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.

Keywords: 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 ➢ ZnO 1% and 2% inhibited *Aspergillus niger* and no mold growth on the bread for 15 days	[1]
	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]
	ZnO nanoparticles	**Gelatin- polyethylene film**	**Sponge cake**	➢ Prevented fungal growth for 28 days and maintained cake chemical and organoleptic quality	[6]

Functional Packaging	Active Agents	Packaging Form	Type of Bakery	Remarkable Results	References
	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]
	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]

Functional Packaging	Active Agents	Packaging Form	Type of Bakery	Remarkable Results	References
Volatile active compounds	**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 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	[13]
	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]

Functional Packaging	Active Agents	Packaging Form	Type of Bakery	Remarkable Results	References
	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 media and sliced bread without affecting the sensory properties of bread	[16]
	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]

Functional Packaging	Active Agents	Packaging Form	Type of Bakery	Remarkable Results	References
	Carvacrol	**PLA/PBAT film**	**Preservative-free bread**	➢ PLA/PBAT blend ratio controlled the strength, permeability and release behavior of carvacrol ➢ Film showed delayed fungal growth and sporulation of *Penicillium* sp. and *Rhizopus* sp. with 2.0–2.3 times increased shelf life	[20]
	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]
	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]

Functional Packaging	Active Agents	Packaging Form	Type of Bakery	Remarkable Results	References
	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 Packaging	Active Agents	Packaging Form	Type of Bakery	Remarkable Results	References
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 because the coated paper minimized moisture loss from milk cake	[28]
	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]

Functional Packaging	Active Agents	Packaging Form	Type of Bakery	Remarkable Results	References
	Chitosan	**Coating paper**	**-**	➢ Coating increased the glossiness of paper as the chitosan filled surface porosity and improved moisture resistance, mechanical characteristics and flexibility	[31]
	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]

Functional Packaging	Active Agents	Packaging Form	Type of Bakery	Remarkable Results	References
	Chitosan/Ag/TiO_2	**Coated paper**	**Clarified butter**	➢ Coated paper had better opacity values, reduced water vapor and oxygen 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	[35]
	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]
	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]

Functional Packaging	Active Agents	Packaging Form	Type of Bakery	Remarkable Results	References
Edible and non-edible coating	***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, moisture, elasticity and cohesiveness of panettones with additives, whereas the reverse occurred in the controls	[40]
	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]

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

Functional Packaging Components	Active Agents	Package Conversion Technology	Type of Bakery	Remarkable Results	References
	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 ➢ Incorporation of lactic acid bacteria in a coating containing alginate ensured good viability for 120 h ➢ Coating diminished *A. niger* and *P. chrysogenum* in wheat bread	[44]
	Okra mucilage	Edible okra mucilage gum surface coating	Biscuit	➢ Coated biscuits were preserved from deterioration and microbial spoilage with improved moisture barrier quality	[45]

Materials and Packaging	Packaging Form	Packaging Form	Bakery	Key Technology	Results	References
• Rigid container • Oxygen scavenger and indicator	Oxygen detection system	Rigid container with an oxygen detection system	Bakery products	• A rigid container comprising: (a) An oxygen barrier having an oxygen transmission rate of no more than 100 cc/m²/24 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.	• A rigid container with oxygen barrier properties • Can measure oxygen concentration within the headspace of an assembled package • Indicates oxygen level with luminescent compound	[60]

Active Agents	Packaging Form	Type of Bakery	Remarkable Results	References
Absorber/ Emitter				
Iron-based oxygen absorber	Sachet (FreshPax®)	Cracker	➢ Prevented oxidation and extended the shelf life of military ration crackers packaged in hermetically sealed tin cans for 44 weeks	[46]
Oxygen absorber and ethanol emitter	Sachet	Wheat bread	➢ Ethanol emitter increased the shelf life of bread by up to 24 days based on sensory and microbiological formation, and by up to 30 days when both ethanol emitters and oxygen absorbers were used	[47]
Iron-based oxygen scavenger sachets	Sachet	Sliced wheat bread	➢ Maintained wheat bread quality for up to 7 days of storage	[48]
Ethanol emitter	Sachet	Ciabatta bread	➢ Ethanol emitter extended shelf life to 16 days while maintaining acceptable microbiological quality, whereas the usage of ethanol spray revealed no effect on product sensorial properties	[49]
Oxygen absorber and ethanol emitter	Sachet	Chinese steamed bread	➢ The shelf life of Chinese steamed bread with an oxygen absorber and 1 v% ethanol emitter was extended by up to 11 days	[50]
Oxygen scavenger and ethanol emitter	Pouch	Sponge cake	➢ The oxygen scavenger and ethanol emitter have high barrier packaging and extended shelf life of sponge cake to at least 42 days by delaying lipid oxidation, color change, cake hardening, and microbial growth	[51]

Functional Packaging Materials and Components	Packaging Form	Package Conversion Technology	Bakery	Key Technology	Results	References
• PET • Indium tin oxide • Aluminum • Silicone-based • Chrome complex • Wax	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; (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	• The absorbent sheet had a non-stick food-contacting surface • The absorbent sheet can be incorporated into or used with a tray and formed into a roll of absorbent material comprising at least two overlapping absorbent sheets	[61]

Active Agents	Packaging Form	Type of Bakery	Remarkable Results	References
Oxygen absorber	Nylon/LLDPE/cast polypropylene film	Preservative-free Chinese pastry (kha-nom pia)	➢ Nylon/CPP film retarded microbial growth better than Nylon/LLDPE and extended shelf life up to 25 days ➢ Hardness of crust and firmness of filling decreased during storage ➢ Oxygen absorber effectively inhibited the growth of total microbial count and yeasts and molds, with no visible mold appearing on the pastries	[52]
Iron-based oxygen scavenger	Sachet	Preservative-free white bread	➢ The oxygen scavenging sachet's shelf life lasted for only 4 days ➢ Bread shelf life was prolonged up to 5–7 days with a low initial oxygen level of 5% by volume ➢ When packaging film possesses a high oxygen barrier, an oxygen scavenger is unnecessary	[53]
Vacuum conditioning	Bag	Chinese steamed bread	➢ Thermal–vacuum packaging kept a higher water content and a longer shelf life, and maintained good taste with lower retrogradation rate of the bread	[54]
Iron based oxygen absorbers	Bag	Sourdough sliced bread	➢ The most effective application was the high-capacity oxygen absorber combined with 100% N_2, giving 12 days of a shelf life ➢ With 50% CO_2 + 50% N_2, oxygen conc. increased above 2% due to the trapped O_2 in the pores of bread and had a shelf life of only 3 days ➢ Atmospheric conditions prolonged the shelf life for 6 days	[55]

Functional Packaging Materials and Components	Packaging Form	Package Conversion Technology	Bakery	Key Technology	Results	References
• 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 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	• Coated paper or paperboard had improved barrier properties including water resistance of less than 10 g/m^2, moisture vapor transfer rate of less than 120 g/m^2, and was heat sealable.	[62]

2. Non-Volatile Active Ingredients

Numerous natural and synthetic ingredients have been incorporated into conventional and biodegradable plastic polymers to produce functional polymers for active packaging. The antimicrobial and antioxidant capacities of these functional polymers depend on several factors, e.g., release behavior, interaction between polymers and ingredients, and morphology of the matrices. Recent applications of these functional polymers are shown in Table 1. To increase the safety and quality of mini panettones, Ferreira et al. (2016) [40] modified citric acid and sorbate potassium by incorporating with edible coating solution, either separately or in combination, to increase shelf life of mini panettone by three times compared to the control. Thanakkasaranee et al. (2018) [3] found that a film made of polypropylene and sodium propionate with a concentration range of 0.5 to 5% enhanced mechanical properties and thermal stability, while increasing hydrophilicity, and demonstrated antimicrobial activity against both Gram-negative and Gram-positive microbes. Packed bread also showed less mold spoilage on day 7 of storage. Tsiraki et al. (2018) [2] investigated a combination of chitosan and natamycin as an effective antifungal agent that 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 packaging. Sulfur quantum dots (5.3 nm, aqueous suspension) were used by Riahi et al. (2022) [9] in alginate-based multifunctional films for bread packaging. The integrated film revealed tensile strength improvement of 18%, UV barrier property at 82% and antioxidant activity. Film stiffness and water vapor permeability were unaffected. Sulfur-based compounds had antibacterial action against *L. monocytogenes* and *E. coli*, as well as against fungi such as *A. niger* and *P. chrysogenum*. These delayed the appearance of mold on bread for 14 days. The nanosulfur mechanism disrupted metabolic activities by interacting with the target molecules in the microbial cell wall and altering cellular signals. Furthermore, the reactive oxygen species produced by nanosulfur interacted with and weakened the cell walls of microorganisms, causing cell lysis and death. Another mechanism involved the reaction of sulfur nanoparticles inside bacterial cells under acidic conditions, which interfered with cellular component breakdown or prevented DNA replication. Nanosulfur disrupts enzyme SH capabilities that are required for the metabolism of proteins, lipids, and carbohydrates. This results in the breakdown of cellular machinery and cell death [9].

Bio-based polymers, including starch, PBAT, and PLA, showed a high potential to produce biodegradable sustainable packaging [66][67][68]. Likewise, Huntrakul et al. (2020) [69] successfully combined edible heat-sealed acetylated cassava starch with pea protein isolated sachets, demonstrating effective protection for soybean and olive oil stored for up to three months. Pea protein improves interaction between the polymer and glycerol and effectively prevents humidity-induced film shrinkage. To extend the shelf life of bread, Luz et al. (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,

Materials and Components	Packaging Form	Package Conversion Technology	Bakery	Key Technology	Results	References
• Polyolefin • LDPE • PVOH • Carvacrol • Allyl-isothiocyanate (AITC)	Film	Coating film	Sliced bread	• Antifungal packaging comprising a polyolefin with a water-soluble polymer coating as a synergistic mixture of volatile natural compounds selected from carvacrol and allyl-isothiocyanate for extending the shelf life of bakery products	• PVOH had sufficient coating functional properties, showing high uniformity and adhesion 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*	[65]

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 p-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].

References

1. Noshirvani, N.; Ghanbarzadeh, B.; Mokarram, R.R.; Hashemi, M. Novel active packaging based on carboxymethyl cellulose-chitosan-ZnO NPs nanocomposite for increasing the shelf life of bread. Food Packag. Shelf Life 2017, 11, 106–114.
2. Tsiraki, M.I.; El-Obeid, T.; Yehia, H.M.; Karam, L.; Savvaidis, I.N. Effects of Chitosan and Natamycin on Vacuum-Packaged Phyllo: A Pastry Product. J. Food Prot. 2018, 81, 1982–1987.
3. Thanakkasaranee, S.; Kim, D.; Seo, J. Preparation and characterization of polypropylene/sodium propionate (PP/SP) composite films for bread packaging application. Packag. Technol. Sci. 2018, 31, 221–231.
4. Braga, L.R.; Rangel, E.T.; Suarez, P.A.Z.; Machado, F. Simple synthesis of active films based on PVC incorporated with silver nanoparticles: Evaluation of the thermal, structural and antimicrobial properties. Food Packag. Shelf Life 2018, 15, 122–129.
5. Luz, C.; Calpe, J.; Saladino, F.; Luciano, F.B.; Fernandez-Franzón, M.; Mañes, J.; Meca, G. Antimicrobial packaging based on ε-polylysine bioactive film for the control of mycotoxigenic fungi in vitro and in bread. J. Food Process. Preserv. 2017, 42, e13370.
6. Sahraee, S.; Milani, J.M.; Ghanbarzadeh, B.; Hamishehkar, H. Development of emulsion films based on bovine gelatin-nano chitin-nano ZnO for cake packaging. Food Sci. Nutr. 2020, 8, 1303–1312.
7. Shulga, O.; Chorna, A.; Shulga, S. Antimicrobial biodegradable packaging for sliced bakery. Food Sci. Technol. 2021, 15, 71–78.
8. Kongkaoroptham, P.; Piroonpan, T.; Pasanphan, W. Chitosan nanoparticles based on their derivatives as antioxidant and antibacterial additives for active bioplastic packaging. Carbohydr. Polym. 2021, 257, 117610.
9. Riahi, Z.; Priyadarshi, R.; Rhim, J.-W.; Lotfali, E.; Bagheri, R.; Pircheraghi, G. Alginate-based multifunctional films incorporated with sulfur quantum dots for active packaging applications. Colloids Surf. B Biointerfaces 2022, 215, 112519.
10. Viscusi, G.; Bugatti, V.; Vittoria, V.; Gorrasi, G. Antimicrobial sorbate anchored to layered double hydroxide (LDH) nano-carrier employed as active coating on Polypropylene (PP) packaging: Application to bread stored at ambient temperature. Future Foods 2021, 4, 100063.
11. Balaguer, M.P.; Lopez-Carballo, G.; Catala, R.; Gavara, R.; Hernandez-Munoz, P. Antifungal properties of gliadin films incorporating cinnamaldehyde and application in active food packaging of bread and cheese spread foodstuffs. Int. J. Food Microbiol. 2013, 166, 369–377.
12. Passarinho, A.T.P.; Dias, N.F.; Camilloto, G.P.; Cruz, R.S.; Otoni, C.; Moraes, A.R.F.; Soares, N.D.F.F. Sliced Bread Preservation through Oregano Essential Oil-Containing Sachet. J. Food Process Eng. 2014, 37, 53–62.
13. Priyadarshi, R.; Kumar, B.; Deeba, F.; Kulshreshtha, A.; Negi, Y.S. Chitosan films incorporated with Apricot (Prunus armeniaca) kernel essential oil as active food packaging material. Food Hydrocoll. 2018, 85, 158–166.
14. Wang, K.; Lim, P.N.; Tong, S.Y.; Thian, E.S. Development of grapefruit seed extract-loaded poly(ε-caprolactone)/chitosan films for antimicrobial food packaging. Food Packag. Shelf Life 2019, 22, 100396.
15. Srisa, A.; Harnkarnsujarit, N. Antifungal films from trans-cinnamaldehyde incorporated poly(lactic acid) and poly(butylene adipate-co-terephthalate) for bread packaging. Food Chem. 2020, 333, 127537.
16. Ju, J.; Xie, Y.; Yu, H.; Guo, Y.; Cheng, Y.; Qian, H.; Yao, W. A novel method to prolong bread shelf life: Sachets containing essential oils components. LWT 2020, 131, 109744.
17. Suwanamornlert, P.; Kerddonfag, N.; Sane, A.; Chinsirikul, W.; Zhou, W.; Chonhenchob, V. Poly(lactic acid)/poly(butylene-succinate-co-adipate) (PLA/PBSA) blend films containing thymol as alternative to synthetic preservatives for active packaging of bread. Food Packag. Shelf Life 2020, 25, 100515.
18. Jha, P. Effect of plasticizer and antimicrobial agents on functional properties of bionanocomposite films based on corn starch-chitosan for food packaging applications. Int. J. Biol. Macromol. 2020, 160, 571–582.

19. Oliveira, M.A.; Gonzaga, M.L.; Bastos, M.S.; Magalhães, H.C.; Benevides, S.D.; Furtado, R.F.; Zambelli, R.A.; Garruti, D.S. Packaging with cashew gum/gelatin/essential oil for bread: Release potential of the citral. Food Packag. Shelf Life 2019, 23, 100431.

20. Klinmalai, P.; Srisa, A.; Laorenza, Y.; Katekhong, W.; Harnkarnsujarit, N. Antifungal and plasticization effects of carvacrol in biodegradable poly(lactic acid) and poly(butylene adipate terephthalate) blend films for bakery packaging. LWT 2021, 152, 112356.

21. Songtipya, P.; Sengsuk, T.; Songtipya, L.; Prodpran, T.; Kalkornsurapranee, E. A novel natural rubber pressure sensitive adhesive patch amended with cinnamon oil for preserving bakery product. Food Packag. Shelf Life 2021, 29, 100729.

22. Bui, Q.T.P.; Nguyen, T.T.; Nguyen, L.T.T.; Kim, S.H.; Nguyen, H.N. Development of ecofriendly active food packaging materials based on blends of cross-linked poly (vinyl alcohol) and Piper betle Linn. leaf extract. J. Appl. Polym. Sci. 2021, 138, 50974.

23. Mahmood, K.; Kamilah, H.; Alias, A.K.; Ariffin, F.; Nafchi, A.M. Functionalization of electrospun fish gelatin mats with bioactive agents: Comparative effect on morphology, thermo-mechanical, antioxidant, antimicrobial properties, and bread shelf stability. Food Sci. Nutr. 2021, 10, 584–596.

24. Sharma, P.; Ahuja, A.; Izrayeel, A.M.D.; Samyn, P.; Rastogi, V.K. Physicochemical and thermal characterization of poly (3-hydroxybutyrate-co-4-hydroxybutyrate) films incorporating thyme essential oil for active packaging of white bread. Food Control 2021, 133, 108688.

25. Natesan, S.; Samuel, J.S.; Srinivasan, A.K. Design and development of Schiff's base (SB)-modified polylactic acid (PLA) antimicrobial film for packaging applications. Polym. Bull. 2021, 79, 4627–4646.

26. Rhim, J.-W.; Lee, J.-H.; Hong, S.-I. Increase in water resistance of paperboard by coating with poly(lactide). Packag. Technol. Sci. 2007, 20, 393–402.

27. Rakchoy, S.; Suppakul, P.; Jinkarn, T. Antimicrobial effects of vanillin coated solution for coating paperboard intended for packaging bakery products. Asian J. Food Agro-Ind. 2009, 2, 138–147.

28. Landge, S.N.; Chavan, B.R.; Kulkarni, D.N.; Khedkar, C.D. Effect of packaging materials, storage period and temperature on acceptability of milk cake. J. Dairy. Foods Home Sci. 2009, 28, 20–25.

29. Rodríguez, A.; Nerín, C.; Batlle, R. New Cinnamon-Based Active Paper Packaging against Rhizopusstolonifer Food Spoilage. J. Agric. Food Chem. 2008, 56, 6364–6369.

30. Peter, A.; Mihaly-Cozmuta, L.; Mihaly-Cozmuta, A.; Nicula, C.; Ziemkowska, W.; Basiak, D.; Danciu, V.; Vulpoi, A.; Baia, L.; Falup, A.; et al. Changes in the microbiological and chemical characteristics of white bread during storage in paper packages modified with Ag/TiO2–SiO2, Ag/N–TiO2 or Au/TiO2. Food Chem. 2016, 197, 790–798.

31. Brodnjak, U.V. Influence of ultrasonic treatment on properties of bio-based coated paper. Prog. Org. Coat. 2017, 103, 93–100.

32. Mihaly-Cozmuta, A.; Peter, A.; Craciun, G.; Falup, A.; Mihaly-Cozmuta, L.; Nicula, C.; Vulpoi, A.; Baia, M. Preparation and characterization of active cellulose-based papers modified with TiO2, Ag and zeolite nanocomposites for bread packaging application. Cellulose 2017, 24, 3911–3928.

33. Efiyanti, L.; Hastuti, N.; Indrawan, D.A. Potential Utilization of Nano Carbon Wrapping Paper from Bamboo for Packaging of Brownies Cake. In Proceedings of the 5th International Symposium on Innovative Bio-Production Indonesia, Bogor, Indonesia, 10 October 2018; Research Center for Biotechnology: Bogor, Indonesia, 2018.

34. Shankar, S.; Rhim, J.-W. Antimicrobial wrapping paper coated with a ternary blend of carbohydrates (alginate, carboxymethyl cellulose, carrageenan) and grapefruit seed extract. Carbohydr. Polym. 2018, 196, 92–101.

35. Apjok, R.; Cozmuta, A.M.; Peter, A.; Cozmuta, L.M.; Nicula, C.; Baia, M.; Vulpoi, A. Active packaging based on cellulose-chitosan-Ag/TiO2 nanocomposite for storage of clarified butter. Cellulose 2019, 26, 1923–1946.

36. Mizielińska, M.; Kowalska, U.; Tarnowiecka-Kuca, A.; Dzięcioł, P.; Kozłowska, K.; Bartkowiak, A. The Influence of Multilayer, "Sandwich" Package on the Freshness of Bread after 72 h Storage. Coatings 2020, 10, 1175.

37. Petchwattana, N.; Naknaen, P.; Cha-Aim, K.; Suksri, C.; Sanetuntikul, J. Controlled release antimicrobial sachet prepared from poly(butylene succinate)/geraniol and ethylene vinyl alcohol coated paper for bread shelf-life extension application. Int. J. Biol. Macromol. 2021, 189, 251–261.

38. Altamirano-Fortoul, R.; Moreno-Terrazas, R.; Quezada-Gallo, A.; Rosell, C. Viability of some probiotic coatings in bread and its effect on the crust mechanical properties. Food Hydrocoll. 2012, 29, 166–174.

39. Cozmuta, A.M.; Peter, A.; Cozmuta, L.M.; Nicula, C.; Crisan, L.; Baia, L.; Turila, A. Active Packaging System Based on Ag/TiO2Nanocomposite Used for Extending the Shelf Life of Bread. Chemical and Microbiological Investigations.

Packag. Technol. Sci. 2014, 28, 271–284.

40. Saraiva, L.E.F.; Naponucena, L.D.O.M.; Santos, V.D.S.; Silva, R.P.D.; de Souza, C.O.; Souza, I.E.G.L.; Mamede, M.E.D.O.; Druzian, J.I. Development and application of edible film of active potato starch to extend mini panettone shelf life. LWT 2016, 73, 311–319.
41. Bartolozzo, J.; Borneo, R.; Aguirre, A. Effect of triticale-based edible coating on muffin quality maintenance during storage. J. Food Meas. Charact. 2015, 10, 88–95.
42. Lee, J.; Park, M.A.; Yoon, C.S.; Na, J.H.; Han, J. Characterization and Preservation Performance of Multilayer Film with Insect Repellent and Antimicrobial Activities for Sliced Wheat Bread Packaging. J. Food Sci. 2019, 84, 3194–3203.
43. Heras-Mozos, R.; Muriel-Galet, V.; López-Carballo, G.; Catalá, R.; Hernandez-Munoz, P.; Gavara, R. Development and optimization of antifungal packaging for sliced pan loaf based on garlic as active agent and bread aroma as aroma corrector. Int. J. Food Microbiol. 2018, 290, 42–48.
44. Gregirchak, N.; Stabnikova, O.; Stabnikov, V. Application of Lactic Acid Bacteria for Coating of Wheat Bread to Protect it from Microbial Spoilage. Mater. Veg. 2020, 75, 223–229.
45. Senanayake, C.M.; Nayanakanthi, T.; Siranjiv, P. Development of an Edible Coating from Okra Mucilage to Preserve the Crispiness in Soft Dough Biscuits Upon Storage. Adv. Technol. 2021, 1, 307–320.
46. Berenzon, S.; Saguy, I.S. Oxygen Absorber for Externsion of Crackers Shelf-life. LWT-Food Sci. Technol. 1998, 31, 1–5.
47. Latou, E.; Mexis, S.; Badeka, A.; Kontominas, M. Shelf life extension of sliced wheat bread using either an ethanol emitter or an ethanol emitter combined with an oxygen absorber as alternatives to chemical preservatives. J. Cereal Sci. 2010, 52, 457–465.
48. Muizniece-Brasava, S.; Dukalska, L.; Murniece, I.; Dabina-Bicka, I.; Kozlinskis, E.; Sarvi, S.; Santars, R.; Silvjane, A. Active Packaging Influence on Shelf Life Extension of Sliced Wheat Bread. Int. J. Nutr. Food Eng. 2012, 6, 480–486.
49. Hempel, A.W.; O'Sullivan, M.G.; Papkovsky, D.B.; Kerry, J.P. Use of smart packaging technologies for monitoring and extending the shelf-life quality of modified atmosphere packaged (MAP) bread: Application of intelligent oxygen sensors and active ethanol emitters. Eur. Food Res. Technol. 2013, 237, 117–124.
50. Sheng, Q.; Guo, X.-N.; Zhu, K.-X. The Effect of Active Packaging on Microbial Stability and Quality of Chinese Steamed Bread. Packag. Technol. Sci. 2015, 28, 775–787.
51. Janjarasskul, T.; Tananuwong, K.; Kongpensook, V.; Tantratian, S.; Kokpol, S. Shelf life extension of sponge cake by active packaging as an alternative to direct addition of chemical preservatives. LWT 2016, 72, 166–174.
52. Chuaythong, C.; Rachtanapun, C. Effect of packaging film and oxygen absorber of shelf life extension of Chinese pastry (kha-nom pia). Ital. J. Food Sci. 2017, 30, 51–56.
53. Upasen, S.; Wattanachai, P. Packaging to prolong shelf life of preservative-free white bread. Heliyon 2018, 4, e00802.
54. Liu, Y.; Wang, X.; Li, X.; Ma, Z.; Liu, L.; Hu, X. Chinese steamed bread: Packaging conditions and starch retrogradation. Cereal Chem. 2018, 96, 95–103.
55. Kütahneci, E.; Ayhan, Z. Applications of different oxygen scavenging systems as an active packaging to improve freshness and shelf life of sliced bread. J. Consum. Prot. Food Saf. 2021, 16, 247–259.
56. Promsorn, J.; Harnkarnsujarit, N. Pyrogallol loaded thermoplastic cassava starch based films as bio-based oxygen scavengers. Ind. Crop. Prod. 2022, 186, 115226.
57. Shashikumar, J.N.; Nidoni, U.; Ramachandra, C.T. Influence of active packaging materials on microbial characteristics of wheat flour bread during storage. Pharma Innov. J. 2022, 11, 531–537.
58. Rüegg, N.; Röcker, B.; Yildirim, S. Application of palladium-based oxygen scavenger to extend the mould free shelf life of bakery products. Food Packag. Shelf Life 2021, 31, 100771.
59. Gaikwad, K.K.; Deshmukh, R.K.; Lee, Y.S. Natural phenolic compound coated oxygen scavenging active polyolefin film for preserving quality of fish cake. Biomass Convers. Biorefinery 2022, 1–10.
60. Charles, B.R.; Drew, S.V.; Thomas, K.D.; Marvin, H.R. Oxygen Detection System for a Ridig Container. WO2004/052644A2, 25 November 2004.
61. Scott, M.W.; Terrence, L.P.; William, S.J.; Norman, J.L.; Jonh, F.C.; Tom, W. Absorbent Microwave Interactive Packaging. WO 2006/026345 A2(PCT/US2005/030231), 2006.
62. Sirkku, R.J. Coated Recyclable Paper or Paperboard and Methods for Their Production. WO 2010/052571A2, 10 May 2010.
63. Minna, A.; Gerhard, S. Multilayer Film. WO2012/016938A1, 2012.

64. Carolina, L.D.D.B.A.; Alicia, G.L.M.J.; Abel, G.M.; Jose, V.V.E.; Simon, R.F. Antifungal Polymeric Multilayer Active Packaging with Inner Polymeric Coating Comprising Mustard Oil, Useful for Extending the Shelf Life of Bakery Products for Coeliacs. WO2021207864 (A1), 21 October 2021.
65. Carolina, L.D.D.B.A.; Virginia, M.G.; Simon, R.F.; Abel, G.M.; Alicia, G.L.M.J. Active Antifungal Packaging, Polyolefin with a Water-Soluble Polymer Coating and Synergistic Mixture of Volatile Natural Components, Carvacrol and al-lyl-Isothiocyanate, Useful for Extending the Useful Life of Bakery Products. WO2021068089 (A1), 15 April 2022.
66. Phothisarattana, D.; Wongphan, P.; Promhuad, K.; Promsorn, J.; Harnkarnsujarit, N. Blown film extrusion of PBAT/TPS/ZnO nanocomposites for shelf-life extension of meat packaging. Colloids Surf. B Biointerfaces 2022, 214, 112472.
67. Wadaugsorn, K.; Panrong, T.; Wongphan, P.; Harnkarnsujarit, N. Plasticized hydroxypropyl cassava starch blended PBAT for improved clarity blown films: Morphology and properties. Ind. Crop. Prod. 2021, 176, 114311.
68. Wongphan, P.; Panrong, T.; Harnkarnsujarit, N. Effect of different modified starches on physical, morphological, thermomechanical, barrier and biodegradation properties of cassava starch and polybutylene adipate terephthalate blend film. Food Packag. Shelf Life 2022, 32, 100844.
69. Huntrakul, K.; Yoksan, R.; Sane, A.; Harnkarnsujarit, N. Effects of pea protein on properties of cassava starch edible films produced by blown-film extrusion for oil packaging. Food Packag. Shelf Life 2020, 24, 100480.
70. Phothisarattana, D.; Harnkarnsujarit, N. Migration, aggregations and thermal degradation behaviors of TiO2 and ZnO incorporated PBAT/TPS nanocomposite blown films. Food Packag. Shelf Life 2022, 33, 100901.
71. Bhardwaj, A.; Alam, T.; Talwar, N. Recent advances in active packaging of agri-food products: A review. J. Postharvest Technol. 2019, 7, 33–62.
72. Fasihi, H.; Fasihi, H.; Noshirvani, N.; Noshirvani, N.; Hashemi, M.; Hashemi, M.; Fazilati, M.; Fazilati, M.; Salavati, H.; Salavati, H.; et al. Antioxidant and antimicrobial properties of carbohydrate-based films enriched with cinnamon essential oil by Pickering emulsion method. Food Packag. Shelf Life 2019, 19, 147–154.