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Review

Starch based films and coatings for food packaging: Interactions with phenolic compounds

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ABSTRACT

Biodegradable starch based films and coatings have been a research focus for food packaging. Phenolic compounds have many benefits for food and health applications. This review summarized the recent advances in the development of starch based films and coatings with added phenolic compounds and extracts. The impact of the added phenolic compounds and extracts on physicochemical, mechanical, barrier, antioxidant and antimicrobial properties of starch films and coatings were described. The starch films and coatings with added phenolics were applied in the packaging of both plant and animal based food products with increased shelf life. For intelligent packaging, anthocyanins were formulated into the starch films and coatings to reflect the degree of food freshness. Composite starch materials with the addition of nanoparticles, proteins and other polysaccharides were also formulated to improve the mechanical and biological functions of the films and coatings. Significant limitations in the studies were noted due to the lack of understanding of the nature of starch-phenolics interactions at the molecular level. Overall, optimal formulations of added phenolic compounds and extracts should be obtained to have targeted mechanical, barrier, and biological properties.

1. Introduction

There is a high need to develop robust biodegradable packaging materials to reduce the impact of fossil oil based pollution on our environment (Li et al., 2024; Kong et al., 2023). Various biopolymers such as polysaccharides and proteins have been made into films and coatings for food packaging (Wu et al., 2023; de Souza Falcão et al., 2024; Ghoshal & Singh, 2020; Aguilar-Palazuelos et al., 2025; Gürdal and Çetinkaya, 2024). Starch as a type of natural biopolymers is abundant, relatively cheap and GRAS. There have been many studies on the structure and properties of starches from diverse plant materials (Wang, 2020). Starch in native and modified forms has great potential to make biodegradable films and coatings for food applications (Bengs and Grande, 1999; Matheus et al., 2023; An & Fu, 2024; Xie et al., 2024; Hashimoto, 2024). Starch is mostly amorphous in the film and coating matrix (Jiang et al., 2023). Various types of physical and chemical modifications have been done for desired properties of starch films and coatings (Zidan et al., 2023; Zhai et al., 2023). Another way to functionalize starch based films and coatings is via the addition of optional ingredients for active and intelligent packaging. For example, diverse natural additives derived from spices, herbs, vegetables, seeds and fruits were applied in edible coatings and films (Hamed, Jakobsen, & Lerfall, 2022; Kaur et al., 2023; Kola & Carvalho, 2023; Huang et al., 2024). Various additives including nanoparticles and essential oils were added in starch based packaging materials to improve the functions (Muñoz-Gimena et al., 2023; Yong & Liu, 2021; Kong et al., 2023; Pedreiro et al., 2021; Ordoñez et al., 2022a, 2022b; Ghoshal & Shivani, 2022; Ghoshal & Chopra, 2022; Pająk et al., 2025). Phenolic compounds have many health effects such as antioxidant, anticancer, and anti-inflammatory activities (Jakobek and Blesso, 2024). It is expected that edible films and coatings may be imparted with these health effects by incorporating phenolic compounds. For example, diverse plant extracts were incorporated into films of different chemical natures including those rich in phenolic compounds for packaging muscle foods and aquatic products with improved shelf-life (Xie et al., 2023). The structure of phenolic compounds influences their interactions with starch (Chen et al., 2022; Wang et al., 2023). Adding phenolic compounds or extracts could increase or decrease chemical and/or physical parameters of starch films and coatings, more fundamental studies are required to obtain films and coatings with desired properties (Pedreiro et al., 2021; Ghoshal & Singh, 2024). This will in turn stimulate our interest in the development of future food packaging for zero emission.

Overall, there is a lack of systematic information on the effect of adding phenolic extracts and compounds on properties, functions and

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applications of starch based films and coatings. Precise design of starch based films and coatings incorporated with phenolic compounds and extracts remains impossible without ad hoc exhaustive testing. This is largely due to the lack of mechanistic understanding on the interactions between starch and phenolic compounds in film and coating systems. Many of the studies reported results without being able to provide underlying mechanisms for the interactions. As a result, a very large number of papers have been published about this topic, though our capacity to precise design of the films and coatings remains low.

2. Approach and scope of this review

This review comprehensively summarized the effects of added phenolic compounds and extracts of various types on physicochemical, mechanical, thermal and biological properties of starch based films and coatings. The food applications of these films and coatings were also reviewed. The literature was focused from the past 3 years or so. Databases of Google Scholar, Web of Science and Scopus were used. There are many papers and patents published in this area. It was impossible to summarize all or even most of them due to the limitation in space and word count. Therefore, representative publications were used with an aim to cover the broad range of topics related to this review. Some of the publications with special interest from over 3 years ago were also used to provide better understandings of topics. The publications were summarized in the various Tables and Figures. In the main text, only representative results (e.g., for the purpose of contrasting results from different reports of same parameter) from a limited number of publications and also representative Figures were described. Therefore, readers should refer to the Tables, Figures and main text for complementary information.

The publications summarized in this review were critically examined to reveal the gap in mechanistic understandings of results. The nature of the interactions between phenolic compounds and starch were critically discussed in relation to film and coating properties. Phenolics related factors affecting film and coating properties were critically assessed in relation to optimal formulations. Research gaps to better use the phenolics enriched starch films and coatings were suggested. There are many publications on the basics of starch and phenolic compounds since decades ago (Wang, 2020; Nollet & Gutierrez-Uribe, 2018). Therefore, they were not included in this review. This review contributes to the development of future food packaging.

3. Starch, phenolic extracts and compounds, formulations and fabrication methods for films and coatings, and retention of phenolic compounds during film and coating making

3.1. Diversity in starch types used in film and coating formulations

Starches from diverse sources including conventional and commercially available (e.g., corn starch) as well as underutilized (e.g., jackfruit seed starch) sources were used in the film and coating formulations (Table 1 and Table 2). The structure of the starches used in the studies varied greatly. For example, starches with A-, B, and C-type polymorphisms as well as chemically modified starches were used in film and coating formulations (Mileti et al., 2024; Zeng et al., 2024; Aydin & Yildiz, 2022; Rong et al., 2023; dos Santos et al., 2023; Zhai et al., 2023; Li et al., 2023). Most of the studies employed commercially available starches such as potato, corn and cassava starches (Mileti et al., 2024; Thakwani et al., 2023; Ludka et al., 2024). Starches from underutilized sources such as jackfruit seeds and *Pouteria campechiana* seeds were tested (Bodana et al., 2024; Jiang et al., 2023). Starch based flours such as sweet potato and faba bean flours were used to make films (Emir et al., 2023; Li et al., 2023) (Supplementary Fig. 1). Modified starches such as hydroxypropyl starch and phosphorylated oxidized starch were also tested (Li et al., 2023; Zhai et al., 2023). It can be expected that commercial starches with large scale production have much higher potential for commercial applications than unconventional and underutilized starches. It has been established that starches with different structure and composition such as varying amylose contents can have different film forming capacity (Myllärinen et al., 2002; Putri et al., 2023). For example, starch with higher amylose content had stronger film forming capacity (Alves et al., 2007). Therefore, not all types of starch are suitable to formulate films and coatings. The interplay between the types of starch and added phenolic extracts and compounds in relation to film and coating properties should be studied.

3.2. Diversity in phenolic extracts and phenolic compounds used in film and coating formulations

Both plant extracts rich in phenolic compounds and pure phenolic compounds were formulated into starch films and coatings (Table 1 and Table 2). Great diversity in the phenolic/plant extracts rich in phenolics and phenolic compounds used to fortify starch films and coatings was obtained (Table 1 and Table 2) (Supplementary Figs. 2 and 3 showing some representative phenolic compounds used). For example, the extracts used in different studies were obtained from grapefruit seeds (Ramakrishnan et al., 2023), pineapple peel (Gürler, 2023), beetroot stem waste (Kathait et al., 2023), tea (Miao et al., 2021), red hibiscus petals (Poudel et al., 2023), brewers' spent grain (Ludka et al., 2024) and other sources (Table 1 and Table 2). The chemical components and composition of these extracts varied greatly, though these extracts were considered rich in phenolic compounds. Pure phenolic compounds of different categories were also used to fortify starch films and coatings. These compounds varied greatly in their physicochemical properties and structures, including gallic acid (Almeida et al., 2023), ferulic acid, cinnamic acid (Ordoñez et al., 2021), resveratrol (Wu et al., 2023) and chlorogenic acid (Zhang et al., 2024). In many of the studies using plant extracts, authors claimed that the extracts were rich in phenolics (Ludka et al., 2024; Sarak et al., 2024; Zidan et al., 2023). However, chemical and phenolic composition of these extracts may not have been given. This has created a degree of confusions due to the lack of this important information. It has been well known that the chemical composition of plant extracts can vary depending on the extraction methods, varieties and growing environment (Abhishek et al., 2024). The lack of the compositional data in some of the studies may not allow other researchers to reproduce their results reported.

3.3. Film and coating fabrication methods and retention of phenolic compounds during fabrication

Most of the studies used casting methods to produce starch films and coatings (Table 1 and Table 2). The ingredients were mixed and heated in the presence of water to gelatinize starch. The gelatinized samples were casted on a plate such as Petri dish before drying (Wang et al., 2023; Todhanakasem et al., 2022; Kathait et al., 2023; Zhang et al., 2024; Zhang et al., 2023; Wu et al., 2024; Thakwani et al., 2023; Jiang et al., 2023; Xu et al., 2022; do Nascimento et al., 2024; Li et al., 2024) (Supplementary Fig. 4). Other methods to make formulated starch films and coatings included compression-moulding (Freitas, González-Martínez, & Chiralt, 2023; Ordoñez, Atarés, & Chiralt, 2021; Wu et al., 2023) and electro-spinning (Khaledian et al., 2024; Zhang et al., 2021). These two methods were less used and tended to have a higher production cost than the casting based method.

A major aspect for consideration is the retention of phenolic compounds during the fabrication processes which tend to involve high temperatures (Zhai et al., 2023). It has been well known that heating can lead to degradation of phenolic compounds in food systems (Piepiórka-Stepuk et al., 2023). For example, during melt-blending and compression-moulding process for starch based film-making, a total of up to 40 % of ferulic acid was lost mostly due to heating (Ordoñez et al., 2021). The extents of loss were dependent on the type of phenolic compounds, and cinnamic acid was significantly less susceptible to the

Table 1
Impact of added phenolic compounds and extracts on physicochemical, mechanical, thermal and barrier properties of pure starch based films and coatings.

Starch types	Extract/phenolic compounds	Formulations	Fabrication methods	Impact on basic physicochemical properties	Impact on mechanical properties	Impact on thermal properties	Impact on barrier properties	References
Pure starch systems								
Potato	Tannin-rich extract of *Castanea sativa* (hydrolysable tannins)	Starch, glycerol (50% of starch content), tannin (up to 3% of total weight)	Solutions were casted and dried at 75 °C for 3 h	Increasing tannin concentration increased film thickness, surface roughness, contact angle, and decreased thermal conductivity	Increasing tannin concentration decreased elastic modulus before increasing it, while increasing elongation at break before decreasing it	na	na	Mileti et al., 2024
Potato	Tea polyphenols	Starch (4 g), glycerol (1.2 g), sodium carboxymethylcellulose (0.2 g), konjac glucomannan (0.1 g), calcium chloride (0.05 g), tea polyphenols (up to 7.5% of total starch)	Gelatinized solution was casted on Petri dish and dried for 36 h at 45 °C	Increasing polyphenol concentration had no effect on thickness, decreased the moisture content, and increased surface homogeneity	Increasing polyphenol concentration increased tensile strength and elongation at break	na	At 550 to 800 nm, increasing polyphenol concentration increased light transmittance. Increasing polyphenol concentration decreased oxygen and water vapor permeability	Chen et al., 2023
Potato	Resveratrol	Potato starch and gelatin (2:1), glycerol (30%), resveratrol (various concentrations)	The mixtures were processed using a twin-screw extruder (110 °C, 35 r/min). The pellets cut from the extrudates were compression-moulded	Adding resveratrol increased the surface roughness, surface hydrophobicity and thickness of the film, while decreasing the water solubility	Adding resveratrol increased the tensile strength and elongation at break	Adding resveratrol increased thermal stability	Adding resveratrol decreased oxygen and water vapor permeability and transmittance and increased opacity	Wu et al., 2023
Potato (amylose content of 21%)	Grapefruit seed extract	Sodium alginate, carboxymethylcellulose, starch (ratio of 1:1:1), extract at various concentrations	Petri dish	Extract was homogeneously distributed in the films without cracks. The addition increased the moisture content, decreased the contact angle and had no effect on film thickness	Adding extract increased elongation at break and decreased tensile strength and Young's modulus	Adding extract little affected the thermal stability	Adding extract increased water vapor permeability, light transmissions	Ramakrishnan et al., 2023
Potato	Pineapple peel extract	Chitosan (1.5 g), gelatin (na), starch (2 g), glycerol (30% of total weight), extract (up to 30%)	Heated mixtures were homogenized and casted onto Petri dish before drying at 50 °C	Adding extract increased moisture content and solubility	Adding extract decreased tensile strength	Adding extract increased thermal stability	Adding extract increased water vapor permeability	Gürler, 2023
Potato starch (20% amylose)	Gallic acid	Thermoplastic starch, gallic acid (up to 1.5% of total starch), bacterial nanocellulose (up to 10% of total starch)	Solvent casting	Adding gallic acid together with the nanocellulose decreased the solubility and moisture absorption	Adding gallic acid together with the nanocellulose increased the tensile strength and Young's modulus	Adding gallic acid little affected the thermal stability	Adding gallic acid together with the nanocellulose increased UV and oxygen blocking capacity	Almeida et al., 2023
Potato starch (20% amylose)	Microencapsulated flavonoids from *Lycium barbarum* leaf	Starch and watermelon peel pectin (1:3), glycerol (40% of total dry weight), TiO_2 and microencapsulated flavonoids (various concentrations)	Heated and gelatinized solution was casted onto a polyethylene disk before drying (44 h, 35 °C)	Increasing flavonoids concentration increased thickness, moisture content, roughness and porosity of the films	The flavonoids together with TiO_2 could optimize the mechanical properties	The flavonoids together with TiO_2 increased the thermal stability	Increasing flavonoids concentration increased water vapor permeability and UV-barrier capacity	Xie et al., 2023
Potato starch	Turnip peel extract	Starch (12 g), extract (6%)	Heated slurry was electro-spun into nanofibers. Guar gum-cinnamaldehyde was also electro-spun to form a double layer mat	Adding extract increased the diameter of the mat, decreased the water solubility and moisture content	Adding extract increased elongation at break and decreased tensile strength	Adding extract increased the thermal stability	Adding extract decreased the water vapor permeability	Khaledian et al., 2024
Potato starch	Polyphenols of *Piper betle* leaf petioles	Starch (3.7 g), guar gum (0.4 g), glycerol (0.615 g), extract (up to 8% of weight of starch and gum)	Heated and gelatinized solution was casted on Teflon Petri dishes and dried at 37 °C for 1 day	Increasing extract concentration increased thickness, moisture content, solubility, surface roughness and crack formation (Supplementary Fig. 5)	Increasing extract concentration decreased tensile strength and increased percentage of elongation	Adding extract at lower concentrations had little effect but at higher concentrations (6 and 8%) decreased the thermal stability	Increasing extract concentration increased water vapour permeability	Nandi & Guha, 2024

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Table 1 (*continued*)

Starch types	Extract/phenolic compounds	Formulations	Fabrication methods	Impact on basic physicochemical properties	Impact on mechanical properties	Impact on thermal properties	Impact on barrier properties	References
Jackfruit seed starch	Pomegranate peel extract	Starch and glycerol (ratio at 5:3), extract at various concentrations	Heated and gelatinized solution was casted onto Petri dish at 45 °C	Increasing extract concentration increased film thickness, decreased solubility	Increasing extract concentration increased the tensile strength before decreasing it	Increasing extract concentration increased the thermal stability before decreasing it	Increasing extract concentration increased water vapor and oxygen permeability	Bodana et al., 2024
Pouteria campechiana seed starch	Passion fruit peel extract	Starch, glycerol (30% of starch weight), extract (up to 9% of starch weight)	Heated starch slurry was mixed with other ingredients before casting and drying (40 °C)	Increasing extract concentration had no effect on film thickness and moisture content, and increased water solubility and smoothness and homogeneousness of films	Increasing extract concentration decreased tensile strength and increased elongation at break	Increasing extract concentration decreased the thermal stability	Increasing extract concentration had little effect on water vapor permeability and increased opacity	Jiang et al., 2023
Lotus root	Quercetin encapsulated in carboxymethyl lotus root starch nanoparticles	Starch (2 g), quercetin nanoparticles (up to 20% of nanoparticles), glycerin (0.5 g), gellan gum (0.3 g)	Gelatinized samples were dried at 50 °C for 5 h	The nanoparticles (5%) were homogeneously distributed in film. Increasing nanoparticle concentration decreased moisture content and water solubility, and had no effect on thickness	Increasing concentration of nanoparticles increased tensile strength and Young's modulus before decreasing it, while increasing elongation at break	Adding quercetin nanoparticles increased thermal stability	Increasing concentration of nanoparticles decreased water vapor permeability before increasing it	Zeng et al., 2024
Arrowhead	Black chokeberry (*Aronia melanocarpa*) extract	κ-Carrageenan (1.35 g), starch (4.5 g), extract (up to 3 mL/g), glycerol (1.15 g)	Heated and gelatinized solution was casted onto Plexiglas plates (dried at 35 °C for 24 h)	Adding the extract increased film thickness and homogeneity	Increasing extract concentration decreased tensile strength and increased elongation at break	na	Adding extract increased water vapor permeability before decreasing it	Wang et al., 2023
Corn	Tea polyphenol	Starch (2.5 g), polyphenol (up to 2.5 g)	Starch and polyphenols in DMSO were electrospun into fibers. Glutaraldehyde was used to cross-link the fibers	Increasing polyphenol concentration decreased the diameter of fiber, increased water contact angle	Increasing polyphenol concentration increasing tensile strength and elastic modulus before decreasing them, while decreasing elongation at break	na	na	Zhang et al., 2021
Corn	Watermelon rind extract	Starch (1 g), polyvinyl alcohol (PVA) (5 g), water (100 mL), glycerol (20%, v/v), extract (10%, v/v)	Film solution was casted onto acrylic sheets and dried at 45 °C for 8 h	Adding the extract had no effect on the film thickness	Adding the extract increased the tensile strength without affecting the elongation at break	na	Adding the extract had no impact on water vapor permeability	Todhanakasem et al., 2022
Corn	*Phoenix dactylifera* (date palm) seed extract	Starch (1.5 g) and date extract (1 mL), chitin (0.3 g), cellulose (0.3 g), glycerol (1 mL), acetic acid (1 mL)	Gelatinized solution was casted on acrylic base and dried in oven	Adding extract, chitin and cellulose increased the moisture content, contact angle and thickness	The composite films had much higher tensile strength than that of starch	na	Water vapor permeability was increased or decreased depending on the formulations	Thakwani et al., 2023
Corn	Rice straw extract	Starch, extract (up to 8% of total starch), rice straw cellulose fibres (3% of total starch), glycerol (30 % of total starch)	Sample mixtures were melt-blending for compression moulding	Adding extract decreased the moisture content in the films with the addition of cellulose fiber and little affected the water solubility	Adding extract of up to 6% increased the elastic modulus (up to 40%) and tensile strength (up to 20%), and little affected elongation at break	Adding extract decreased the thermal stability	Adding extract decreased oxygen permeability and increased water vapour permeability and increased UV blockage	Freitas et al., 2023
Corn	Beetroot stem waste extract	Starch (1 g), PVA (4 g), sorbitol (30% of PVA), extract at various concentrations	Gelatinized solutions were casted onto Petri dish before drying at 50 °C for 42 h	Adding extract had little influence on thickness	Adding extract increased elongation at break and tensile strength	Adding extract had little influence on thermal stability	Adding extract had little influence on water vapor permeability	Kathait et al., 2023
Corn	Chlorogenic acid	Starch, glycerol (20% of starch weight), chlorogenic acid (5% of starch weight)	Sample mixtures were homogenized (10–50 MPa) and heated before casting onto a polystyrene dish and then drying at 40 °C for 24 h	Adding chlorogenic acid reduced the rapidly digestible starch content by up to 40%	Homogenization at suitable pressures increased the tensile strength and elastic modulus	na	na	Zhang et al., 2024

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Table 1 (*continued*)

Starch types	Extract/phenolic compounds	Formulations	Fabrication methods	Impact on basic physicochemical properties	Impact on mechanical properties	Impact on thermal properties	Impact on barrier properties	References
Corn	Gallic acid	Starch (3.5 g), pullulan (1.0 g), glycerol (40% of total starch), gallic acid (up to 1.5%)	Mixtures were casted onto plastic plate and dried at room temperature for 72 h	Increasing gallic acid concentration increased the film thickness and roughness and decreased contact angle	Increasing gallic acid concentration decreased tensile strength, and increased elongation at break	na	Adding gallic acid decreased water vapor permeability, increased opacity	Zhang et al.,2023
Corn	Blueberry anthocyanins	Starch (1 g), PVA (4 g), glycerol (30% of total starch), anthocyanins loaded ovalbumin-carboxymethyl cellulose nanocomplexes (diameter at around 206 nm), UiO-66 (diameter at around 300 nm) (up to 4.5% of total starch)	Starch and PVA mixtures were mixed and heated. Then, the nanocomplexes and UiO-66 were added and the mixtures were homogenized. The solution was casted on molds and dried at 37 °C	Adding nanocomplexes increased the homogeneity of films. Increasing concentrations of UiO-66 firstly increased uniformity, compactness and surface hydrophobicity of the films before decreasing them. Adding UiO-66 increased the adsorption/desorption of N_2 of the films and color-sensitivity to ammonia. Color reversibility and film stability were improved	Increasing concentrations of UiO-66 firstly increased tensile strength and elongation at break before decreasing them	Increasing concentrations of UiO-66 increased thermal stability	Adding nanocomplexes and UiO-66 decreased light and UV transmittance. Increasing concentrations of UiO-66 firstly decreased oxygen and water vapour permeability at before increasing them	Wu et al., 2024
Corn	Tea polyphenols	Starch (5.5 g), glycerol (1.65 g), polyphenol loaded porous starch (0.55 g)	Starch slurry was gelatinized before the porous starch was added. The mixtures were stirred and casted on organic glass plate before drying at room temperature	Adding the polyphenol loaded porous starch had no effect on water content and solubility, increased thickness	Adding the polyphenol loaded porous starch increased tensile strength and elastic modulus without affecting elongation at break	Adding the polyphenol loaded porous starch increased thermal stability	Adding the polyphenol loaded porous starch increased opacity and water vapor permeability	Miao et al., 2021
Corn	*Hibiscus sabdariffa* extract	Starch (5 g), glycerol (2 g), extract (5%), graphene oxide (up to 1.5% of starch weight)	Gelatinized samples were casted on Petri plates and dried for 2 days at room temperature	Adding extract and increasing graphene oxide concentration increased film thickness, moisture content and solubility. Adding extract increased surface roughness	Adding extract and increasing graphene oxide concentration decreased tensile strength and increased elongation at break	na	na	Aydin & Yildiz, 2022
Corn	Gallic acid, vanillic acid, syringic acid	Phenolic acids were grafted onto the aminated starch using laccase. Corn starch (2 g), glycerol (0.9 g), starch conjugate (1 g)	Air bubbles in film solution were removed using ultrasound. Gelatinized samples were dried at room temperature (70 h)	Adding the conjugates increased the roughness of the film surface, hydrophobicity and also the film thickness, while decreasing the swelling capacity	Adding conjugates of gallic acid and vanillic acid increased the tensile strength of the films, while adding those of syringic acid decreased it	Adding the conjugates increased thermal stability of the films	Adding conjugates of syringic acid and vanillic acid decreased water vapor permeability, while add those of gallic acid increased it	An & Fu, 2024
Sweet potato	*Oxalis triangularis* leaf extract	Starch (4.5 g), glycerol (1.25 g), κ-carrageenan (1.35 g), extract at various concentrations	Gelatinized solutions were casted onto Plexiglas plates and dried at 30 °C for 1 day	Adding extract together with κ-carrageenan in the films increased the thickness and the moisture content of the films. The color of films was the sensitive to the changes of pH and ammonia concentration of the environment. Increasing extract concentration increased the roughness of the microstructure of the films. The films were pH- and ammonia-sensitive	Increasing extract concentration little affected the tensile strength and increased elongation at break	Increasing extract concentration decreased the thermal stability	Increasing extract concentration increased the water vapor permeability and decreased the light transmittance	Jiang et al., 2023
Yam	Extracts from red hibiscus petals (*Hibiscus rosa-sinensis*)	Starch (1 g) and extract (up to 0.1g), glycerol (up to 0.15 g), cellulose (0.3 g), citric acid (up to 0.015 g)	Gelatinized solution was casted on Petri dish and air-dried	Adding extract decreased the transmittance and thickness of the films	Mechanical properties (tensile strength and elongation at break) were more positively affected by non-extract	The extract only increased the thermal stability of the films	na	Poudel et al., 2023

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Table 1 (*continued*)

Starch types	Extract/phenolic compounds	Formulations	Fabrication methods	Impact on basic physicochemical properties	Impact on mechanical properties	Impact on thermal properties	Impact on barrier properties	References
					ingredients including glycerol and citric acid			
Yam (*Dioscorea zingiberensis*)	Butterfly pea (*Clitoria ternatea* Linn.) flower extract	1 % CMC–Na, 2 % glycerin, starch (1 to 6%) (w/v), extract (0 to 4%)	Gelatinized starch solution was casted on Plexiglas molds and dried at 30 °C	The extract was homogeneously dispersed in the films. Increasing extract concentration decreased the moisture content of the films from 7.6 to 5.6% and increased the thickness from 0.078 to 0.211 mm	Increasing extract concentration decreased tensile strength (from 16 down to 6 MPa) and increased the elongation at break by up to 2-fold	na	Increasing extract concentration increased the water vapor permeability by up to about 2-fold, oxidation and UV resistance	Wang et al., 2023
Chinese yam	Gallic acid	Starch (20 g), gallic acid (40 g), chitosan (various amounts)	Gelatinized starch solution was casted on Teflon mold before drying (3 h and 55 °C)	Increasing gallic acid concentration decreased the film thickness	Adding gallic acid increased the tensile strength	na	Increasing gallic acid concentration increased the light transmittance	Rong et al., 2023
Common bean	Extracts from the pomace of *Campomanesia xanthocarpa*, *Butia eriospath*, *Eugenia uvalha*, *Psidium cattleianum*	Starch, glycerol (30% of total starch) and various amounts of different extracts	Gelatinized samples were cased on acrylic plates and dried for 20 h at 35 °C	Adding extract increased the film thickness, either increased or decreased the moisture and solubility, depending on the type of extract	Adding extracts decreased mechanical resistance and Young's modulus, while increasing the elongation at break	na	na	dos Santos et al., 2023
Cassava	Grape skin extract	Starch, isomalt and glycerol mixtures (various proportions, 33% of total starch), grape skin extract (concentrations unknown)	Gelatinized samples were casted on acrylic plates and dried for 24 h at 40 °C	The extract was distributed with the films evenly and reduced solubility and swelling. The film color was sensitive to pH	The extract addition decreased elongation at break and increased tensile strength	The extract addition decreased thermal stability	na	Góes et al., 2023
Cassava	Ferulic acid, cinnamic acid	Starch, glycerol (30% of starch weight), phenolic acid (up to 2% of total film weight)	Sample mixtures were melt blended and compressed	Adding phenolic acids little affected moisture content and decreased water solubility	Increasing the concentration of phenolic acids decreased tensile strength and elastic modulus and increased elongation at break	Increasing the concentration of phenolic acids decreased glass transition temperature and increased thermal degradation stability	Increasing the concentration of phenolic acids increased water vapor and oxygen permeability	Ordoñez et al., 2021
Cassava	Brewers' spent grain extract	Starch (3 g), PVA (20 g), extract (up to 5% of total starch)	Casting	Adding extract had little effect on the film thickness, solubility, and increased the density and surface roughness without creating cracks	Adding extract had little effect on mechanical properties of the films	na	Adding extract had little effect on water vapour permeability and apparent opacity	Ludka et al., 2024
Cassava	Hom Nil rice extract	Starch (8 g), extract (up to 8% of total starch), glycerol (1.6 g)	Gelatinized samples were casted on plastic plates before drying at 50 °C (up to 10 h)	Adding the extract at 6 and 8% decreased the starch retrogradation and increased the water contact angle (Supplementary Fig. 6). The surface and microstructure of the films were not affected	Adding the extract at 6% and 8% increased the tensile strength and decreased the elongation at break. The addition at lower levels had no effect	na	na	Sarak et al., 2024
Cassava	Wolfberry extracts (3 varieties)	Starch (20 g), PVA (20 g), extract (2% of starch and PVA weight), glycerol (25%)	Gelatinized samples were casted on Plexiglas mold before drying at 30 °C for 2 days	Adding the extracts enhanced the water contact angle	Adding the extracts enhanced tensile strength and had little effect on elongation at break	Adding the extracts little affected the thermal stability of the films	Adding extract decreased water vapor permeability, light transmittance, and oxygen permeability	Xu et al., 2022
Cassava	*Clitoria ternatea* flower extract	Starch to PVA at 1 :1, glycerol (20% of polymer), extract at various concentrations	Gelatinized samples were casted on acrylic plates and dried at 40 °C for 1 day	Increasing extract concentration increased film thickness	Increasing extract concentration decreased	na	Increasing extract concentration increased opacity	do Nascimento et al., 2024

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Table 1 (*continued*)

Starch types	Extract/phenolic compounds	Formulations	Fabrication methods	Impact on basic physicochemical properties	Impact on mechanical properties	Impact on thermal properties	Impact on barrier properties	References
					tensile strength and elongation at break			
Pea	Apple polyphenols	Starch and pulp cellulose nanofiber (1:0.02), polyphenols at various concentrations	Sample mixtures were heated at 86 °C under an ultrasonic homogenizer and casted onto Petri dish before drying (45 °C, 8 h)	Adding polyphenols increased film thickness and water solubility and decreased moisture content and water contact angle with increasing polyphenol concentration. Moderate amounts of polyphenols can be dispersed homogeneously, whereas excessive amounts created cavities and surface roughness	Tensile strength and elongation at break increased before decreasing with increasing amounts of added polyphenols	Adding the polyphenols increased the thermal stability of the films	Adding the polyphenols increased barrier effect against UV–visible light	Li et al., 2024

na, not available.

heating than ferulic acid. Zhai et al (2023) showed that the retention of tea phenolic compounds in the cassava starch based films was 95 % regardless of amounts of tea phenolics added. One-pot pelleting method with reduced heating in the fabrication process was considered a strategy for the high retention of the phenolics (Zhai et al., 2023). In most of the studies, the casting methods used to make phenolic compound-starch composite films and coatings involved heating with the purpose of starch gelatinization (Table 1 and Table 2). It may be expected that phenolics are partially lost during the heating. Overall, the retention of the phenolic compounds in starch based films and coatings during the fabrication process remains largely under-studied. The degradation products of phenolics have not been analyzed well. This understudied aspect is especially relevant to edible films and coatings since some products from thermally degraded phenolics may be toxic to humans (Doyle et al., 1988).

4. Impact of added phenolic compounds and extracts on physicochemical, microstructural, mechanical and barrier properties, and color of starch films and coatings

Physicochemical and textural parameters including moisture, solubility, surface hydrophobicity and thickness, microstructure, mechanical and barrier properties, and color of starch based films and coatings affected by the added phenolic compounds and extracts were studied (Table 1 and Table 2).

4.1. Impact on thickness

Adding phenolic compounds/extracts or increasing their concentrations increased, had no effect on, or decreased the thickness of starch films and coatings, depending on the formulations and processing (Wang et al., 2023; Todhanakasem et al., 2022; Kathait et al., 2023; Zhang et al.,2023; Rong et al., 2023). For example, Zhang et al. (2023) showed that increasing gallic acid concentration increased the thickness of corn starch based film. In contrast, Rong et al. (2023) revealed that increasing gallic acid concentration decreased the thickness of Chinese yam based films. The thickness of starch based films and coatings is related to the viscosity of film-forming solutions (Rong et al., 2023). The changes in the rheological properties of film-forming solutions as affected by the added phenolic compounds/extracts could be responsible for the changed thickness as observed in the studies. Lower viscosity may be associated with thinner films and coatings of starch. They are affected by factors including the types and composition of the extracts, phenolic compounds, starch as well as film forming methods (Zhu et al., 2008; Zhang et al., 2023; Rong et al., 2023; Jiang et al., 2023). However, most of the studies did not measure the viscosity of their film forming solutions. Previous studies on model wheat starch systems showed that the viscosity of starch in the presence of water may be increased, decreased or not affected, depending on the type of phenolic compounds added (Zhu et al., 2008). The addition may also change the pH of the systems to different extents, which in turn can change the viscosity of starch paste (Zhu et al., 2008). The precise relationship between the properties of the solutions and the thickness of the films and coatings has not been established in the form of mathematical models in most of the studies. It is impossible to predict the relationship in starch films and coatings so far.

4.2. Impact on microstructure

Addition of phenolic extracts and compounds significantly affected the microstructure of starch based films and coatings (Table 1 and Table 2). The microstructure of the starch films and coatings was mostly studied using scanning electron microscopy (SEM) and atomic force microscopy (AFM). The addition increased, had no effect or decreased the homogeneity and surface roughness, depending on the composition and types of the films, starch, phenolic extracts and compounds (Wang

Table 2
Impact of added phenolic compounds and extracts on physicochemical, mechanical, thermal and barrier properties of films and coatings of starch rich and modified starch systems.

Starch type/ systems	Extract/ phenolic compounds	Formulations	Fabrication methods	Impact on basic physicochemical properties	Impact on mechanical properties	Impact on thermal properties	Impact on barrier properties	References
Starch rich flour system								
Faba bean flour	Sumac (*Rhus coriaria*) extract	Flour at a concentration of 4 %, sumac extract (4 concentrations), glycerol (0.4 % w/v)	Gelatinized samples were casted on Petri plates and dried at 25 °C (50 % RH) for 6 h	Adding extract decreased the moisture content and increased the solubility	Increasing extract concentration increased tensile strength and elongation at break by up to about 10 and 3 folds, respectively	Thermal stability was increased by the extract addition with increasing concentration	Adding extract decreased water vapor permeability by about 80 % and increased the opacity	Emir et al., 2023
Modified starch								
Carboxymethyl starch	Date palm kernel extract	Carboxymethyl chitosan (1.6 g), carboxymethyl starch (1.2 g), of glycerol (1 mL), citric acid and extract at various levels	Dissolved ingredients were on Petri dish and air-dried	The morphology of the films was not affected by the extract addition. Increasing extract concentration decreased the solubility of the films	Increasing extract concentration decreased elongation at break and increased the tensile strength	Increasing extract concentration increased thermal stability of the films	Increasing extract concentration increased the UV blockage, oxygen and water vapor permeability	Zidan et al., 2023
Hydroxypropyl starch	Tea polyphenols	Poly(butylene adipate-co-terephthalate (800 g), starch (150 g), glycerol (50 g), polyphenols (up to 50 g)	Twin-screw extruder was used to melt and blend the ingredients. The blend was blown into films	Increasing polyphenol concentration increased heterogeneity	Increasing polyphenol concentration decreased elongation at break and tensile strength	Increasing polyphenol concentration increased thermal stability of the films	Increasing polyphenol concentration increased opacity, decreased oxygen and water vapor permeability	Zhai et al., 2023
Phosphorylated oxidized	Ferulic acid	Phosphorylated oxidized starch (4 %), ferulic acid (2 %), glycerol (33 %)	Gelatinized samples were cased on Petri dish and dried at 40 °C for 6 h	Adding ferulic acid little affected film thickness	Adding ferulic acid increased tensile strength without affected elongation at break	Adding ferulic acid little affected thermal stability of the films	Adding ferulic acid significantly blocked UV transmittance (Supplementary Fig. 7), decreased opacity and water vapor permeability	Li et al., 2023

et al., 2023; Jiang et al., 2023; Nandi & Guha, 2024; Xie et al., 2023; Chen et al., 2023; Li et al., 2024). For example, Jiang et al. (2023) showed that increasing the concentration of passion fruit peel extract increased homogeneousness and surface smoothness of *Pouteria campechiana* seed starch based films. The authors suggested that the extract had high compatibility with the film matrix. However, the exact mechanism responsible for these results remains elusive. In contrast of the results of Jiang et al. (2023), Nandi and Guha (2024) revealed that increasing the concentration of phenolic extract of *Piper betle* leaf petioles increased the surface roughness and crack formation of potato starch in the presence of guar gum (Supplementary Fig. 5). The increased surface roughness and crack formation was attributed to the decreased hydrogen bonding among and between guar gum and potato starch induced by the phenolic addition. The phenolic extract had solids that were not compatible with the starch and guar gum. Some of the solids might have migrated to the film surface during the formulation and film drying process (Nandi & Guha, 2024). However, this hypothesis remains unconfirmed. Moderate amounts of added polyphenols can be dispersed homogeneously within film and coating matrix, whereas excessive amounts may create cavities and surface roughness (Li et al., 2024). Therefore, it appeared difficult to predict the outcomes of the addition on the microstructure of starch films and coatings without obtaining the "optimal" amount of phenolics addition.

4.3. Impact on moisture content and solubility

Addition of phenolic extracts and compounds significantly increased or decreased the moisture content and solubility of starch based films and coatings, depending on the formulations and processing (Table 1 and Table 2). For example, Li et al. (2024) showed that adding apple polyphenols increased water solubility and decreased moisture content of pea starch film. dos Santos et al. (2023) found that adding extracts from the pomace of *Campomanesia xanthocarpa*, *Butia eriospath*, *Eugenia uvalha*, or *Psidium cattleianum* either increased or decreased the moisture content and solubility of common bean starch, depending on the type of extract. The effect on the moisture content and solubility may be related to hydrophilicity of the components in the extract, the microstructure, and the formulations and making process of the films and coatings. For example, the extracts with higher hydrophilicity may relate to higher moisture content of the films and coatings (Li et al., 2024). Overall, it seems difficult to design films and coatings with targeted hydrophilicity and solubility without the detailed composition of the added phenolic extract. There is also a lack of information on the physical and chemical properties (e.g., solubility) of phenolic compounds presented in the studies.

4.4. Impact on water contact angle

Addition of phenolic extracts and compounds significantly increased or decreased the water contact angle of starch based films and coatings (Table 1 and Table 2), depending on the composition and formulations (Supplementary Fig. 6). For example, increasing concentration of tannin rich extract of *Castanea sativa* increased the contact angle of potato starch based films (Mileti et al., 2024). The authors suggested that the starch-tannin complexes were hydrophobic and accumulated on the film surface, decreasing the film wettability. However, the hydrophobicity of the starch-tannin complexes remains not clear and should be tested separately. In contrast of the results of Mileti et al. (2024), Zhang et al. (2023) found that adding gallic acid at 0.5 % increased the water contact angle of corn starch film, whereas further increase in the gallic acid concentration decreased the contact angle. The authors suggested that the initial increase in the contact angle was attributed to the absence of free hydroxyl groups available for water interaction. More gallic acid brought more hydroxyl groups to interact with water (Zhang et al., 2023). The actual occurrence and distribution of added gallic acid on the film surface, however, were not studied. To design starch films and coatings with targeted surface hydrophobicity using phenolics remains to be explored.

4.5. Impact on color

The addition of phenolic extracts and compounds significantly changed the color of starch based films and coatings (Emir et al., 2023; Kola & Carvalho, 2023; Kaur et al., 2023; Jiang et al., 2023). In most of the studies, the CIELAB color space was used, though the detailed results were not summarized in this review. It has been well known that phenolic compounds such as anthocyanins are natural colorants (Cruz et al., 2022). The changes in the color of the starch films and coatings induced by the addition of phenolics are largely expected. However, mathematical models to predict the color of formulated starch films and coatings remain lacking. Currently, it is impossible to design precise color of the films and coatings without exhaustive ad hoc testing. The color can significantly affect the consumer's choices (Spence, 2024). The consumer acceptance of the color of the formulated films and coatings with phenolic extracts and compounds has not been well understood.

4.6. Impact on mechanical properties

Adding phenolic compounds and extracts either increased or decreased the mechanical parameters (e.g., elastic modulus, elongation at break and tensile strength) of starch based films and coatings (Mileti et al., 2024; Chen et al., 2023; Xie et al., 2023; Nandi & Guha, 2024; Wu et al., 2024; dos Santos et al., 2023). Factors contributing to the effects of added phenolic compounds and extracts included the amounts of the addition, the types of the phenolics and starch, the composition of films and coatings, and the formulation methods (Wu et al., 2023; Almeida et al., 2023; Zhang et al., 2021). Phenolic compounds may act as natural cross-linkers for hydrogen bond formation, and interact with the starch molecules to form stronger interactions. Excessive amounts of phenolic compounds may lead to the formation of aggregates, diluting the interactions of the starch molecules (Zhang et al., 2021). It is not clear about the importance of starch type (e.g., potato starch *vs* corn starch) in affecting the effect of the added phenolics and extracts. The interplay between starch type and phenolics remains to be better studied.

4.7. Impact on thermal properties

Thermal properties of the films and coatings were mostly measured using thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) (Freitas et al., 2023; Jiang et al., 2023). Adding phenolic compounds and extracts increased, had little effect or decreased the thermal stability of starch films and coatings (Wu et al., 2023; Ramakrishnan et al., 2023; Freitas et al., 2023; Kathait et al., 2023; Miao et al., 2021; Góes et al., 2023; Ordoñez et al., 2021; Zhai et al., 2023; Emir et al., 2023; Jiang et al., 2023; Poudel et al., 2023). For example, Freitas et al. (2023) showed that adding rice straw extract into corn starch based films decreased the thermal stability and glass transition temperatures. The authors suggested that the addition of the extracts increased the free volume of the starch chains and promoted their mobility. The addition also facilitated starch polymer degradation at high temperature. In contrast, Li et al. (2024) showed that adding apple polyphenols increased the thermal stability of the pea starch films. The authors suggested that the interactions between the polyphenols and matrix components including starch increased the crystallinity of the film (Li et al., 2024). However, the exact structure of the crystals newly formed was not studied.

For films and coatings made using melt-blending method, the mechanism of the effect on thermal properties appeared to be different. For example, hydrolytic effect of phenolic acids such as cinnamic acid degraded starch chains during the melting process (Ordoñez et al., 2021). This led to increased chain mobility and reduced glass transition temperatures. It would be interesting to study the interactions between the degraded starch products and the phenolics in the films. Therefore, a range of factors including the types of phenolics and starch as well as the process of making films and coatings can affect the thermal properties of the films and coatings with the addition of phenolic compounds and extracts.

Too small amount of phenolic compounds/extracts may not have any effect on the physicochemical and biological properties of films and coatings. On the other hand, too high concentrations of phenolic compounds/extracts may lead to the deterioration of certain functions such as mechanical performance. For example, the addition of moderate amount of pomegranate peel extract significantly increased the tensile strength and thermal stability of the films (Bodana et al., 2024). Further increase in the amount of the extract addition decreased them. The further increase in the extract concentration may have diluted the intermolecular interactions between the starch and extract components.

4.8. Impact on barrier properties

Adding phenolic compounds and extracts increased, had little effect or decreased the oxygen and water vapor permeability of starch based films and coatings, depending on the types and concentrations of the compounds and extracts for specific studies (Chen et al., 2023; Ramakrishnan et al., 2023; Xie et al., 2023; Jiang et al., 2023; Khaledian et al., 2024; Nandi & Guha, 2024). For example, increasing tea polyphenol concentration decreased oxygen and water vapor permeability of potato starch film (Chen et al., 2023). The interactions between the polyphenols and potato starch led to the formation of more compacted structure as suggested by the authors. However, the nature of the so called "interactions" and "compacted structure" and the exact mode of action remain unclear. In contrast of the results of Chen et al. (2023), increasing the concentrations of passion fruit peel extract up to 6 % had little effect on water vapor permeability and increased opacity of *Pouteria campechiana* seed based starch. Increasing the concentration to 9 % slightly increased the permeability (Jiang et al., 2023). It was thought that the extract acted as plasticizers increasing the molecular mobility within the films. This allowed the moisture with increased mobility to penetrate through the films (Jiang et al., 2023). Increasing pomegranate peel extract concentration increased water vapor and oxygen permeability of jackfruit seed starch films (Bodana et al., 2024). The hydrophilicity of phenolic compounds was thought to contribute to the increased permeability of the starch films. However, the hydrophilicity of the phenolics was not measured in the study.

Adding phenolic compounds and extracts increased the UV blocking capacity of different starch based films and coatings irrespective of the types of starch and (Wang et al., 2023; Li et al., 2024; Freitas et al. 2023; Wu et al., 2024; Zidan et al., 2023; Li et al., 2023) (Supplementary Fig. 7). The addition also increased the light blocking effect in most of the studies (Almeida et al., 2023). The UV and light blocking capacity could be readily attributed to the unsaturated bonds and chromophiles in the phenolic compounds added (Jiang et al., 2023). Overall, it seems that mechanistic understanding for the effect of added phenolic compounds and extracts on the barrier properties is lacking.

4.9. Impact on digestibility and storage stability

It is generally expected that adding phenolic compounds such as phenolic acids may decrease starch digestibility (Raza et al., 2023). The phenolics either bind with the digestive enzymes or form non-inclusion or inclusion complexes with starch, decreasing the starch digestibility (Raza et al., 2023; Wang et al., 2023). Therefore, a reduction in starch digestibility in edible films and coatings via the addition of phenolics may be expected (Zhang et al., 2024). It should also be noted that not all phenolics have inhibitory capacity against starch digestion (Zhu, 2015). Overall, research on the impact of added phenolic compounds and extracts on starch digestibility in the films and coatings remains very limited.

The storage stability of the color of yam (*Dioscorea zingiberensis*) starch based films fortified with anthocyanin rich extract of butterfly pea (*Clitoria ternatea* Linn.) flower was tested (4 % of the extract, stable up to 3 months at 25 °C, relative humidity of 35 %) (Wang et al., 2023). The mechanical stability of starch films and coatings in relation to water adsorption and types of foods packed during storage remains to be studied.

4.10. Impact on biodegradability

The biodegradability of starch films and coatings affected by adding phenolic extracts and compounds was studied (Thakwani et al., 2023; Jiang et al., 2023; Poudel et al., 2023; Todhanakasem et al., 2022; Ramakrishnan et al., 2023; do Nascimento et al., 2024; Hossain et al., 2023; Li et al., 2024) (Supplementary Fig. 8). Overall, the starch films and coatings showed high biodegradability under burial conditions in soil. Environmental bacterial strains including *Pseudomonas aeruginosa* and *Bacillus subtilis* can effectively degrade starch materials (Poudel et al., 2023). Some of the studies showed that adding phenolic extracts and compounds increased the biodegradability of starch films and coatings. However, the addition of purple passion fruit peel anthocyanin extracts little affected the biodegradability of *Pouteria campechiana* seed starch based films (Jiang et al., 2023). The mechanisms responsible for the increase remain unclear. The addition of the phenolic extracts changed the microstructure of the films and coatings (described in section 4.2 above), which may facilitate or retard the attachment of the microbes onto the films. Loosened structure with cracked induced by phenolic addition could facilitate microbe-film interactions, whereas compacted structure with smooth surface induced by the addition may retard the interactions. Nevertheless, it can be concluded that starch based films and coatings with the added phenolic extracts and compounds have high biodegradability for environmentally friendly applications.

4.11. Impact of phenolic types on properties of starch based films and coatings

The results summarized above showed that the type of phenolic extracts and compounds can influence physicochemical, mechanical, barrier and optical properties of starch films and coatings significantly (Table 1 and Table 2). For example, the addition of the extracts from different varieties of wolfberry had different effects on the properties of starch/PVA composite films (Xu et al., 2022). The extract of black wolfberry increased the film compactness, whereas those of yellow and red wolfberry enhanced the film homogeneity. The films with the black wolfberry extract showed higher antimicrobial activities against *Salmonella typhimurium* and *Staphylococcus aureus* than those with the other two extracts. The color of the films with the black wolfberry extract but not the color of those with the other two extracts showed pH and ammonia sensitivity. Only the black wolfberry contained anthocyanins (Xu et al., 2022). An and Fu (2024) fortified corn starch films with aminated starch conjugates of three different phenolic acids (gallic acid, vanillic acid, and syringic acid). The effects of the addition on the physicochemical properties of the starch films were dependent on the type of the phenolic acids. Adding conjugates of gallic acid and vanillic acid increased the tensile strength of the films, while adding those of syringic acid decreased it. Adding conjugates of syringic acid and vanillic acid decreased water vapor permeability, while adding those of gallic acid increased it (An & Fu, 2024). The differences could be attributed to the different physicochemical properties of the conjugates with different phenolic acids. Mechanistically, this aspect remains to be understood. Overall, it has become very clear that the types of phenolic extract and compounds should be carefully selected to achieve desired properties. Future studies should also provide the compositional information of the extracts used in their studies to help establish structure/composition-property relationships of film and coating components.

4.12. Impact of starch type on properties of starch based films and coatings with added phenolic compounds and extracts

The starch type can significantly affect physicochemical and mechanical properties of films and coatings (Myllärinen et al., 2002; Putri et al., 2023). The starch type can also affect the interactions with phenolic compounds (Zhu, 2015). Previous studies have well documented that the amylose content of starch and structure of amylopectin and amylose significantly determine the properties of starch films and coatings (Myllärinen et al., 2002; Agarwal, 2021; Putri et al., 2023). A great variety of starches form different sources was used in forming films and coatings with added phenolics (Table 1 and Table 2). However, the interactions between starch types and phenolics on the properties of the films and coatings remain little studied.

4.13. Impact of preparation methods

A few studies explored the impact of preparation methods on starch-phenolics films and coatings (Zhang et al., 2024; Li et al., 2023). For example, Zhang et al. (2024) used high pressure homogenization to blend starch and chlorogenic acid. This process facilitated the esterification between starch and chlorogenic acid (Zhang et al., 2024). The resulting modified starch was used to make films with improved homogeneity of the structure, mechanical properties and reduced digestibility. Li et al. (2023) used purple sweet potato flour naturally rich in phenolics including anthocyanins to prepare films for intelligent packaging. The flour was cooked using different methods (including steaming, roasting and boiling) to gelatinize starch, an essential step for film making (Supplementary Fig. 1). Boiling and steaming better retained anthocyanins in the flours than roasting. The films made using the steamed and boiled samples showed higher crystallinity, more homogeneous microstructure, enhanced barrier ability, pH-/ammonia-sensitivity, antioxidant activity, and mechanical and thermal stability (Li et al., 2023). The making of starch films and coatings with added phenolics involved heat treatment (Table 1 and Table 2). It should be noted that the stability of phenolic compounds may be sensitive to heat. It is expected that process of making starch films and coatings should be optimized to maximize the retention of phenolics.

5. Component interactions and nature of starch-phenolic compound interactions in films and coatings

Component and intermolecular interactions between starch, phenolic compounds and other ingredients in starch films and coatings were mostly studied using Fourier transform infrared spectroscopy (FTIR) (Wang et al., 2023; Ramakrishnan et al., 2023). For example, FTIR analysis showed that only non-covalent bonds of hydrogen bonding were formed among the components in *Pouteria campechiana* seed starch, purple passion fruit peel extracts and glycerol of film matrix (Jiang et al., 2023). Most of the studies, however, did little to reveal the nature of the starch-phenolics interactions. In some studies, their FTIR results only revealed the existence of component interactions in starch films and coatings without further elaborating (Bodana et al., 2024). Some only showed the interactions were non-covalent in nature and no new bonds were formed (Li et al., 2024; Wang et al., 2023; Thakwani et al., 2023). The lack of the knowledge of the phenolic-starch interactions leads to very incapacity to control the interactions for targeted properties. As a result of this lack of understanding, individual and exhaustive tests are needed to make films and coatings with specific formulations of starch and phenolics.

There have been model systems of mixtures of starch and phenolic compounds to study their interactions (Zhu, 2015; Wang et al., 2023) (Fig. 1). The mixtures of phenolic compounds and starch in the presence of water and under heating/extrusion are used to make films and coatings (Table 1 and Table 2). Starch granules are disrupted, and the starch molecules are released to interact with phenolic compounds. Wide angle X-ray diffraction analysis showed that the starch in films and coatings was mostly amorphous or with much reduced crystallinity compared to native starch (Almeida et al., 2023; Khaledian et al., 2024; Zhang et al., 2024). This indicated that the hydroxyl groups of starch molecules were much more exposed in films and coatings than when they were in the granule form. Overall, it appeared that the addition of phenolic extracts and compounds had little effect on the crystalline structure of starch films and coatings.

The interactions between the amorphous starch and phenolic compound may be modulated by hydrophobic interaction, hydrogen bonds, van der Waals forces and/or CH–π bonds, depending on the status of starch and phenolics and processing conditions (Wang et al., 2023) (Fig. 1). Starch molecules of amylose and amylopectin and phenolic compounds in films and coatings may mostly form non-inclusion complexes (Zhu, 2015). Bulky phenolic compounds such as tannins may form non-inclusion complexes via hydrogen bond with starch molecules. Phenolic compounds of small sizes may form V-type inclusion complexes with amylose. The helical structure of the inclusion complexes varies, depending on the cavity size and molecular configuration (Wang et al., 2023). Eventually, these interactions between starch and phenolics should be quantified and be controlled precisely to facilitate the design of films and coatings with targeted properties. So far, we don't have the capacity for this precision design.

It should be emphasized that some phenolic compounds are crystalline at room temperature or even at heating conditions in the presence of water during the film and coating preparation stage (Karunaratne & Zhu, 2016). For example, the melting point of rutin, a flavonoid, is 242 °C. Rutin also has a very low solubility in water (Zi et al., 2007). Phenolics may be not dispersed well and homogeneously inside the film and coating matrix. Instead, they may be in the form of crystals or aggregates there. Unfortunately, this physical aspect of phenolic compounds was mostly not considered in the studies. Methods to well disperse this kind of phenolics in the films and coatings should be developed.

Co-valent bond formation may occur between starch and phenolic compounds in film and coating matrix (Luo et al., 2024; Zhang et al., 2024). Some fabrication methods including high pressure homogenization may lead to esterification of starch with phenolics. For example, chlorogenic acid and corn starch based films were formed under high pressure homogenization leading to esterification (Zhang et al., 2024). The authors suggested that the high pressure homogenization (10 MPa) largely decreased the starch size and starch paste viscosity. This exposed the carboxyl group of chlorogenic acid to the C2, C3, and C6 hydroxyl groups of starch molecules to form co-valent bond in the films (Zhang et al., 2024). In contrast, starch-gallic acid complexes were formed under high pressure homogenization via non–covalent interactions (Luo et al., 2024). It has been rather confusing about the experimental conditions to form covalent bonds between starch and phenolics. More studies are needed to repeat any of the reported results for confirmation. Therefore, the mechanisms regulating the esterification and formation of covalent bond between starch and phenolic compounds remain largely unclear. To make things worse, there have been studies published on the interaction mechanisms, many of them made false claims and wrong conclusions. This misleading trend has continued to plague our discourse on "future packaging". Future packaging, as a concept proposed in this review, denotes the packaging systems designed for sustainability and zero emission. Starch based packaging systems described in this review belong to this category.

Overall, in the films and coatings of starch fortified with phenolics, it is not clear how these interactions may affect the properties and functions of the starch films and coatings. It is still not possible to precisely design starch films and coatings by fine-tuning these interactions. The author believes that this is the reason of why exhaustive ad hoc testing is needed for obtaining the properties of the films and coatings, as reflected by the very large number of publications in this topic in recent years. Similar research has been repeated over and over again. The number of publications is expected to increase exponentially in the near future.

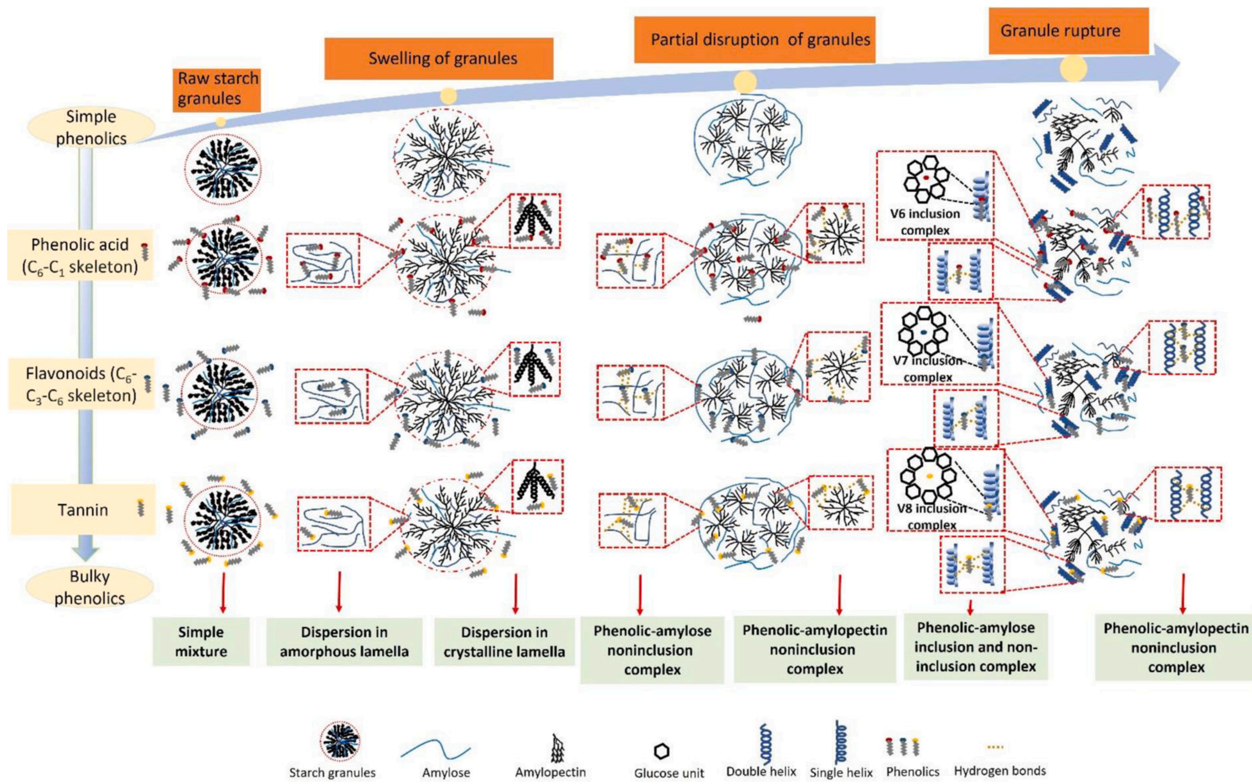

Fig. 1. Possible formation of inclusion and noninclusion complexes between amylose or amylopectin and simple or bulky phenolics (Wang et al. 2023) (Reprinted with permission from John Wiley & Sons).

6. Importance of ingredients other than starch and phenolics

Apart from starch and phenolic compounds, other ingredients including plasticizers, proteins, non-starch polysaccharides, nanoparticles, graphene oxide, polyvinyl alcohol and copolymers were also formulated into starch based composite films and coatings (Freitas, González-Martínez, & Chiralt, 2023; Gürler, 2023; Iaccheri et al., 2023; Nandi & Guha, 2024; Thakwani, Karwa, Kumar, Purkait, & Changmai, 2023; Todhanakasem et al., 2022; Wang et al., 2023; Xie et al., 2023; Zeng et al., 2024; Zhai, Li, Zhang, Wang, & Hou, 2023; Zidan et al., 2023). These ingredients can be critical components to achieve desired mechanical, barrier and physicochemical properties of the films and coatings. For example, the addition of rice straw cellulose fibers increased mechanical and barrier functions of corn starch based films fortified with rice straw extract (Freitas et al., 2023). The mechanical and barrier properties of films and coatings could be much more effectively managed using other ingredients such as nanocellulose than using phenolic extracts or compounds (Freitas et al., 2023; Almeida et al., 2023). Wang et al. (2023) showed that the addition of κ-carrageenan reinforced arrowhead starch film. In contrast, the films with the addition of only the extract were not as effective in achieving the preservation of food stuff (Freitas et al., 2023).

The phenolic extracts used in many of the studies summarized could contain other bioactive components that can also contribute to the physicochemical properties and biological functions of starch based films (Thakwani et al., 2023). For example, increasing the amount of date palm kernel extract decreased water solubility and increased thermal stability in the films of carboxymethyl chitosan and carboxymethyl starch (Zidan et al., 2023). This could be due to the formation of cross-links. Apart from phenolic compounds, fatty acids present in the extract of date palm seed extract also contributed to the antioxidant and antimicrobial functions of the films (Thakwani et al., 2023). Therefore, adding those ingredients can be a feasible strategy to improve the functions of these films and coatings fortified with phenolic extracts and compounds. It may be expected that there are multiple-component interactions and complexation in the films and coatings. However, the interactions of the components including starch, phenolics and the added ingredients in relation to the film and coating properties have been largely under-studied at the molecule level.

7. Economic analysis and cost effectiveness

Starch based films and coatings have high production cost compared with fossil oil based ones. This greatly hinders their commercial applications. Few studies analyzed the production cost of starch films and coatings incorporating phenolic compounds and extracts. For example, the cost analysis of making corn starch films with added date palm extract, chitin and cellulose indicated economic feasibility (Thakwani et al., 2023). However, the economic analysis was focused only on the cost associated with the needed chemicals for the film formulation. Some of the studies employed flour based materials instead of pure starch (Li et al., 2023). For example, Li et al. (2023) used purple sweet potato flour to formulate phenolics rich edible films (Supplementary Fig. 1). It may be expected that the cost of flour based films and coatings would be lower than that of pure starch based systems. In some of the studies summarized (Table 1 and Table 2), pure phenolic compounds were used, which tended to be much more expensive than phenolic extract. For example, a total of 100 g of gallic acid costs over US$200 according to Sigma-Aldrich. The studies of Rong et al. (2023), Almeida et al. (2023) and Zhang et al. (2023) employed pure gallic acid for their starch film formulations. It may be expected that the cost of their products would be high for practical commercial applications. Cheap but functional phenolic compounds remain to be developed if pure phenolics are to be incorporated in starch films and coatings. Unfortunately, this aspect remains to be analyzed practically for future food packaging.

8. Impact of added phenolic extracts and compounds on biological properties of starch based films and coatings

8.1. Antioxidant activity

The addition of phenolic extracts and compounds increased *in vitro* antioxidant activities of starch films and coatings (Table 3). It has been well established that phenolic compounds have *in vitro* and *in vivo* antioxidant activities (Chiorcea-Paquim et al., 2020). Therefore, the results of *in vitro* antioxidant activities of the starch films and coatings fortified with phenolic extracts were expected. The effect of the types of phenolic compounds on antioxidant activities of starch films was studied by a very limited number of researchers (An & Fu, 2024). Different phenolics with different structures showed different antioxidant activities (Chiorcea-Paquim et al., 2020). The *in vivo* and clinical significance of these results remain largely unknown and has been contested.

8.2. Antimicrobial activity

The addition of phenolic extracts and compounds imparted starch films and coatings with antimicrobial activities (Table 3) (Supplementary Fig. 9). The types of microorganisms inhibited depended on the types of phenolic compounds and extracts (Emir et al., 2023; An & Fu, 2024). The antimicrobial functions of the starch films and coatings could be readily attributed to the presence of the phenolics added. There have been many previous studies demonstrating the antimicrobial activities of phenolics via diverse mechanisms such as alteration of the membrane permeability, and inhibition of energy metabolism and nucleic acids synthesis in the microorganisms. Diverse phenolics with different structures possess antimicrobial properties to different extents (Lobiuc et al., 2023). The major question is how the phenolic compounds embedded in the starch matrix may be released into the food environment for antimicrobial action. This aspect was described in Section 9 below.

9. Food applications of starch based films and coatings with phenolic compounds and extracts

9.1. Packaging of animal based foods

Starch based films and coatings fortified with phenolic extracts and compounds were used for the packaging of a range of different animal based food products such as fish, beef and chicken (Table 4). Overall, the addition of the phenolic extracts and compounds increased the shelf life of these products. Increasing the concentrations of the extracts and compounds increased the food protection effects (Poudel et al., 2023; Li et al., 2023; Wang et al., 2023; Rong et al., 2023; Jiang et al., 2023; Ordoñez et al., 2021; Emir et al., 2023; Jiang et al., 2023; Xie et al., 2023; Khaledian et al., 2024; Nandi & Guha, 2024; Wu et al., 2024; Wang et al., 2023) (Fig. 2). For example, Poudel et al. (2023) used citric acid modified yam starch bioplastics fortified with anthocyanins from the petals of *Hibiscus rosa-sinensis* to pack raw cut fish. The changes in the color of these intelligent films effectively reflected the freshness of the raw fish during storage (Poudel et al., 2023) (Fig. 2). The color of starch films and coating with the incorporation of anthocyanins was sensitive to pH and ammonia (Wang et al., 2023; Jiang et al., 2023; Khaledian et al., 2024). It has been well established that the color of anthocyanin solution is sensitive to the changes in pH and ammonia concentration (Janseerat et al., 2024). During storage, bacterial decomposition of meat products, such as beef, chicken, pork and fish, generates compounds such as trimethyl-amine methylamine, and dimethylamine with alkaline pH of ~ 10. This results in an increase in the pH for the color of anthocyanins to change (Waimin et al., 2022). These increased food protection effects of the films and coatings could be largely due to the antioxidant and antimicrobial functions of the added phenolics as described in sections 8.1 and 8.2 above.

9.2. Packaging of plant based foods

Starch based films and coatings fortified with phenolic extracts and compounds were used for the packaging of a range of different plant based foods including vegetables, fruit and oils (Table 4). Overall, the addition of the phenolic extracts and compounds increased the shelf life of these products. Increasing the concentrations of the extracts and compounds increased the food protection effects (Thakwani et al., 2023; Freitas et al., 2023; Todhanakasem et al., 2022; Ramakrishnan et al., 2023; Almeida et al., 2023; Wu et al., 2023; Gürler, 2023; Chen et al., 2023; Li et al., 2023; Ordoñez et al., 2021; Sarak et al., 2024; Bodana et al., 2024; Zeng et al., 2024) (Fig. 3 and Supplementary Fig. 10). It has been well established that phenolics could be antioxidants against lipid oxidation via radical scavenging and peroxidation-mediation effect (Machado et al., 2023). Mechanistically, these enhanced food protection effects could be largely due to the biological functions of the added phenolics as described in sections 8.1 and 8.2 above. Zong et al. (2023) employed starch/gelatin composite films with added phenolic extracts from purple sweet potato roots to monitor the freshness of *Flammulina velutipes* (mushroom) (Fig. 3). The color changes of the mushrooms during storage were sometimes not easily distinguishable by human eyes. For example, the color difference for the samples between 48 h and 60 h appeared rather small. This was a drawback of the packaging system, which may be improved using other types of anthocyanins.

9.3. Release of phenolic compounds from film matrix via food contact

The release of phenolic compounds from film matrix via food contact is a major consideration for applications (Ordoñez et al., 2022; dos Santos et al., 2023; Zhai et al., 2023; Zhang et al., 2024; Ludka et al., 2024; Nandi & Guha, 2024; do Nascimento et al., 2024). Factors affecting the release properties include the types and composition of films and coatings, concentrations of phenolic compounds as well as the food materials (dos Santos et al., 2023; Ordoñez et al., 2022a). Starch films fortified with the extracts from the pomace of different plant materials were used to contain different model foods including non-acidic aqueous foods, acidic aqueous foods and fatty foods. The release of phenolic compounds from film matrix depended on the types of the extracts and the foods as well as the temperature (dos Santos et al., 2023).

Starch films and coatings could be sensitive to water when coming into contact with the aqueous culture medium. The starch materials may absorb water and swell with increased molecular mobility. This swelling facilitates the movement and release of the phenolics from the matrix to interact with food materials and the microbes for any antimicrobial effect (Ordoñez et al., 2022a). The release of phenolic compounds from potato starch based film in aqueous and fatty food simulants was studied (Nandi & Guha, 2024). More phenolic compounds were migrated from the films into the aqueous foods than into the fatty foods. The presence of water in food matrix facilitated the release of the compounds. Water interacted with the starch, swelling the matrix for the compounds to release. Increasing the extract concentration increased the release of phenolic compounds. In contrast, other films and coatings such as those with PLA allowed very limited motion for the molecules embedded and showed no antibacterial activity even with the incorporation of phenolics (Ordoñez et al., 2022b).

In some cases of food applications, the release rate of phenolic compounds from the starch films and coatings needs to be sustained (Zhang et al., 2024; Ludka et al., 2024; Zhai et al., 2023). Chlorogenic acid was encapsulated in corn starch based films via high pressure homogenization with an encapsulation efficiency of 99 %. The releasing of chlorogenic acid was sustained for up to 4 h upon digestion (Zhang et al., 2024). The release of phenolic compounds from starch-PVA films fortified with *Clitoria ternatea* flower extract kinetically followed zero- and first-order models (do Nascimento et al., 2024). The released phenolic compounds may affect the sensory property of the food materials in

Table 3
Impact of added phenolic compounds and extracts on antioxidant and antimicrobial activities of starch based films and coatings.

Starch types	Plant and phenolic types	Microbial models	Impact on antimicrobial properties	*In vitro* antioxidant assays	Impact on antioxidant properties	References
Pure starch systems						
Corn	*Hibiscus sabdariffa* extract	*S. aureus*, *E. coli*, *K. pneumoniae*, *B. subtilis*	Gram-positive and Gram-negative bacteria were inhibited significantly	na	na	Aydin & Yildiz, 2022
Corn	*Phoenix dactylifera* (date palm) seed extract	*E. coli*	Adding the extract imparted antibacterial capacity to the films	na	na	Thakwani et al., 2023
Corn	Rice straw extract	na	na	DPPH	Increasing extract concentration increased antioxidant capacities	Freitas et al., 2023
Corn	Aminated starch-phenolic acid conjugates	*E. coli*, *S. aureus*	Adding the conjugates increased antibacterial capacity of the films (gallic acid > syringic acid = vanillic acid)	DPPH, ABTS	Adding the conjugates increased antioxidant activities (gallic acid > syringic acid > vanillic acid)	An & Fu, 2024
Potato (amylose content of 21 %) (composite films with sodium alginate, carboxymethyl cellulose)	Grapefruit seed extract	*E. coli*, *S. aureus*	Increasing extract concentration increased the antibacterial capacity against both bacteria tested	DPPH, ABTS	Increasing extract concentration increased antioxidant capacities	Ramakrishnan et al., 2023
Potato starch based electro-spun fiber matt	Turnip peel extract	*S. aureus*, *S. typhimurium*, *L. monocytogenes*, *E. coli*	Adding the extract imparted the mat with antibacterial property against these species	DPPH	Adding the extract imparted the mat with antioxidant property	Khaledian et al., 2024
Potato starch (20 % amylose) with nanocellulose	Gallic acid	*S. aureus*	Adding gallic acid imparted the films with antibacterial capacity against the bacteria	DPPH	Adding gallic acid imparted the films with antioxidant activity	Almeida et al., 2023
Potato starch (20 % amylose)	Microencapsulated flavonoids from *Lycium barbarum* leaf	*B. cereus*, *E. coli*	Adding the flavonoids together with TiO_2 increased the antimicrobial activities	DPPH, ABTS	Adding flavonoids together with TiO_2 increased antioxidant activity	Xie et al., 2023
Potato	Pineapple peel extract	*S. aureus*, *E. coli*	Adding extract inhibited the growth of the bacteria	DPPH	Adding the extract imparted the films with antioxidant activity	Gürler, 2023
Common bean	Extracts from the pomace of *Campomanesia xanthocarpa*, *Butia eriospath*, *Eugenia uvalha*, *Psidium cattleianum*	*L. monocytogenes*, *L. inoccua*, *B. cereus*, *S. aureu*	Adding the extracts increased the antimicrobial activities against the species to various extents	ABTS	Adding the extracts increased the antioxidant activities to various extents	dos Santos et al., 2023
Cassava	Wolfberry extracts (3 varieties)	*S. typhimurium*, *S. aureus*, *E. coli*, *L. monocytogenes*	Adding the extracts increased the antimicrobial activities against the species to various extents	DPPH, ABTS	Adding the extracts increased the antioxidant activities to various extents	Xu et al., 2022
Cassava starch	Cinnamic acid, ferulic acid	*E. coli*, *L. innocua*	Adding phenolics imparted antibacterial capacity to the films. *L. innocua* was more inhibited using the films and the films with cinnamic acid were more effective than ferulic acid	na	na	Ordoñez et al., 2022b

(*continued on next page*)

Table 3 (*continued*)

Starch types	Plant and phenolic types	Microbial models	Impact on antimicrobial properties	*In vitro* antioxidant assays	Impact on antioxidant properties	References
Sweet potato	*Oxalis triangularis* leaf extract	na	na	DPPH, ABTS	Increasing extract concentration increased antioxidant capacities	Jiang et al., 2023
Lotus root	Quercetin encapsulated in carboxymethyl lotus root starch nanoparticles	*Botrytis cinerea*	Adding quercetin nanoparticles imparted the films with anti-fungal capacity	DPPH, ABTS	Increasing extract concentration increased antioxidant capacity	Zeng et al., 2024
Flour based systems rich in starch						
Faba bean flour	Sumac (*Rhus coriaria*) extract	*S. aureus, E. coli*	Adding the extract imparted antibacterial capacity to the films against *S. aureus* but not *E. coli*	DPPH, ABTS	Adding the extract imparted antioxidant activities to the films	Emir et al., 2023
Modified starch						
Carboxymethyl starch	Date palm kernel extract	*E. coli* O157, *Rhizopus oryzae, Listeria monocytogenes, Salmonella typhimurium, Aspergillus niger, Staphylococcus aureus*	Zone of inhibition and minimum inhibitory concentrations were measured. Increasing extract concentration increased the antimicrobial capacity against the 6 strains tested and their biofilm inhibition	na	na	Zidan et al., 2023
Hydroxypropyl starch	Tea polyphenols	*E. coli, S. aureus*	Increasing polyphenol concentration increased antibacterial capacity of the films	DPPH	Increasing polyphenol concentration increased antioxidant capacities	Zhai et al., 2023

DPPH, 2,2-diphenyl-1-picrylhydrazyl; ABTS, 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid); na, not available.

contact with the phenolics. This aspect remains to be studied.

10. Phenolics related factors affecting properties of starch films and coatings

The type of phenolic compounds in the extracts, the solvent used for the extraction, the source of phenolics (e.g., fruit, grains or vegetables), and the extract concentration used to produce the films and coatings can have significant influence on the properties (Table 1 and Table 2). The effect of the type of phenolic compounds was exemplified by the study of Ordoñez et al. (2021) who compared the effect of ferulic acid with that of cinnamic acid on starch film properties. The addition of cinnamic acid reduced the water solubility of the films more than that of ferulic acid. The formulations containing cinnamic acid were more active in food matrices as well as in culture medium than those containing ferulic acid. The films with ferulic acid were more extensible than those with cinnamic acid (Ordoñez et al. (2021). The solvents used for the extraction can influence the phenolic composition as exemplified by many previous studies focusing on the effect of extraction (Edo et al., 2025; Kalinowska, Płońska, Trusiak, Gołębiewska, & Gorlewska-Pietluszenko, 2022). Thus, it is expected that the solvents and methods used for extraction may have direct effect on film and coating properties, though this aspect remains under-studied.

The effect of the source of phenolics on films and coatings was exemplified by the studies of Xu et al. (2022) and dos Santos et al. (2023). Xu et al. (2022) compared the effect of extracts of 3 types of wolfberry varieties on film properties. The film with black wolfberry extract had the lowest oxygen permeability and light transmittance. This film had the highest antioxidant and antimicrobial activities, and also remarkable color changes under ammonia atmosphere and different buffer solutions (Xu et al. (2022). These differences could be readily attributed to the different phenolic composition in the 3 extracts. The extract of black wolfberries contained a significant amount of anthocyanins whose color served to be indicative of the environmental changes (Teixeira et al., 2023). dos Santos et al. (2023) compared the effects of the extracts from the pomace of *Campomanesia xanthocarpa*, *Butia eriospatha*, *Eugenia uvalha*, and *Psidium cattleianum* on film properties. The film with the butia extract had the highest elongation (63 %) and the lowest mechanical resistance (1.42 MPa). In contrast, the film with the uvaia extract had the least impact on the mechanical properties (3.70 MPa and 58 %). The film with the guabiroba extract had the lowest antimicrobial capacity. Such differences could be due to the differences in their phenolic and bioactive composition of the extracts (de Oliveira Raphaelli et al., 2021; Rockett et al., 2020; Rodrigues et al., 2021; Dos Santos et al., 2023). Hydroxybenzoic acid in *B. eriospatha* extract showed antimicrobial activity (Cho et al., 1998). However, the structural basis of the phenolics responsible for the different mechanical properties of the films remains elusive.

The effect of the extract concentration used to produce the films was exemplified by the study of Zhang et al. (2023). The authors used different concentrations (up to 1.5 %) of gallic acid to formulate starch films. The addition of gallic acid at 1 % increased the opacity, mechanical strength, and antioxidant activity, and decreased the water vapor permeability, at 0.5 % gave highest water contact angle to the films, and at 1.5 % gave the highest antibacterial capabilities (Zhang et al., 2023). A very vast range of phenolic types and structures were used to formulate starch films and coatings (Supplementary Table 1, Supplementary Figs. 2 and 3). Therefore, precise design of starch films and coatings with added phenolics should take these phenolics related factors into consideration. However, systematic studies on these phenolics related factors mentioned above remain to be done.

11. Lack of suggestions and conclusions on "optimal" formulations for practical applications

The ultimate purpose of the studies on starch films and coatings

Table 4
Applications of starch films and coatings with added phenolics for food packaging.

Starch, plant and phenolic types	Packaged foods	Major results	References
Plant foods			
Corn starch with date palm seed extract	Blueberry	The addition of the extract significantly increased the shelf life of the berries	Thakwani et al., 2023
Corn starch with rice straw extract	Sunflower seed oil	Under UV radiation in an accelerated model system (50 days of experiment), adding the extract and cellulose fiber largely retarded the oil oxidation and improved the shelf life of the oil packed in the films	Freitas et al., 2023
Corn starch/PVA composite films with watermelon rind extract	Fresh-cut purple cabbage	The addition of the extract significantly increased the microbiological and sensory shelf life of the cabbage	Todhanakasem et al., 2022
Potato starch (composite films with sodium alginate, carboxymethylcellulose) with grapefruit seed extract	Green chilli	The texture, color and moisture of the chilli were much better retained during 25 days of storage at room temperature (Supplementary Fig. 10)	Ramakrishnan et al., 2023
Potato starch (20 % amylose) with gallic acid and nanocellulose	Fresh cut apple	The films significantly delayed the browning as well as weight loss of the apple samples during storage at 4 °C (7 days)	Almeida et al., 2023
Potato starch and gelatin (2:1) with resveratrol	Soybean oil	The addition of resveratrol into the films significantly delayed the oxidative rancidity during storage of 24 days at 50 °C compared with the control film and the oil without film package	Wu et al., 2023
Potatostarch, chitosan, gelatin with pineapple peel extract	Strawberry	The coating with the extract addition increased the sensory shelf life of the strawberries significantly at room temperature and 4 °C	Gürler, 2023
Potato starch with tea polyphenols	Fresh-cut banana, blueberry	Increasing polyphenol concentration decreased the changes in weight loss, chewiness and hardness of blueberries, and the changes in color of fresh-cut banana	Chen et al., 2023
Phosphorylated oxidized starch with ferulic acid	Strawberry and fresh-cut apple	The films with the addition of ferulic acid decreased the changes in appearance, color, weight loss and polyphenol oxidase activity of the fruit samples to larger extents than the films without the addition	Li et al., 2023
Cassava starch with ferulic acid and cinnamic acid	Fresh-cut melon	Increasing concentrations of cinnamic acid in the films increased the inhibitory activity against *L. innocua* and *E. coli*	Ordoñez et al., 2021
Cassava starch with Hom Nil rice extract	Biscuit	The films containing the extracts of up to 6 % were feasible to pack biscuits, whereas that with the extract of 8 % broke easily and was not suitable for biscuit packaging	Sarak et al., 2024
Jackfruit seed starch with pomegranate peel extract	White grape	The coating containing the extract significantly delayed the deterioration in the appearance, texture, and weight of white grape during a storage period of 8 days at ambient temperature and humidity	Bodana et al., 2024
Lotus root starch with quercetin encapsulated in carboxymethyl lotus root starch nanoparticles	Black grape	The films with the addition of 5 % of quercetin nanoparticles slowed the changes in weight loss, firmness, titratable acidity, activities of the antioxidant enzymes, profiles of volatiles, anthocyanin and vitamin C in the grapes during storage (26 °C and 77 % RH) of 21 days	Zeng et al., 2024
Animal foods			
Yam starch with extracts from red hibiscus petals (*Hibiscus rosa-sinensis*)	Raw fish	The films with the extracts showed that its color was pH sensitive for smart packaging (Fig. 2)	Poudel et al., 2023
Purple sweet potato flour was cooked using different methods to make coatings	Shrimp	The color of the films made using steamed and boiled samples turned from purple to blue-violet during storage, whereas that of the films made using roasted and uncooked samples showed little change in the color type	Li et al., 2023
Yam (*Dioscorea zingiberensis*) starch with butterfly pea (*Clitoria ternatea* Linn.) flower extract	Chicken	At room temperature, the color of the films changed obviously during storage and quality deterioration	Wang et al., 2023
Chinese yam starch with gallic acid and chitosan	Pork	At 25 °C, during storage of 24 h, chemical, physical and sensory properties of pork were better reserved in the starch based films than in polyethylene film	Rong et al., 2023
Pouteria campechiana seed starch with passion fruit peel extract	Shrimp	At 0 °C, the color of the films changed (from pinkish brown to green) obviously during storage and quality deterioration (changes in total volatile basic nitrogen and pH)	Jiang et al., 2023
Cassava starch with ferulic acid and cinnamic acid	Chicken breast	Increasing concentrations of ferulic acid and cinnamic acid in the films increased the inhibitory activity against *L. innocua* and *E. coli*	Ordoñez et al., 2021
Faba bean flour with sumac (*Rhus coriaria*) extract	Chicken	At 4 °C, the meat packed using the films with the extract had 7 days of microbiological shelf life, while those packed using the films without the extract only had 3 days	Emir et al., 2023
Sweet potato starch with *Oxalis triangularis* leaf extract	Beef	The color changes of the films reflected the amount of ammonia present and the degree of freshness of the beef product and its value of volatile basic nitrogen	Jiang et al., 2023
Potato starch (20 % amylose) with microencapsulated flavonoids from *Lycium barbarum* leaf	Mutton	The microbiological, chemical and sensory deterioration of the beef were significantly retarded at 4 °C during storage of 15 days	Xie et al., 2023
Potato starch based electro-spun fiber matt with turnip peel extract	Lamb meat	The microbiological deterioration of the lamb meat was significantly retarded at 4 °C during storage by up to 13 days. The color changes of the films reflected the degree of microbiological spoilage. White to purplish color indicated fresh to spoiled status	Khaledian et al., 2024
Potato starch with polyphenols of *Piper betle* leaf petioles	Chicken	The texture, chemical and physicochemical properties (total volatile basic nitrogen, pH, color, and hardness) of the chicken meat were significantly retained using the coatings with the added extracts at 4 °C for 12 days	Nandi & Guha, 2024
Corn starch and PVA composite films with blueberry anthocyanins and UiO-66	Shrimp and pork	The changes in the contents of total volatile basic nitrogen of shrimp and pork were related to the color of the films during a two day of storage (25 °C, 25 % RH)	Wu et al., 2024
Arrowhead starch, κ-carrageenan with black chokeberry extract	Chicken wing	Increasing extract concentration increased the shelf life of the chicken wings, while the color of the films was sensitive to the storage and indicated freshness	Wang et al., 2023

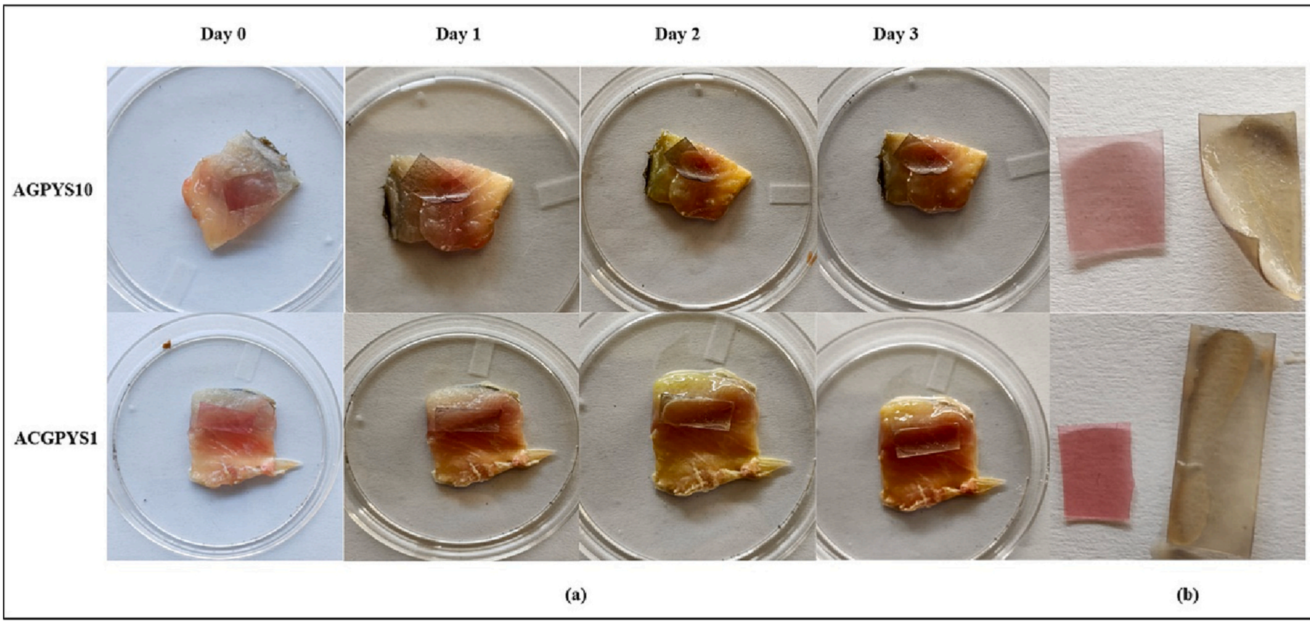

Fig. 2. (a) Yam starch films with the extracts from petals of *Hibiscus rosa-sinensis* (with (ACGPYS1) or without citric acid (AGPYS10)) showed change in the freshness of raw fish after day 1, 2 and 3; and (b) difference in the color of the films before and after the test (Poudel et al., 2023) (Reprinted with permission from Elsevier).

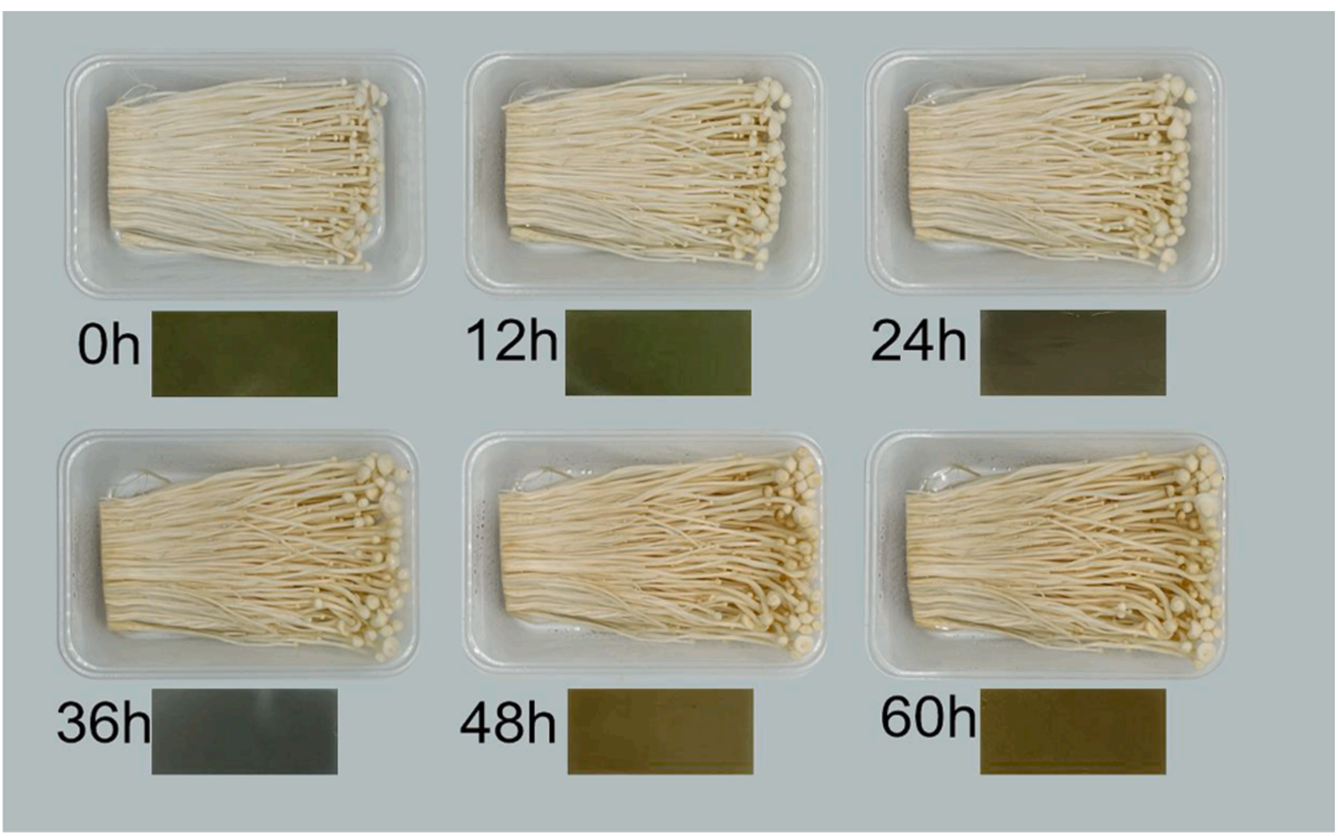

Fig. 3. Use of starch/gelatin-purple sweet potato anthocyanin films in monitoring freshness level of *Flammulina velutipes* mushroom (Zong et al., 2023). The color changes were not easily distinguishable by human eyes, a drawback of this packaging system. For example, the color difference between 48 h and 60 h appeared rather small (Reprinted with permission from Elsevier).

incorporated with phenolics/extracts is to suggest an optimal formulation for targeted applications. This suggestion/conclusion needs to take various factors and film functions into account. So far, a limited number of studies suggested an optimal formulation regarding the addition level of the phenolics as a conclusion. This information was summarized in Supplementary Table 1. Many studies did not make a study on the effect of addition levels of phenolics. Many reports did not make a conclusion regarding the optimal formulation, partly due to the nature and purpose of their studies (Freitas et al., 2023; Kathait et al., 2023; Miao et al., 2021; Aydin & Yildiz, 2022; Wang et al., 2023). Furthermore, many of the studies made very general and even vague conclusions in their reports which greatly decreased their readability and usefulness.

Some of the studies only targeted the effect of phenolics/extracts on a limited number of film and coating functions such as antioxidant and antimicrobial activities (Kathait et al., 2023; Jiang et al., 2023). For example, a high antioxidant activity of the films and coatings may be achieved, though the mechanical functions were not considered (Chen et al., 2023; Wu et al., 2023; Ramakrishnan et al., 2023). For conclusions, many studies didn't suggest an optimized formulation for overall functional performance of the films and coatings, they mostly suggested optimized formulations for only specific and targeted functions (Supplementary Table 1). It should be stressed that suitable quality attributes such as mechanical and barrier properties are also critical for films and coatings to be practical. There is a lack of comparison between the data reported (e.g., mechanical and functional properties) and the parameters of commercially available films and coatings (e.g., plastics). As a result of the lack, it is impossible to gain practical insights from these studies. Overall, holistic approaches including consumer acceptance to address the film and coating quality should be employed for future studies.

12. Future research directions

The analysis of the literature summarized above have indicated many research opportunities. In some studies, the formulations of the films and coatings were not given clearly. The composition of the final films and coatings should be clearly given on dry weight basis to make reports meaningful in any future studies. A significant number of the studies used plant extracts and claimed that these extracts were rich in phenolics. It is critical to analyse the extract composition to facilitate mechanistic understanding of the effects of added phenolic extracts.

The uses of food waste and processing by-products to obtain both phenolic compounds/extracts and starch for film and coating formulations may be explored further (Sani et al., 2023). Efficient and economic extraction methods to obtain extracts rich phenolics remain to be developed (Alara et al., 2021). The use of deep eutectic solvents in preparation of phenolic extracts and formulation of films and coatings may be further explored (Wei et al., 2023). Efficient methods to produce phenolic compounds at large scale and with much reduced cost remain to be developed to support our ongoing discourse. There are many different types of phenolic compounds such as flavonoids and stilbenes with diverse biological benefits, physicochemical properties and production cost (Nollet & Gutierrez-Uribe, 2018). Phenolics from fungi and seaweeds also have great potential to be added to starch films and coatings for active food packaging (de Souza Falcão et al., 2024). However, these compounds remain to be tested in film formulations and applications.

Phenolic compounds may be lost during film making and processing such as heat treatment. More studies are needed to optimize the process to maximize the retention of phenolics. There has been increasing interest in developing starch based composite films for desired properties with diverse ingredients (Zhang et al., 2023). These composite films with various ingredients should be tested on the effect of added phenolic compounds and extracts. Multiple layer films and coatings for the packaging of high-moisture foods may be developed (Ordoñez et al., 2023).

Releasing properties of phenolic compounds from starch matrix and their subsequent interactions with food materials have been understudied. For example, the effect of starch type, formulation, composition, and matrix type on the releasing of the phenolics should be analyzed. Starch film as delivery systems of phenolic compounds is a potential direction for controlled release applications.

At a fundamental level, the very serious lack in understanding of the nature of starch-phenolic compound interactions affected by experimental conditions leads to the lack of capacity to precise-design and predict the functions of the films and coatings. Ad hoc testing is required for film and coating functions. In order to establish structure/composition-property relationships of film and coating components, the nature of the interactions should be systematically analysed. The binding between starch and phenolic compounds may be tuned using controlled process such as high hydrostatic pressure (Li et al., 2024). Rheological properties (e.g., steady shearing and temperature ramp tests) of film forming solutions containing phenolic compounds in relation to physicochemical properties of films and coatings should the studied. This may be used to optimize the formulations of ingredients and to predict the properties of the films and coatings using simple model systems (Mileti et al., 2024) (Supplementary Fig. 11). However, there is a lack of such approach from the current literature.

13. Conclusions

Phenolic compounds/extracts were formulated into starch based films and coatings for active and/or intelligent packaging using casting, electrospinning and compression-moulding methods. The preparation methods and conditions could be optimized to maximize the retention of the phenolics in the films and coatings. The physicochemical, microstructural, mechanical and barrier properties, and color of the starch films and coatings were affected by the types and levels of starch, phenolics, extracts and other ingredients, interactions among the ingredients especially starch and phenolics, and processing methods. Too little of phenolic compounds/extracts added may not have any effect on the physicochemical, hydrophobicity, barrier and mechanical properties of starch films and coatings. Too high concentrations of the phenolic compounds/extracts added may lead to the deterioration of certain functions such as mechanical and barrier performance. Optimal amounts of phenolic addition could be obtained for targeted properties. The release of phenolic compounds from film matrix was affected by the composition, matrix structure and surrounding environment. The added phenolics imparted the starch films and coatings with antioxidant and antimicrobial activities suitable for food preservation. These intelligent and active starch films and coatings were successfully used to package a range of animal and plant based food products.

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Declaration of competing interest

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Appendix A. Supplementary data

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