasts from 100% to 56% at 25 °C and from 90% to 26% at 35 °C of storage conditions. Furthermore, the use of essential oils in sachets had minimal effect on the smell or taste of the bread. Sliced bread packed in LDPE, PP and HDPE bags containing the same essential oil sachets did not develop mold until day 16, 14, and 14, respectively. Mahmood et al. (2022) [23] used electrospinning techniques to produce fish-gelatin-based nanofiber mats embedded with cinnamaldehyde (CEO), limonene (LEO), and eugenol (EEO) at 1, 3, and 5% for bread packaging improvement. Results showed that all essential oils had radical scavenging activity such as CEO = 73.50%, LEO = 51.20%, and EEO = 89.37%, which was the highest at 5% concentration, whereas they also showed ferric-reducing antioxidant power and improved encapsulation with the electrospinning method. They also inhibited the growth of *E. coli*, *S. aureus* and *A. niger* because the gelatin-based mats had good release of essential oils, with no fungal spots on bread antimicrobial packing. Balaguer et al. (2013) [11] developed gliadin films incorporating cinnamaldehyde that were highly effective against fungal growth both in vitro and in food packing systems. Cinnamaldehyde volatility from the solution forming film inhibited the activity of *P. expansum* and *A. niger* over 10 days. Similarly, Fasihi et al. (2019) [72] used the Pickering stabilization method to enrich cinnamon essential oil (CEO) and carboxymethyl cellulose (CMC)–polyvinyl alcohol (PVA) in the solution-forming film and bread coating to increase the anti-UV properties and antifungal properties to prolong bread shelf life. Pickering stabilization impacted CEO by several mechanisms including (i) the generation of a uniform and regular structure of dispersed phase throughout the film matrix leading to increased contact between CEO and fungi, (ii) controlled and regular release of CEO from the film to the outside, which maintained sufficient antimicrobial and antioxidant agents in the headspace, and (iii) protection of CEO from oxidation against undesirable external effects that increased its efficiency as an active compound. PLA and PBAT blend films containing *trans*-cinnamaldehyde were studied by Srisa and Harnkarnsujarit (2020) [15]. Results showed increased water vapor and oxygen permeability because blending of PBAT/PLA reduced the orientation and non-homogeneity of the network formation. Volatility was higher at increased cinnamaldehyde concentration, and different blending ratios of the film released compounds and inhibited the growth of *Aspergillus niger* and *Penicillium* sp., effectively inhibiting microorganism growth for up to 21 days at 30 °C with slightly affected organoleptic properties of cinnamaldehyde taint at 5% concentration. Songtipya et al. (2021) [21] designed a patch that combined natural rubber pressure-sensitive adhesive and cinnamon oil for banana cake packaging.

The NR-PSA/CO patch delayed the growth of bacterial and fungal strains of *Escherichia coli*, *Staphylococcus aureus* and *Aspergillus niger* with further extension of the 4-day shelf life. Cashew gum and gelatin were combined with ferulic acid and lemon grass essential oil by Oliveira et al. (2020) [19] to develop a casting film that showed increased water vapor permeability, decreased solubility and enhanced mechanical characteristics. The incorporated film also prevented the formation of mold for up to 7 days of storage, but the barrier properties of the film were limited, and bread was harder than commercial packaging (PE). Priyadarshi et al. (2018) [13] produced chitosan (CA) film integrated with apricot kernel essential oil (AKEO) for sliced bread packaging. The blended film increased water vapor barrier performance by up to 41%, with a solubility of only 4.76% and a moisture content of 8.33% compared to the control film of 18.42%, and 16.21%, respectively. This film had enhanced tensile strength and scavenging activity with both H_2O_2 and DPPH tests. Moreover, it delayed the bacterial development of *Bacillus subtilis* and *Escherichia coli* and protected sliced bread against fungal growth within the packaging on day 10 with a low concentration ratio of essential oil of 1:0.125 (CA:AKEO) film. Bui et al. (2021) [22] produced a blended film of poly (vinyl alcohol) and *Piper betel* Linn. leaf extract to extend bread shelf life. The film showed high UV blocking and antimicrobial efficiency, with inhibitory efficacy against *E. coli*, *S. typhimurium*, *S. aureus* and *P. aeruginosa* at 3% of extract concentration. Moreover, bread quality was preserved for 45 days at room temperature. Jha (2020) [18] produced bio-nanocomposite films based on corn starch chitosan with plasticizer sorbitol and grapefruit seed extract. The film showed maximum inhibition zone against *A. niger* and extended bread shelf life up to 20 days at 25 ℃ and 59% RH because it had low moisture content, water vapor permeability, solubility, high tensile strength, and high antifungal activity.

Furthermore, based on patents in **Table 2**, Carolina et al. (2022) [65] found that antifungal packaging comprising a polyolefin with a water-soluble polymer coating such as PVOH with a synergistic mixture of volatile natural compounds selected from carvacrol and allyl-isothiocyanate showed enhanced antifungal activity against the main fungi responsible for damage and spoilage of sliced bread such as *A. niger* and *Penicillium*. Bread samples packed in multilayers and coated with a film of LDPE, EVOH, acrylic coating, and mustard oil as an active essential oil showed improved storage for 30 days without any visible fungal growth on the surface of gluten-free bread [64].

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