

Review Article

Jingxian Jiang, Weiran Zhang, Xijian Yi, Qin Lei, Yuru Liao, Yimin Tan, and Wenxi Yu*

Recent progress in properties and application of antibacterial food packaging materials based on polyvinyl alcohol

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Abstract: Polyvinyl alcohol (PVA) is well-known for its excellent mechanical properties and eco-friendliness in food packaging. Recently, PVA has gained significant attention in research due to its potential as antibacterial substrates. However, because of its high hydrophilicity, practical application of pure PVA film has been limited by low water resistance and rapid bacterial growth in humid conditions. Diverse effective strategies have been developed to decrease hydrophilicity and endow films with antibacterial properties. This review provides an overview of universal antibacterial agents and their functions in PVA-based packaging films. It also introduces the changes in the mechanical and physical properties of PVA-based films after adding antibacterial agents. Additionally, the release behavior of antibacterial agents in PVA-based film materials and their practical applications in the food industry is discussed in fresh food packaging. Biodegradability of PVA-based films is also mentioned, with a promising future for more effective and eco-friendly food packaging materials.

Keywords: PVA, food packaging, antibacterial agent, release behavior, application

Abbreviations

AgNPs	silver nanoparticles
AHSG	<i>alyssum homolocarpum</i> seed gum
BRS	boiled rice starch
CA	citric acid

CD	<i>cynodon dactylon</i>
CEO	cinnamon essential oil
CIN	cinnamaldehyde
CMC	carboxymethylcellulose
CNC	cellulose nanocrystals
CNP	chitosan nanoparticle
CO	clove oil
CS	chitosan
D_p	diffusion coefficient
EB	elongation at break
GD	glutaraldehyde
HNT	halloysite nanotube
LNP	lignin nanoparticles
MC	moisture content
MFC	microfilamentous cellulose
MMT	montmorillonite
mBNCs	modified bacterial nanocelluloses
NAC	<i>N</i> -acetylcysteine
OEO	oregano essential oil
PC	proanthocyanidins
PVA	polyvinyl alcohol
RPE	rose petal extract
ST	starch
TS	tensile strength
WVP	water vapor permeability
XG	xanthan gum
YM	Young's modulus
ZIF-8	zeolite imidazole skeleton-8
4-HR	4-hexylresorcinol

1 Introduction

Food products are extremely susceptible to microbial contamination and spoilage under certain temperature and humidity, which not only leads to the wastage of resources but can also do harm to human health. Food packaging mainly separates the food inside from internal and external environmental factors (such as microorganisms, oxygen,

* **Corresponding author: Wenxi Yu**, School of Packaging and Materials Engineering, Hunan University of Technology, Zhuzhou, 412007, China, e-mail: yuwx@hut.edu.cn

Jingxian Jiang, Weiran Zhang, Xijian Yi, Qin Lei, Yuru Liao, Yimin Tan: School of Packaging and Materials Engineering, Hunan University of Technology, Zhuzhou, 412007, China

temperature, and humidity) to maximize the protection, ensuring the quality and shelf life. With the development of food industry, food safety and quality have become more significant, which could be solved by antimicrobial food packaging to a great extent (1).

Antimicrobial food packaging presents as food packaging composite films with the addition of antimicrobial substances induced or on the surfaces, which are in contact with food to achieve a preservative function for the products inside the packaging (2,3). Among many film materials, polyvinyl alcohol (PVA) has been reported as an excellent candidate as antibacterial packaging polymer material (4,5). PVA is a non-toxic, environmentally friendly polymer film material utilized in food packaging for its good barrier properties, flexibility, transparency, and biodegradability (6). With the addition of appropriate antimicrobial agents and non-toxic plasticizers, PVA-based films can be endowed with improved performance, including mechanical properties, barrier properties, and other packaging physical properties stable with antimicrobial properties at the same time. For example, silver nanoparticles (AgNPs) were added to PVA/chitosan (CS) to prepare food packaging films with excellent mechanical properties. The inclusion of AgNPs reduced water vapor permeability (WVP) and solubility, enhancing food preservation. These composite films, known for their mechanical strength, antibacterial properties, flexibility, and transparency, hold significant potential for fruit storage and transportation (7). In food contact applications, the use of PVA has been defined by European Food Safety Authority (EFSA (2005)) (8). PVA can be used as a covering material for a variety of foods without raising health concerns.

PVA was discovered in 1924 by German chemists Dr. W. O. Herrmann and W. Hachnel. PVA is a water-soluble polymer obtained by the alcoholysis of polyvinyl acetate (9). Its molecular structure is simple and linearly arranged. There are several free hydroxyl groups on PVA molecules, which have strong hydrophilicity. Compared with biopolymers, petroleum-based polymer material PVA is suited for food packaging applications because of its low cost, good physical strength, and excellent gas barrier properties. PVA is recognized as a promising sustainable biopolymer with the potential to replace plastic-based packaging materials due to its biocompatibility, degradability, and excellent film-forming properties. Recently, research on developing antibacterial food packaging films using PVA has been actively conducted. Several antibacterial food packaging films based on PVA have been developed and used for actual food storage. There are varied degrees of increased food shelf life, ranging from PVA-based antimicrobial packaging to packaging such as strawberries (10), fresh beef (11), and cheese (12), among other foodstuff. Therefore,

there is a need to develop a PVA-based film as food packaging with growth potential.

This review provides the recent research progress of PVA-based antimicrobial packaging film materials. In this work, we discuss the preparation and properties of PVA-based film materials with a variety of properties and types of antimicrobial agents in PVA-based films, including mechanical properties, water resistance and antibacterial effect. It also introduces the release behavior of antimicrobial agents in PVA-based film materials and their practical applications in the food industry. For the future development of PVA-based antimicrobial food packaging, the new thought which includes the categories of antimicrobial agents and their antimicrobial effects, the study of antimicrobial agent release, and the development of PVA-based antimicrobial packaging film applications in food packaging should be taken into consideration.

2 Film preparation

The methodology of manufacturing PVA packaging films involves various techniques including solution casting (13), extrusion (14,15), electrostatic spinning (16), coating (17), layer-by-layer assembly (18), hydrogels (19), etc. These different preparation methods have influences on the physical, structural, and mechanical properties of the films (20). Among these preparation techniques, solution casting, coating, and electrostatic spinning are the methods most commonly used due to simple process, low cost, and good controllability.

Solution casting method is a common method of film preparation, based on the principle of dissolving the desired material in a suitable solvent, then pouring the solution into a mold and leaving the solution to dry before peeling off to obtain the film. The advantage of the solution casting method is that a high purity and homogeneous film material is obtained (Figure 1a).

The extrusion method for PVA involves using an extruder machine to process and shape PVA into various forms, such as films, sheets, or filaments. Extrusion is a common manufacturing technique for thermoplastic polymers like PVA (Figure 1b). A twin-screw extruder was used to prepare PVA/starch/montmorillonite (MMT) nanocomposite films for food packaging (14). In the same study, Wang *et al.* added clay to PVA/starch and produced PVA/starch/clay nanocomposite films with high mechanical and barrier properties using extrusion blowing (15).

Electrospinning is currently one of the simplest, most efficient, and cost-effective methods of preparing nanofibers.

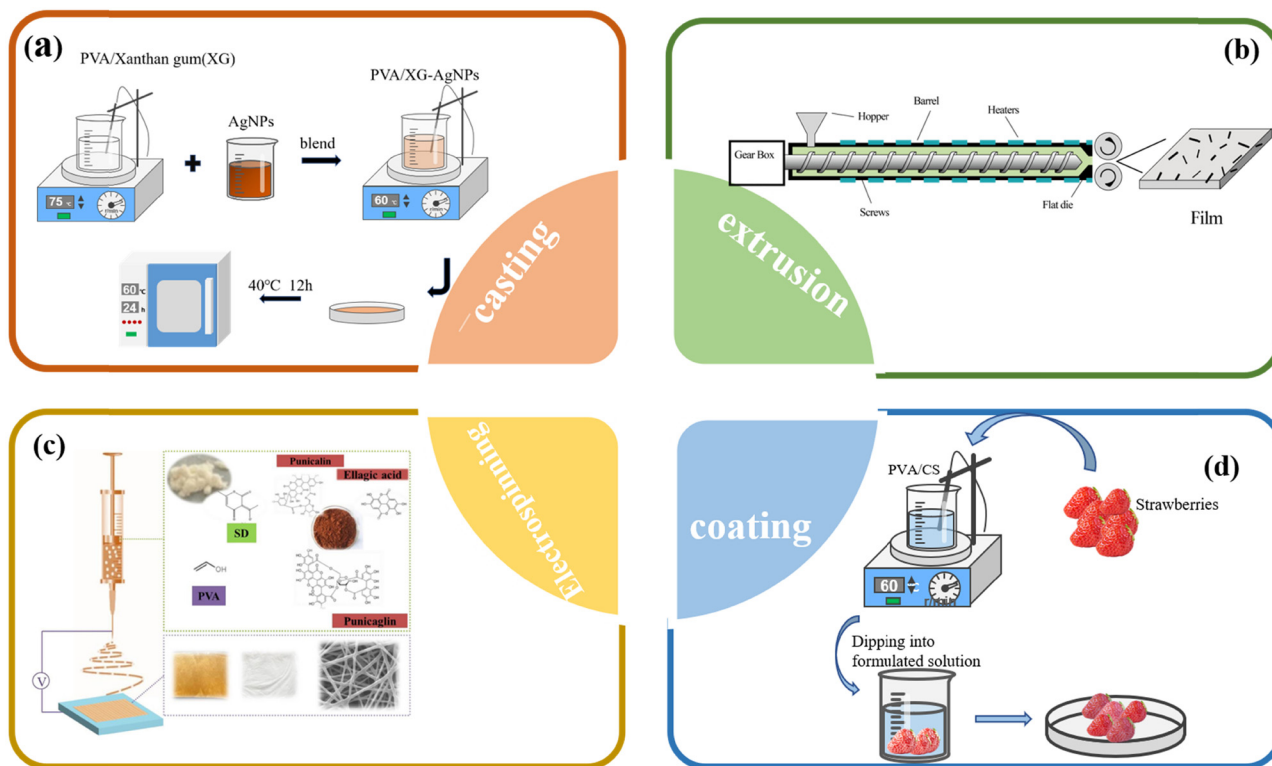


Figure 1: Common preparation methods in PVA based (a) casting, (b) extrusion, (c) electrospinning (31), and (d) coating.

Nanofibers prepared by electrospinning methods have high specific surface area, high loading rate, high porosity, easy modification, and adjustable structures, which allows nanofibers to be used as delivery or controlled release carriers for antimicrobial agents and other active compounds, effectively extending the shelf life of food products (21,22). These unique advantages have promoted the development and application of nanofibers in various fields such as biomaterials, sensing, protective materials, energy, and food packaging. Nanofibers as food packaging materials are a very promising method for the preparation of antimicrobial food packaging films (Figure 1c).

Coating is the process of immersing the packaged material in a film-forming solution to obtain a dense film that evenly wraps the contents. Film coating is a new and simple method of storage and preservation introduced in recent years. The results of film coating depend on the choice of film materials and the method of film formation (Figure 1d). For example, strawberries coated with the edible PVA/cashew gum polysaccharide (23).

In these methods, various other substances such as starch (24), CS (16), soy protein (25), carboxymethyl cellulose (26), and β -cyclodextrin (27) can be blended with PVA to fabricate food film substrates. To improve the barrier properties, and mechanical properties of the film, plasticizers

such as glycerol, sorbitol, and citric acid (CA) are usually added to the film solution. Additionally, cross-linking agents such as glutaraldehyde (GD) (28), boric acid (29), and glyoxal (30) are used to further enhance the film's properties. GD was used to crosslink PVA composite films containing cellulose nanocrystals (CNC) and lignin nanoparticles (LNPs) (28). Due to the powerful interactions between LNP, CNC, and PVA in the presence of GD, the thermodynamic study revealed better thermal stability. Meanwhile, the tensile strength (TS) of PVA/CNC/LNP increased from 26 for neat PVA to 35.4 MPa, and PVA/CNC/LNP films crosslinked by GD showed excellent barrier ability to the WVP. Furthermore, the selection and addition of antimicrobial agents play crucial roles in the performance and effectiveness of PVA-based film materials. It is essential to consider various factors such as compatibility with PVA, dispersibility, stability, and release when choosing the appropriate antimicrobial agents.

3 Properties of PVA-based film

PVA is a water-soluble polymer synthesized by polymerization alcoholysis of vinyl acetate (9). PVA molecules contain

a substantial hydrogen bonding, tight structure, with good mechanical properties. While there are also a large number of hydrophilic hydroxyl groups, resulting in the water absorption rupture of PVA film when packaging products with high water content (Figure 2). Thus, it is necessary to add additives and active substances to enhance the application of PVA composite film (32). Moreover, the addition of antimicrobial agents not only endues the film antibacterial properties but also certain mechanical properties and additional barrier properties (20,33,34).

3.1 Mechanical properties

Mechanical properties play important roles in food packaging, which ensure the food quality by influencing the resistance to deformation or breakage. The elongation at break (EB) and TS show the toughness and strength of the film, respectively. Measurement of the mechanical properties of PVA-based films can evaluate the feasibility of their practical use as food packaging materials. As shown in Table 1, mechanical properties are remarkable parameters for developing food packaging materials combined with different antimicrobials.

Mechanical strength of the PVA film was highly improved after the incorporation of 2.5 wt% calcium propionate (35) compared with pure PVA film (31). This may be due to the uniform distribution of calcium propionate in the film and the interaction with PVA molecular chains, which enhanced the strength and toughness of the film. Among all the films prepared, the PVA/carboxymethyl CS composite film with CA showed highly improved mechanical properties (36). In another study, the EB of PVA/CS films was $223.89 \pm 7.50\%$, and it increased to $281.10 \pm 24.69\%$ upon the addition of modified bacterial nanocelluloses (mBNCs) and 4-hexylresorcinol (4-HR) (11). EB raises as the concentration of mBNCs and 4-HR increases, but the composite films show a decrease in TS. Likewise, the solution casting method for the preparation of PVA films containing cinnamic and ferulic acids showed enhanced TS and elastic modulus compared to the pure PVA films, and EB was significantly enhanced for the films after thermo-processing. Moreover, the solution

casting method was used to prepare PVA films containing cinnamic and ferulic acids, which demonstrated enhanced TS and elastic modulus compared to pure PVA films. Furthermore, EB was significantly improved for the films after thermo-processing. In addition, the TS of the films increased, while the EB tended to decrease with the addition of piperic acid, and the results indicated the suitability of the composite films for food packaging (37). The TS of composite films prepared from PVA/ST was increased up to 31.83 ± 0.17 MPa compared to neat films, which is 18.05 ± 0.04 MPa, depending on the nanoparticle filler concentration (38).

3.2 WVP

WVP is the main parameter to evaluate water transfer between the internal and external atmosphere of food packaging, which is considered to be an important parameter of food packaging materials. The difference between the relative humidity in the external environment and the water activity of the food itself can lead to moisture or dehydration during the storage of food, so it is necessary to explore the effect of WVP of the film on food packaging. The WVP of PVA-based films containing different antimicrobial agents are shown in Table 1.

The moisture content (MC) and WVP of the PVA/CS composite films were improved with the addition of mBNCs and 4-HR, while water solubility was reduced (12). The WVP and oxygen permeability of the PVA films containing cinnamic and ferulic acids were significantly reduced (39). The incorporation of AgNPs decreased the WVP of the PVA films, which is in line with that reported in previous studies, suggesting that the addition of nanoparticles enhances the vapor barrier properties of the films (40). This is also consistent with another study which found that the WVP of PVA/CS nanocomposite films incorporated with TiO_2 were observed to decrease the WVP property ranging from 6.57 to $4.36 \times 10^{-12} \text{ g}\cdot\text{cm}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$ (41). The addition of CA into PVA/carboxymethyl CS composite films can induce a decrease in WVP values (36). The presence of nanoparticles reduced the intermolecular spacing within the films, thus reducing the WVP through the film (42). Another study also confirmed that the incorporation of CA into the PVA for the fabrication of food packaging films can decrease the WVP up to $1.28 \times 10^{-14} \text{ g}\cdot\text{m}^{-1}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$ compared to control composites without CA having WVP of $4.02 \times 10^{-14} \text{ g}\cdot\text{m}^{-1}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$ (43).

According to Chen *et al.* (44), the WVP significantly decreased from 3.13×10^{-14} to $1.43 \times 10^{-14} \text{ g}\cdot(\text{cm}\cdot\text{s}\cdot\text{Pa})^{-1}$ for PVA/ST film with the addition of clove oil (CO). The addition

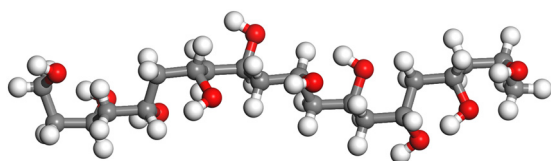


Figure 2: PVA chain.

Table 1: Effect of PVA-based packaging with different antimicrobial agents on microbial inhibition and the performance of film materials

Film substrates	Antimicrobial agent	Tested microorganisms	Mechanical property	Antimicrobial film diameter (mm)	Max. diameter of inhibition circle (mm)	Ref.
PVA	Calcium propionate + ethylparaben	<i>E. coli</i> , <i>S. aureus</i>	TST, EBI, WVP↑	6	8.5, 13.1	(98)
PVA	Quaternary ammonium salt of CS	<i>E. coli</i> , <i>S. aureus</i>	TST, EBI, WVP↑	6	13.4, 13.3	(98)
PVA	Quaternary ammonium salt of CS + tea polyphenols	<i>E. coli</i> , <i>S. aureus</i>	TST, EBI, WVP↑	6	14.1, 10.5	(98)
PVA	Tea polyphenols	<i>E. coli</i> , <i>S. aureus</i>	TST, EBI, WVP↑	6	14.4, 12.3	(98)
PVA	Calcium propionate	<i>Bacillus cereus</i> , <i>E. coli</i>	TST, EBI, WVP↑	6	7.5, 6.8	(35)
PVA/carboxymethyl CS	CA	<i>S. aureus</i>	TST, YMT, WVP↓	8	12	(100)
PVA	Piperic acid	<i>Fusarium solani</i> , <i>Penicillium</i> , <i>Aspergillus</i>	TST, EBI, WVP↑, OP↑	20	5.3, 20.2, 50.5	(37)
PVA	AgNPs	<i>E. coli</i> , <i>S. aureus</i>	TST	6	14, 13.6	(62)
PVA	AgNPs	<i>Aspergillus niger</i>	TST, EBI, WVP↓	10	20.1	(40)
PVA	AgNPs	<i>P. fluorescens</i>	TST	10	10.9	(63)
PVA/CS	TiO ₂	<i>E. coli</i> , <i>Salmonella enterica</i> , <i>L. monocytogenes</i> , <i>Staphylococcus aureus</i>	TST, EBT, WVP↓, OP↓	6	36.0, 47.5, 51.5, 26.0	(41)
PVA/CS	ZnO-SiO ₂	<i>E. coli</i> , <i>S. aureus</i>	TST, WVP↓, OP↓	10	35.0, 37.0	(72)
PVA (single coated paper)	<i>Thymus vulgaris</i> L. essential oil + <i>Ocimum gratissimum</i> L. essential oil	<i>Aspergillus cinerea</i> , <i>Rhizopus</i> , <i>Streptospora actinomyces</i> , <i>Penicillium</i>	NA	20	25.0, 27.0, 14.0, 21.0	(85)
PVA (Double coated paper)	<i>Thymus vulgaris</i> L. essential oil + <i>Ocimum gratissimum</i> L. essential oil	<i>Aspergillus cinerea</i> , <i>Rhizopus</i> , <i>Streptospora actinomyces</i> , <i>Penicillium</i>	NA	20	44.0, 46.0, 25.0, 48.0	(85)
PVA/starch	CIN	<i>S. putrefaciens</i>	TST, EBT, WVP↓, OP↑	6	10.8	(87)
PVA/starch/MFC	CIN	<i>S. putrefaciens</i>	TST, EBT, WVP↓, OP↑	6	10.2	(87)
PVA/AHSG	Nisin	<i>L. innocua</i>	WVP↓	7-9	13.3	(96)
PVA	CA	<i>E. coli</i> , <i>S. aureus</i>	WVP↓	7	20.0, 13.0	(43)
PVA/β-cyclodextrin	CEO	<i>L. monocytogenes</i> , <i>S. enteritidis</i>	NA	6	13.6, 11.4	(99)
PVA/β-cyclodextrin	CEO	<i>A. niger</i> , <i>Penicillium</i>	NA	6	19.1, 40.6	(99)
PVA/β-cyclodextrin	CEO + lysozyme	<i>A. niger</i> , <i>Penicillium</i>	NA	6	15.2, 13.7	(99)
PVA/β-cyclodextrin	CEO + lysozyme	<i>A. niger</i> , <i>Penicillium</i>	NA	6	19.2, 40.7	(99)
PVA	Lysozyme	<i>L. monocytogenes</i> , <i>S. enteritidis</i>	NA	6	15.1, 7.9	(99)
PVA/corn starch	Natamycin	<i>Aspergillus niger</i> , <i>penicillium</i> , yeast	TST, EBI	15	31.2, 28.5, 23.2	(100)
PVA	CNC	<i>Colletotrichum gloeosporioides</i> , <i>Lasioidiplodia theobromae</i>	TST, EBT	20	34.0, 28.0	(101)
PVA	Chitosan nanoparticle (CNP)	<i>Colletotrichum gloeosporioides</i> , <i>Lasioidiplodia theobromae</i>	TST, EBT	20	25.7, 25.0	(101)
PVA	CNC + CNP	<i>Colletotrichum gloeosporioides</i> , <i>Lasioidiplodia theobromae</i>	TST, EBT	20	27.8, 27.2	(101)
PVA	Poría coco	<i>E. coli</i> , <i>S. aureus</i> , <i>Bacillus subtilis</i>	TST, EBT	10	16.8, 14.5, 12.0	(102)

of CO would structure a zigzag route at the hydrophilic hydrophobic interface, which decreased the diffusion capability of WVP.

3.3 Transparency

The transparency of PVA-based food packaging is of great importance. Transparent PVA-based packaging offers several benefits, including expanded product visibility, increased safety assurance, improved food quality assessment, and a platform for promoting eco-friendly materials and sustainability initiatives by manufacturers. PVA-based transparent packaging can contain environmentally friendly packaging materials and promote sustainable development efforts of manufacturers.

The addition of 2–6 wt% of CNC to PVA improved interfacial interactions, yielding clear micro-structures. The bio-nanocomposite films maintained high transparency (90% transmittance in UV-vis), indicating good CNC dispersion. These eco-friendly composites are promising for food packaging (45). The light transmittance of the PVA/starch/glycerol/halloysite nanotube (HNT) nanocomposite films decreased linearly by 26.90% as the HNT content increased from 0 to 5 wt%, making them suitable for sustainable food packaging, especially for lipophilic and acidic foods (46). The transparency of PVA-based films decreased with higher loading of TiO₂ and MMT nanoparticles in the nanocomposite films prepared using the solution casting method (47). Pure PVA had better light transmittance than PVA/xanthan gum (XG) composite films, suggesting better transmittance in pure PVA due to the composite film's internal structure affecting light transmission and scattering. It is worth mentioning that all samples exhibited over 85% transmittance, demonstrating good uniformity and transparency (48).

In summary, the transparency of PVA-based food packaging not only meets practical goals such as product visibility and safety, but also plays a key role in marketing, branding, sustainability, and overall consumer satisfaction. This meets consumers' desire for transparency and helps build trust in food products and their packaging.

4 Types of antimicrobial agents and their antimicrobial effects

There are diverse antibacterial agents and some of them have significant effects on *Escherichia coli* (*E. coli*), *Staphylococcus aureus* (*S. aureus*), etc. Conventional antibacterial agents can

be classified into three categories: organic antibacterial agents, inorganic antibacterial agents, and natural antibacterial agents. PVA-based antibacterial packaging typically involves a range of organic acids and salts, plant essential oils or their extracts, enzymes, CS, bacteriocins, and inorganic metal antibacterial agents to obtain antibacterial properties.

4.1 Organic antimicrobial agents

Organic antimicrobial agents largely disrupt cell membranes by releasing antimicrobial substances, which causes sulfhydryl acidification and protein denaturation. It blocks DNA synthesis and cellular metabolism and inhibits the reproduction of bacteria and fungi. The antimicrobial agent not only has a superior antimicrobial ability, abundant source, fast bactericidal speed, wide antibacterial range, and good bactericidal effect but also has poor safety, poor stability, common drug resistance, and relatively weak effect on bacteria (49). The organic antibacterial agents typically added in PVA substrates includes potassium sorbate (50), calcium propionate (35), CA (36), sodium lactate (51), and caffeic acid (52).

The film material of PVA with calcium propionate additive of 2.5 wt% produced certain antimicrobial effects on *Bacillus cereus*, *E. coli*, and *Aspergillus oryzae* (35). CA was discovered to have a substantial inhibitory impact on *S. aureus* at a certain dose in PVA/carboxymethyl CS packaging film (36). A study (52) of solid caffeic acid and β - or γ -cyclodextrin inclusions embedded in PVA nanofibers demonstrated high antibacterial activity against both *E. coli* and *S. aureus*. This study used a sodium lactate-loaded PVA/CS/MMT composite film with excellent inhibition activity against *E. coli*. PVA/piperic acid composite films demonstrated strong antimicrobial action against the *Fusarium solani*, *Penicillium*, and *Aspergillus foodborne pathogens* (33). Food can be shielded from browning and exposed to less UV light thanks to antibacterial films containing PVA/N-acetylcysteine (NAC) ability (45). At 85°C and when exposed to moisture, the released NAC significantly slowed the growth of *S. aureus* and *E. coli*.

Meanwhile there are some lipid compounds, halides, and organometallics added as antibacterial agents in food packaging film materials. The growth of four major food pathogens, including *Campylobacter jejuni*, *E. coli*, *Listeria monocytogenes* (*L. monocytogenes*), and *Salmonella typhimurium*, was inhibited by PVA/CS conjugate films (34), and the best antibacterial effect was seen for films with 5% and 10% ethyl lauroyl arginate content. Additionally, food packaging films with strong antibacterial activity and severe sensitivity to *E. coli* and *L. monocytogenes* were made using PVA

grafted ethylene radical alteration and N-haloamines (53). The zeolite imidazole skeleton-8 (ZIF-8) metal-organic skeleton, along with PVA and quaternary ammonium CS, constructs ZIF-8 films. These composite films possess high bacterial filtering capabilities and demonstrate effectiveness in eradicating both *E. coli* and *S. aureus* (54).

4.2 Inorganic antimicrobial agent

Inorganic antimicrobial agents are broadly used in medical materials, agricultural antimicrobial agents, optical materials, and semiconductor materials. It is one of the top research hotspots for antibacterial materials because of its high antibacterial efficiency and durability, low drug resistance, high safety, and UV-barrier properties. Pursuant to the inverse antibacterial mechanism, inorganic antibacterial agents can be categorized into two types: dissolution type and photocatalytic type. The soluble type is loaded with inorganic carriers such as Ag, Cu, and Zn; the photocatalytic type consists of inorganic oxides such as TiO_2 and ZnO, which have relatively high heat resistance, but have bactericidal effects only in the presence of UV light, oxygen, or water. A wide range of antibacterial agents have been reported in the literature as metal nanoparticles (e.g., Ag, Cu, etc.) (55,56), metal oxide nanoparticles (e.g., TiO_2 , ZnO, CuO, Cu_2O , etc.) (54,57–59).

Inorganic metal nanometer antimicrobial agents treated with nanotechnology have a wide range of highly effective antibacterial bactericidal properties, AgNPs are most widely used among them. PVA-based film materials enriched with AgNPs exhibited significant inhibition of *Salmonella typhi* (60), *E. coli* (53), *S. aureus* (61), and *Aspergillus niger* (40). *Salmonella typhi* and *S. aureus* growth was greatly slowed down by PVA/boiled rice starch (BRS)/AgNPs composite films. In comparison with the control PVA/BRS composite films, the nanocomposite showed improved mechanical and optical properties and had a lower water sensitivity. Moreover, PVA/BRS/AgNP films function better against environmental microbes (60). Pure PVA film containing AgNPs showed significant inhibition of *Aspergillus niger* (40). In the alternative, the addition of nanocellulose also enhanced the inhibition of *E. coli* and *S. aureus* by PVA/AgNPs film materials (62).

Plant extracts majorly contain polysaccharides, polyphenols, alkaloids, aldehydes, proteins and amino acids, which can be used as reducing and stabilizing agents for the biosynthesis of AgNPs by reaction with silver nitrate solution, and have significant effects on the biosynthesis of AgNPs. AgNPs synthesized by the reaction of *cynodon dactylon* (CD) leaves extract with silver nitrate were added to

PVA film-forming solution to prepare antibacterial film materials, which showed significant inhibition of *Pseudomonas fluorescens*. The addition of biosorbed-AgNPs improved the physical and antibacterial properties of the films (63). Ginger extract was reacted with silver nitrate to synthesize AgNPs and the prepared PVA/MMT/AgNPs composite film materials showed strong antibacterial effect against pathogenic bacteria *S. typhimurium* and *S. aureus* (64). The significant increase in TS of the nanocomposite films could be attributed to the high compatibility between nanofillers (MMT and AgNPs) and PVA. The effective dispersion of nanofillers in the polymer matrix helps to control the stress transfer at the interface between the filler and matrix, which ultimately leads to the increase in TS of the nanocomposites. The increase in Young's modulus (YM) of the nanocomposite blended films may be due to the interaction between the filler and matrix, resulting in the limitation of matrix motion and stiffness. On the other hand, the EB of pure PVA films was found to decrease after blending with ginger extract, MMT, and AgNPs. Similarly, AgNPs synthesized by the reaction of *capparis zeylanica* leaf extract with silver nitrate were added to PVA/polyethylene glycol film-forming solution to make films, and the composite films showed better inhibition of *Pseudomonas aeruginosa* (65). Other AgNPs such as periwinkle (59,66), sodium citrate dihydrate (67), oregano essential oil (OEO) (42), *morinda citrifolia* leaf extract (68), CS (69), and glucose (70) synthesized by reaction with silver nitrate were added to PVA film-forming solution to prepare antibacterial film materials.

The metal oxides that have been reported for antibacterial packaging of PVA substrates are TiO_2 , ZnO, CuO, Cu_2O , etc. *E. coli*, *Salmonella enterica*, *L. monocytogenes*, and *S. aureus* were all significantly inhibited by PVA/CS composite films containing TiO_2 , and the inhibition of the first three bacteria by the composite film materials increased with the increase in the TiO_2 concentration (41). Other studies discovered that film materials made of PVA/corn starch and PVA/carboxymethylcellulose (CMC) that contained ZnO nanoparticles both demonstrated strong antibacterial activity against *E. coli* and *S. aureus* (24,71), while PVA/corn starch film with outstanding UV-shielding capability meanwhile retaining highly optical transparency (approximately 90%) (24).

The antibacterial activity of PVA/CS was further enhanced by the addition of $\text{Cu}_2\text{O}@ \text{NCs}$, with 2% $\text{Cu}_2\text{O}@ \text{NCs}$ achieving 72% and 66% inhibition against *S. aureus* and *E. coli*, respectively (59). Similarly, it was found that the introduction of $\text{CuO}@ \text{ZIF-8}$ nanoparticles into the PVA/quaternary ammonium CS as the inner layer exhibited better antibacterial ability against *S. aureus* and *E. coli* (54). Meanwhile, the films provided low WVP and strong UV-barrier ability. There were also PVA/CS/ZnO- SiO_2 composite film materials made by

adding different ratios (0.50%, 1.0%, 3.0%, and 5.0%) of ZnO-SiO₂ (72) to the PVA/CS mixture, which exhibited better antibacterial properties against *E. coli* and *S. aureus*. The addition of ZnO-SiO₂ nanocomposites substantially reduced the WVP of the films, with values of 954.19, 890.38, 890.38, and 500.60 g·(m²·day)⁻¹, respectively, compared to 980.86 g·(m²·day)⁻¹ for PVA/CS films (72).

4.2.1 Toxicity of the inorganic antibacterial agent

Ensuring the absence of toxicity is crucial in food packaging. Consideration of the toxicity of the inorganic antibacterial agent is of utmost importance, as it necessitates a comprehensive assessment and evaluation to ensure the safety and well-being of individuals and the environment when these particles are employed or present in food packaging.

Toxicity testing on the PVA/CS blend and various PVA/CS/ZnO-SiO₂ nanocomposites films with different ZnO-SiO₂ ratios demonstrated no toxicity towards the marine luminescent bacterium *Vibrio fischeri* (72). The cell viability of NIH 3T3 cells treated with PVA/quaternary ammonium CS composite films remained above 90%, and this trend persisted regardless of the concentration of CuO@ZIF-8 NPs (54).

4.3 Natural antimicrobial agent

Natural antimicrobial agents can be grouped into three main categories in terms of their main sources: natural antimicrobial agents of plant origin, natural antimicrobial agents of microbial origin (73), bacteriocins (*nisin*, *Lantibiotics*, *antibiotics*, etc.) (74–76), biopolymers (CS) (77,78), and enzymes (lysozyme) (79). Section 4.3.1 focuses on the more studied plant-derived antimicrobial agent, streptococin lactate.

4.3.1 Antimicrobial agents of plant origin

Natural antimicrobial agents of plant origin are predominantly extracted from natural substances (10,20,23,80,81), such as plant extracts (essential oils or extracts) (74,82). The essential oils spiced in PVA-based film materials are mainly lauric essential oil, iterative essential oil, OEO, cinnamon essential oil (CEO), thyme essential oil, and clove essential oil (44). The electrostatic spinning method was used for preparing PVA film materials containing essential oils of laurel and iterative. These materials significantly reduced the number of *L. monocytogenes* during refrigeration (20).

The combined film materials prepared by adding emulsifiers made of OEO or CEO to PVA film materials showed better inhibition of both *E. coli* and *S. aureus*, with *E. coli* being more sensitive to CEO (83). The combined film materials made of PVA and clove essential oil had better antifungal (melon fruit rot) activity and lower MC and film solubility, which indicated their suitability for modified atmosphere packaging applications (84). In PVA-based coated papers, addition of thyme essential oil and clove basil essential oil showed good antimicrobial properties against *gray mold*, *root mold*, *cross-streptomyces*, and *penicillium* (85).

Cinnamaldehyde (CIN) is a natural plant extract that has the ability to inhibit the growth of bacteria and fungi (84,86). CIN-encapsulated PVA/granular gum nanofiber films exhibited excellent antibacterial properties against *S. aureus* and *Pseudomonas aeruginosa* (22). Addition of CIN to PVA/maize starch/microfilamentous cellulose (MFC) composite film materials by using the co-blending technique created to considerably suppress the growth of *S. putrefaciens* (87).

Sodium trimetaphosphate and boric acid (88) were used to double cross-link the PVA/potato starch polymer, and further addition of anthocyanin and limonene prepared composite film materials could achieve both colorimetric indication and antimicrobial activity, especially satisfactory antimicrobial activity against three microorganisms, *Bacillus subtilis*, *Aspergillus niger*, and *S. aureus*. It was found (89) that PVA packaging film containing 20% tea polyphenols had a 95.5 ± 4.2% and 91.8 ± 3.7% inhibition against *S. aureus* and *E. coli*. It should be mentioned that the film treated with ultrasound had better bacterial inhibition. It was also found that the PVA/tapioca starch composite films with the addition of red pitaya (*Hylocereus polyrhizus*) peel extract (betaine) had antibacterial effects on *S. aureus*, *L. monocytogenes*, *E. coli*, and *Salmonella*, with stronger inhibition of the first two microorganisms (90). The PVA/tea polyphenol electrostatic spinning nanofiber membrane also showed inhibition of *E. coli* and *S. aureus* with a maximum inhibition activity up to 82.48% and 86.25% (91). The PVA/tannin composite films containing different tannin contents showed good antibacterial ability against *E. coli*, *S. aureus*, and *S. epidermidis*, and the antibacterial activity increased with the increase in tannin content (92). The PVA/algae biomass cellulose nanocrystal composite film containing basil leaf extract had good antibacterial properties, and the addition of 20% basil leaf extract significantly inhibited *Bacillus cereus* (93). The antibacterial films were prepared by impregnating curcumin emulsion with PVA and corn starch as substrates, and it was found that curcumin significantly inhibited *S. aureus* and *Bacillus subtilis*, while *E. coli* was less affected by curcumin (94).

4.3.2 Antimicrobials of microbial origin

Nisin as a natural food preservative, has an inhibitory effect mainly against most Gram-positive bacteria and their budding embrace, addition of nisin to PVA/CS effectively inhibited *S. aureus* colonization (95), and addition of *Alyssum homolocarpum* seed gum (AHSG) to PVA/CS nisin effectively inhibited the multiplication of harmless *L. monocytogenes* (96). Lipopeptides, a class of non-toxic and highly stable antimicrobial agents of microbial origin, can cause damage to microbial cell membranes through electrostatic interactions with negatively charged membranes. The lipopeptides were cultured, isolated, and purified from *bacillus sp.* for column purification and added to a composite film material of PVA/MMT for excellent inhibition of *Salmonella typhimurium* (97).

In a nutshell, PVA-based antimicrobial food packaging film materials have a notable inhibitory effect on the growth of food microorganisms. Table 1 summarizes the

inhibition effect of PVA-based packaging containing different antimicrobial agents on microorganisms such as *E. coli*, *S. aureus*, *B. cereus*, *Streptococcus spoilage*, and the effect of antimicrobial agent addition on the film performance in recent years.

5 Study on the release of antibacterial agent in PVA-based antibacterial film

The process and mechanism of antimicrobial agent release is crucial for assessing the effectiveness and safety of PVA-based antimicrobial packaging materials, and in practical applications, the focus is usually on the antimicrobial agent exerting antimicrobial/antibacterial effects in long-term use, thus ensuring food quality. The key factor determining

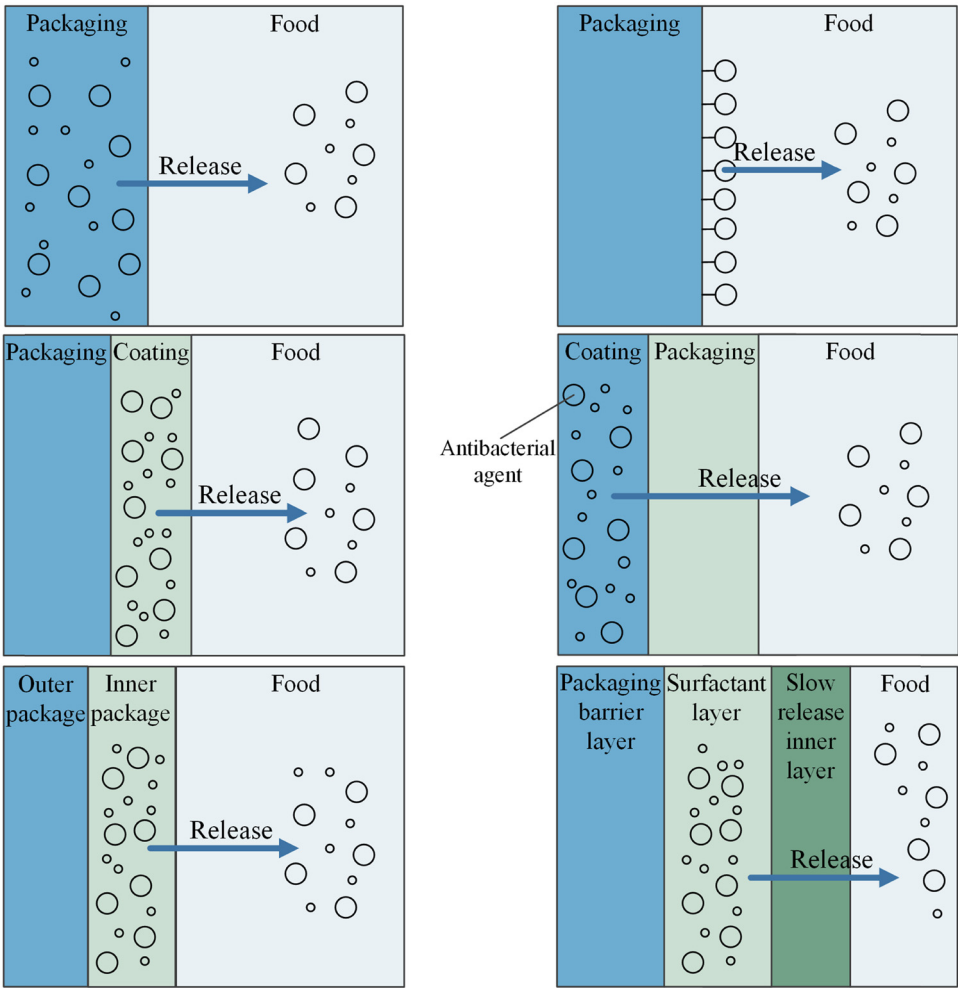


Figure 3: Release of antibacterial agents in the packaging system.

the antimicrobial effect of antimicrobial agents is the regulation of their rate of release in packaging film materials (103–107). The type, content, distribution, structure, and morphology of the antimicrobial agent, as well as the degree of cross-linking, molecular weight, crystallinity, hydrolysis, and porosity of the PVA matrix, all affect the release factors of PVA-based antimicrobial packaging materials. Figure 3 shows the release of antibacterial agents in the packaging system.

5.1 Release factors

By altering the environmental conditions such as temperature and humidity or by adjusting the concentration of antimicrobial agents, researchers have changed the release ability of antimicrobial agents. Figure 4 shows the release of antibacterial agents in the packaging system. For illustration, the release process of thymol from PVA-based films was investigated at different temperatures (4°C, 25°C, and 40°C) using thymol as an antimicrobial agent (108). The release process of CEO at three different temperatures made it clear that the release rate of CEO increases proportionally with the

increase in temperature and relative humidity (109). Nisin was added to PVA/AHSG films and its release rate in 50% ethanol food simulants was regulated by varying the concentration or temperature (4°C, 25°C, and 40°C) and time of nisin release, and the results showed that the migration of nisin from PVA/AHSG films to food simulants accelerated with the increasing temperature (110). When the release of sodium lactate from active antimicrobial packaging with PVA and CS as substrates was also explored, its diffusion from the membrane was found to be influenced by the pH and ionic strength of the aqueous solution (51).

In another study (95), nisin in the PVA/CS film material increased from 0% to 10%, the relative concentration of *S. aureus* decreased sharply from 100% to 11.65%, and then gradually decreased. With the increase in nisin content in the film, the release of nisin in the bacterial suspension increased, thus effectively inhibiting the growth of *S. aureus*. The increase in nisin content had no significant effect on the antimicrobial activity when the nisin content was higher than 10%. The release rate during the release of NAC was proportional to the square of the amount of NAC in the membrane at each moment (111). Other researchers (71) investigated the release process of ZnO nanoparticles in CMC/PVA films, and the release of nanoparticles in the

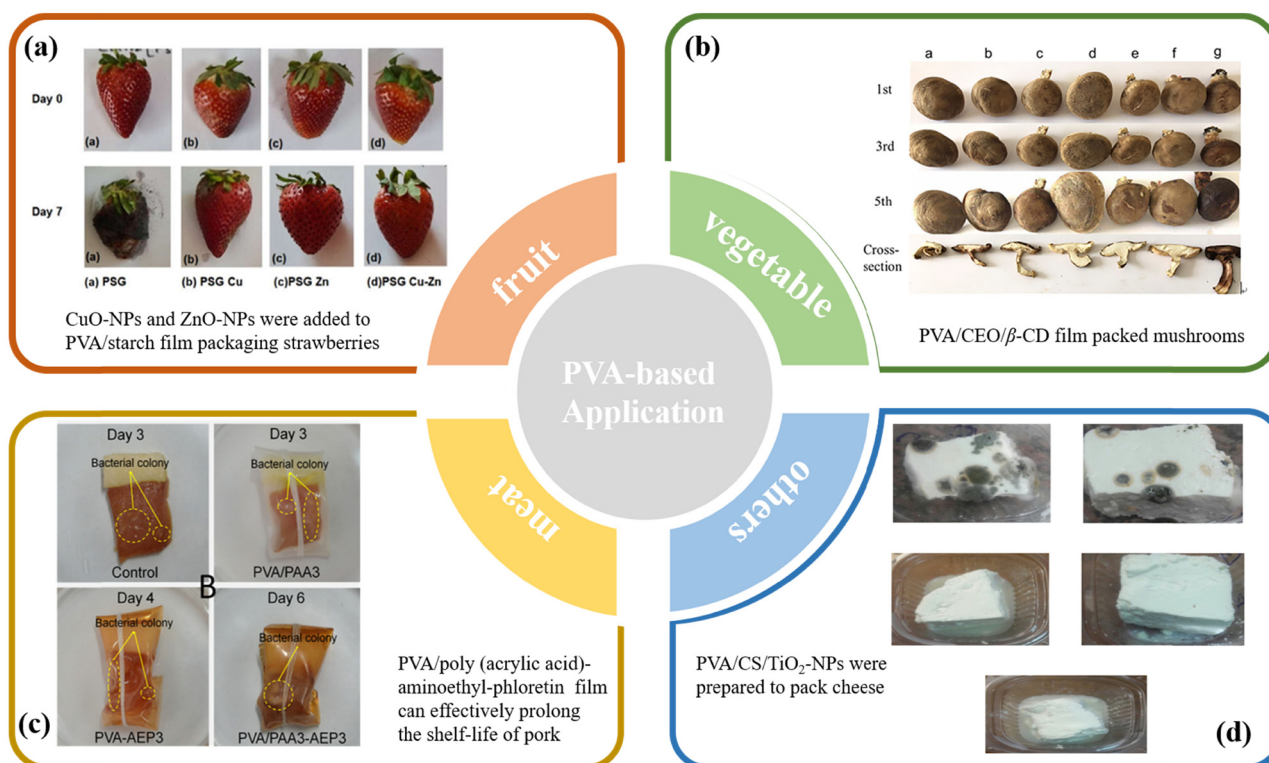


Figure 4: Application of PVA-based food package film in different fields: (a) strawberries (38), (b) mushroom (119), (c) pork (121), and (d) cheese (Karish) (12).

simulants ethanol and acetic acid was related to the concentration of Zn^{2+} in the film. The PVA/MMT/potassium sorbate active packaging materials were prepared by flow casting method, and it was found that adjusting the MMT concentration changed the release effect of potassium sorbate in fatty food simulants. The release process of OEO and CEO in 10% ethanol and 50% ethanol food simulants within PVA composite films at room temperature was found to be higher than OEO release for the same concentration of CEO (83). Antimicrobial food packaging films were synthesized by mixing PVA, starch, and glycerol with embedded CuO and ZnO nanoparticles, and the release of Cu^{2+} and Zn^{2+} metal ions from the films with embedded nanoparticles was explored (38).

Parameters such as pH, temperature, and antimicrobial agent concentration affect the antimicrobial activity of the film, and each of these parameters has a strong influence on the bioactivity, compatibility, and stability of the antimicrobial agent and its rate of release from the film matrix. Regulation of the release of antimicrobial agents from packaging films under different circumstances is therefore necessary.

5.2 Release kinetics

Modeling the release of antimicrobial agents is useful to further explore and predict the release behavior of antimicrobial agents in film materials and to evaluate the diffusion ability and distribution behavior of antimicrobial agents within the film materials to the food products inside, so as to optimize the antimicrobial packaging system and reduce the experimental cost. In the process of exploring the kinetics of antimicrobial agent release, the commonly used model in PVA substrates is the Fickian model (112).

The expression of Fickian's second law is as follows:

$$\frac{\partial C}{\partial t} = D_p \frac{\partial^2 C}{\partial l^2} \quad (1)$$

where D_p is the diffusion coefficient of antimicrobial agent in the packaging material (cm^2s^{-1}); C is the concentration of

active substance ($\text{mg}\cdot\text{cm}^{-3}$); l is the distance in the direction of release (cm); and t is the active substance release time (s).

The limited packaging-limited food system considers a limited volume of packaging and a limited volume of food. At this time

$$\frac{M_{F,t}}{M_{F,\infty}} = 1 - \sum_{n=0}^{\infty} \frac{2\alpha(1+\alpha)}{1+\alpha+\alpha^2q_n^2} \exp(-D_p q_n^2 t/l^2) \quad (2)$$

where $M_{F,t}$ is the amount of active substance released into the food/simulation fluid at time t , mg; $M_{F,\infty}$ is the amount of active substance released into the food/simulation fluid at equilibrium, mg; q_n is the non-zero positive root of the equation $\tan q_n = -\alpha q_n$

The diffusion coefficient (D_p) during the release of potassium sorbate to 95% ethanol in PVA/MMT films ranged from 0.08×10^{-11} to $30.3 \times 10^{-11} \text{ cm}^2\text{s}^{-1}$ when the ambient temperature was increased from 4°C to 60°C (50). The D_p of lactobacillus peptides in membranes was determined by adding lactobacillus peptides to PVA/AHSG films, and the D_p increased from $2.04 \times 10^{-13} \text{ cm}^2\text{s}^{-1}$ to $1.51 \times 10^{-12} \text{ cm}^2\text{s}^{-1}$ as the temperature increased from 4°C to 40°C (110). Fickian equation was used to describe the D_p of sodium lactate in PVA and CS-based active antimicrobial packaging in aqueous solutions with different pH and NaCl concentrations, and it was found that D_p increased with the increase in pH, while higher NaCl concentrations inhibited the movement of ions, especially at pH 7 and NaCl concentration of 0, where D_p was maximum at $12.52 \times 10^{-7} \text{ cm}^2\text{s}^{-1}$, while the D_p is minimal at a NaCl concentration of 0.10, $2.47 \times 10^{-7} \text{ cm}^2\text{s}^{-1}$ (51). In kinetic studies of silver ion release from starch/PVA films into polar food simulants distilled water, ethanol, and acetic acid, the D_p of silver ions was $3.37 \times 10^{-11} \text{ cm}^2\text{s}^{-1}$ in distilled water, $3.2 \times 10^{-11} \text{ cm}^2\text{s}^{-1}$ in ethanol, and $2.88 \times 10^{-11} \text{ cm}^2\text{s}^{-1}$ in acetic acid (113). A study to investigate the release kinetics of rosemary polyphenols from PVA electrospun nanofibers in three food simulants revealed that the D_p of polyphenols showed similar results in hydrophilic and acidic media (114). The diffusion rate of polyphenols was similar in the PVA base layer, while the D_p in

Table 2: Release effect and diffusion coefficient of PVA-based packages of different antibacterial agents

Membrane substrate	Antimicrobial agents	Food/food simulator	Condition	D_p (cm^2s^{-1})	Ref.
PVA	Potassium sorbate	95% ethanol	4–60°C	0.08×10^{-11} – 30.3×10^{-11}	(50)
PVA/CS (1:3)	Nisin	Distilled water (pH 6.5)	5–45°C	8.1×10^{-9} – 2.7×10^{-8}	(95)
PVA/CS (1:2)	Nisin	Distilled water (pH 6.5)	5–45°C	4.3×10^{-9} – 1.9×10^{-8}	(95)
PVA/CS (1:1)	Nisin	Distilled water (pH 6.5)	5–45°C	2.5×10^{-9} – 1.6×10^{-8}	(95)
PVA	Rosemary polyphenols	10% ethanol, 3% acetic acid, 50% ethanol		6.83×10^{-16} , 6.7×10^{-16} , 1.37×10^{-14}	(114)
PVA/polypropylene	Tea polyphenols	50% ethanol	25°C	2.06×10^{-11} – 8.06×10^{-11}	(115)

the lipophilic simulant was the largest at $1.37 \times 10^{-14} \text{ cm}^2 \cdot \text{s}^{-1}$ containing 4% tea polyphenols in a polypropylene/PVA/polypropylene multilayer active film, the D_p increased from 2.06×10^{-11} to $8.06 \times 10^{-11} \text{ cm}^2 \cdot \text{s}^{-1}$ with the increase in the film pore size in 50% ethanol (115). Table 2 summarizes the release effects and diffusion coefficients of some different antimicrobial agents in food simulants.

6 Application in food packaging

6.1 Application in fruits and vegetables packaging

Antimicrobial films or coatings formulated by adding antimicrobial agents to PVA substrates were used to package fruits and vegetables to elongate the shelf life of strawberries (10,23,38,116,117), cherry tomato (59,118), bananas (17), grapes (40), lemons (21), mushrooms (119), etc. According to Wen et al. (10), PVA/ β -cyclodextrin/CEO nanofiber films used for strawberry preservation not only increased the shelf life of strawberries but also preserved their color and look while being stored. Similar to this, strawberries that were wrapped in PVA/starch films with CuO and ZnO nanoparticles demonstrated improved shelf life and kept their fruit's nutritional value (38). As reported by Shao et al. (117), PVA/permutite fibrous/CEO electrostatic spinning films increased the shelf-life of packaged strawberries.

An active nanocomposite coating made by co-blending PVA, agar, and maltodextrin, along with AgNPs, sprayed onto the surface of bananas, significantly extended the shelf life of bananas (17). The novel antimicrobial agent CuO@ZIF-8 was introduced into a composite bilayer film with poly (lactic acid) and PVA-quaternary ammonium CS as the outer and inner substrates, and the bilayer film had good antimicrobial activity and the composite film inhibited the growth of harmful microorganisms on the surface of sainfoin fruits (54). It was also found that the addition of Cu₂O@NCs prolonged the shelf life of sainfoin fruits (59). When compared to PE cling film, PVA/CEO/ β -cyclodextrin electrostatically spun nanofiber films improved the hardness and retained a better color for the mushrooms, but the rate of weight loss was slower (119).

6.2 Application in fresh meat packaging

Microbial contamination and protein oxidation are the main problems in food safety and quality deterioration

of fresh meat products. The packaging materials and technologies have a significant impact on the meat quality and safety characteristics. Therefore, it is highly justified to conducting further research in this area. PVA-based films or coatings prepared by adding antimicrobial agents were used for packing chicken (120), pork (121), beef (11), lamb, fish (122), and shrimp (107) to the extension of their shelf life.

Active food packaging materials containing essential oils were prepared by electrostatic spinning from two commonly used spices (laurel and iteranum *Laurus nobilis* and *Rosmarinus officinalis*) and applied to chicken breasts, which improved the shelf life, decreased lipid oxidation, and reduced the number of *L. monocytogenes* during refrigeration (20). In a study, the combination of 4-HR and mBNC in the PVA/CS composite film was found to effectively suppress spoilage bacteria in vacuum-packed chilled raw beef (9). This innovative approach holds promise for enhancing meat preservation and preventing bacterial growth, thus contributing to the extension of its shelf life (11).

Changes induced by rose petal extract (RPE) have been effectively studied in films using PVA/CMC, the study indicated that the total bacterial count, pH, total volatile alkaline nitrogen, and thiobarbituric acid reactive substances of fish were higher in PVA/CMC composite film compared to the RPE film. This finding suggests that the RPE film exhibits better performance in terms of controlling bacterial growth and maintaining the quality of the fish by reducing the accumulation of volatile alkaline nitrogen and thiobarbituric acid reactive substances (122). Antimicrobial food packaging films prepared from PVA/polyacrylic acid combined with aminoethyl radiciccin aminoethyl-phloretin showed significant inhibition of *L. monocytogenes* and *S. aureus* and potentially extended the shelf life of pork by 4 days at 25°C (121).

Proanthocyanidins (PC) as an active ingredient have also exhibited potent antibacterial properties in food packaging materials. However, it is important to note that PC is susceptible to acid hydrolysis. The CS-graft-PVA film containing PC was used for the preservation of salmon muscle and showed the potential ability to prevent microbial contamination and texture deterioration within 10 days. It is suggested that CS-grafted PVA films had good prospects for future food packaging applications (123).

6.3 Application in other types of food packaging

The physical appearance of bread packed with this bio-nanocomposite film was significantly improved when ZnO-SiO₂ were utilized in PVA/CS nanocomposites (72). The

Table 3: Antibacterial activity of PVA-based packages of different antibacterial agents

Membrane substrate	Antibacterial agent	Preparation method	Food test	Testing duration	Effect	Ref.
PVA/carboxymethyl CS	CA	Solvent casting	Strawberries, cherry tomatoes	5 days, 33 days	Delayed the water loss, reduced the growth of bacteria, and extended the shelf life	(36)
PVA	CEO	Electrospinning	Strawberries	18 days	Higher hardness value, the highest sensory score, no discernible impact on strawberry flavor, extend the shelf life of strawberry	(10)
PVA	Nano-silver	Solvent casting	Grape	10 days	Lighter moisture loss and decay rate, significantly mass loss reduction, and lowest loss of VC content	(40)
PVA/MMT	AgNPs	Solvent casting	Chicken sausages	4 days	Less bacterial growth	(64)
PVA	Laurus nobilis-LEO, Rosmarinus officinalis-REO-)	Electrospinning	Chicken breast fillets	7 days	The pH of the packaged samples did not change significantly or even decrease slightly during storage	(20)
PVA/agar/maltodextrin	AgNPs	Coating	Banana	5 days	Decreased the respiration rate in bananas and delayed their ripening, reduction in the weight loss, acidity loss, pH, total soluble solids, and softening of bananas with the coating during storage period	(17)
PVA/CS	TiO ₂	Coating	Karish cheese	25 days	The rate of weight loss was lower, and the acidity of the cheeses increased significantly and the pH decreased during storage	(64)
PVA/ β -cyclodextrin	CEO	Electrospun	Mushroom	5 days	Reached a minimum weight loss, after 5 days mushrooms were intact and edible	(119)

presence of anthocyanins and limonene was added to the composite of PVA/potato starch, which showed good color development and antibacterial activity against pasteurized milk (88). In other study, the effect of TiO₂ on PVA/CS film antimicrobial properties were investigated. The results showed that the weight loss of the cheese was reduced, the sensory properties was enhanced, and the shelf life was extended due to the nanomaterials during a storage period of 25 days. Among the different compositions tested, the composite containing 3% TiO₂NPs exhibited the highest effectiveness in terms of preserving the quality and prolonging the shelf life of the cheese (12). When PVA/20% sorbitol film-forming solution containing *Salmonella enterica* phage PBSE191 was applied to the surface of eggshells, the PVA coating containing PBSE191 on the eggshell surface showed significant anti-Salmonella activity within 24 h (124).

Figure 4 presents the application of PVA-based food package film in different fields. Table 3 summarizes the antimicrobial activity of PVA-based packages of different antibacterial agents.

6.4 Degradation of the PVA-based films

PVA is a water-soluble synthetic polymer that can degrade under various environmental conditions. The dominant factor is the water solution of the film in the initial stage of degradation, the phenomenon might result from the hydrophilicity of the main component, then the moisture in the soil comes in contact with the surface of films which results in the solution, swelling, and the further osmosis of moisture into the polymer network. As PVA chains break, smaller, water-soluble PVA fragments are formed. These fragments dissolve in water. Microorganisms absorb these water-soluble fragments and use them as a carbon and energy source for growth and metabolism. As long as suitable conditions exist, microorganisms continue producing PVA enzymes and breaking down PVA, allowing them to grow and reproduce. The rate and efficiency of degradation depend on factors like the type of microorganisms, environmental conditions, and the specific PVA material (125).

The PVA/starch/glycerol/HNT films become less degradable and less transparent as the HNT content goes up from 0 to 5 wt% as a biodegradable material (46). PVA/XG composite films can be fully decomposed in soil and water within 12 h, much faster than regular plastic bags and other biodegradable materials (48). This makes it a promising option for eco-friendly, renewable, and sustainable food packaging, potentially replacing traditional plastic bags.

7 Conclusion and prospect

This review summarizes the results of recently published studies on categories of antimicrobial agents, functional and physical properties enhancement of PVA-based films. We discussed the advantages and challenges of some strategies used to improve the performance of PVA-based films, including mechanical properties, water resistance, UV-barrier properties, and antibacterial effect. It also presented the release behavior of antimicrobial agents in PVA-based film materials and their practical applications in the food industry. We also considered the issue of toxicity with the addition of inorganic antimicrobial agents, and discussed the biodegradability of PVA, with a view to producing highly effective antimicrobial, biodegradable PVA-based films with excellent properties in the future.

PVA-based films have an important role to play in the development of more environmentally-friendly, economical, and sustainable food packaging materials in the future. The current limitations are the low water resistance and rapid multiplication of different bacteria in a humid environment of PVA as food packaging films. In order to solve this problem, a variety of antimicrobial agents such as organic acids and salts, plant essential oils or their extracts, and inorganic metals have been used in PVA packaging films, and numerous studies have confirmed the feasibility of PVA-based antimicrobial films for use in the food industry. However, several challenges need to be addressed. First, antimicrobial agents in the PVA substrate dispersion homogeneity, stability, and compatibility issues should be investigated further in order to prepare outstanding mechanical characteristics and antibacterial impact of food packaging. In order to enhance the mechanical properties and antibacterial effectiveness of food packaging, further investigation is needed into the homogeneity, stability, and compatibility of antimicrobial agents in the PVA substrate dispersion. Second, the stability and rate of release of antimicrobial agents from the PVA packing film material, as well as their concentration on the food surface, are important determinants in the performance of their antibacterial activities. Further research should be conducted to develop a set of standard protocols for evaluating the safety of antimicrobial compounds in order to ensure food quality, safety, and sensory qualities.

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