



Review Article

Role of Natural Waxes in Enhancing the Functional Properties of Edible Films: A Review

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SUMMARY

The recent increase in interest in edible, non-toxic, and safe food-packaging materials has stimulated research on edible films and coatings produced from biodegradable biopolymers. The hydrophilicity of many film- and coating-forming constituents used in food packaging, such as polysaccharides and proteins, leads to poor barrier functionality against water transfer. Due to their intrinsic lipophilicity and barrier properties, natural waxes are considered potential ingredients for the functionality enhancement of edible films/coatings. The effects of different natural waxes on moisture-related, mechanical, optical, surface, gas-barrier, and thermal properties, as well as on fresh-produce preservation using edible films and/or coatings, were reviewed. Unlike existing overviews of lipid incorporation into food packaging, this study compared the wax-specific properties and revealed system-specific trade-offs for food-packaging optimisation. Generally, the existing reports demonstrate that the addition of waxes reduces most moisture-related characteristics of films, such as swelling and water-vapour permeability, but increases surface hydrophobicity. However, the reported effects are not uniform and depend strongly on the type and concentration of wax, polymer matrix, wax-polymer interactions, dispersion, and processing conditions. Wax incorporation generally improves hydrophobicity and water-vapour resistance, whereas its effects on tensile strength, flexibility, transparency, and thermal stability vary among formulations. At appropriate concentrations, waxes can enhance film functionality and suitability for food packaging; excessive incorporation, however, may promote phase separation, aggregation, opacity, brittleness, or reduced mechanical performance. Overall, the literature indicates that natural waxes are promising functional components for improving the performance of edible films, but their effectiveness is highly formulation dependent. Further research should therefore focus on optimising wax-polymer interactions and processing conditions to achieve consistent functional and packaging performance.

Keywords: Natural waxes; edible films; food packaging; moisture barrier; hydrophobicity; fresh-produced preservation; biodegradable packaging

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INTRODUCTION

Fruits and vegetables are essential components of the human diet and important sources of nutrients, including vitamins, minerals, fibre, and other health-promoting compounds. Despite these nutritional benefits, fresh produce generally has high moisture content, active metabolic systems, sensitive tissue structures, and relatively short postharvest shelf life [1]. Fresh produce remains physiologically active after harvest and continues to undergo metabolic processes, including respiration, ripening, and transpiration, as well as other physiological and chemical changes that contribute to quality deterioration over time [1]. Loss of turgor, firmness, and freshness, together with water loss, may result from physiological changes and the susceptibility of tissues to damage during handling and storage, while microbial activity can further contribute to cellular damage and eventual decay [1, 2]. Postharvest losses may consequently result in reductions in nutritional value, appearance, and commercial quality. Losses of fruits and vegetables in Sub-Saharan Africa may range between 30 and 50%, with high perishability, poor handling, and inadequate postharvest systems contributing substantially to these losses [3]. These challenges highlight the importance of effective preservation

methods for maintaining the quality and extending the shelf life of fresh produce.

Food packaging is an important factor in preserving the quality and shelf life of foods by protecting them from physical, chemical, and biological deterioration, while also facilitating their containment, transportation, and storage [4]. Conventional food packaging relies largely on petroleum-derived polymers because of their mechanical strength, durability, ease of processing, and good barrier properties [4, 5]. However, the continued use of petroleum-derived plastics contributes to the accumulation of persistent waste in soil and water bodies because many of these materials are non-biodegradable [5, 6]. Concerns about the environmental persistence of conventional plastics and the depletion of resources used in their production have therefore increased interest in alternative packaging materials that can provide adequate functional and protective properties while reducing reliance on petroleum-based plastics [4–6].

Among the alternatives for overcoming the negative environmental effects of conventional packaging, edible films offer advantages because they are produced from biodegradable and biocompatible raw materials. Edible films are defined as discrete thin layers that may function independently or be applied directly to

food as protective barriers or as components of packaging systems [7]. In contrast, edible coatings are formed directly on the surface of food products and can perform similar functions. Both edible films and coatings can limit the transfer of moisture, gases, and aroma, reduce oxidation and spoilage, and help maintain the quality of food products [7, 8]. Edible films are commonly formulated using biopolymer-based materials such as polysaccharides and proteins, while lipids may also be incorporated to provide hydrophobic and moisture-barrier properties [7, 9]. Polysaccharides such as starch and its derivatives, cellulose derivatives, alginate, and chitosan generally exhibit good film-forming capacity and oxygen-barrier properties. Protein-based films can provide useful mechanical and oxygen-barrier properties, whereas lipids can contribute hydrophobicity because of their low affinity for water [8, 9]. Incorporating lipids into other biopolymers can therefore produce films with functional barrier properties suitable for different applications.

Some limitations of existing edible films for large-scale application in the food industry include their high water-vapour permeability, which can make them unsuitable for a range of food products, particularly moisture-sensitive plant products [10, 11]. Starch-based edible films or coatings have the potential to limit the diffusion or transport of moisture, gases, and aroma into and out of foods, reduce oxidation and spoilage, and help

maintain food quality, although their effectiveness depends on the formulation and the specific biopolymer-lipid system employed [10–12].

Waxes are hydrophobic materials that, when incorporated into polysaccharide- or protein-based films, can provide an effective moisture barrier by limiting water transfer during storage [13, 14]. Their incorporation may reduce water-vapour permeability, increase surface hydrophobicity, and modify the optical and mechanical properties of films, depending on wax composition, concentration, dispersion, and interaction with the polymer matrix [14, 15]. Natural waxes of plant and animal origin, including candelilla, carnauba, and beeswax, have been investigated as functional ingredients in edible films and coatings for food applications [13, 14]. However, the effects of wax incorporation vary considerably depending on the type and concentration of wax, polymer matrix, and processing conditions.

The modification of film properties by natural waxes depends on wax composition, concentration, source, and form, as well as interactions with the polymer matrix. This review evaluates current evidence to address the following questions: (1) How do different natural waxes affect film functional properties? (2) What are the key formulation parameters that determine performance trade-offs? (3) What are the priority research gaps for advancing wax-modified edible films toward commercial

application? This paper provides an overview of the modifying functions performed by natural waxes in biopolymer-based films, focusing on moisture and barrier properties, mechanical, optical, and thermal characteristics, and food-preservation applications. While recent reviews have addressed lipid incorporation broadly, this work specifically compares natural wax types and their concentration-dependent effects, identifying key formulation trade-offs and research gaps to guide future optimisation efforts.

REVIEW METHODOLOGY

This review examined natural waxes used in edible films and coatings, focusing on their sources, properties, incorporation into biopolymer matrices, functional effects, and food applications. Literature was searched in Scopus, Web of Science, PubMed, ScienceDirect, and Google Scholar using combinations of search terms including “natural waxes,” “edible films,” “food packaging,” “starch film,” “beeswax,” “carnauba wax,” “candelilla wax,” and “plant wax.” Studies published primarily from 2015 to 2026 were considered, with earlier studies included where relevant. Peer-reviewed studies on natural waxes in food-related edible films and coatings were included, while non-natural waxes, non-food applications, non-edible films/coatings, and studies with insufficient relevant information were excluded. Titles and abstracts were screened, followed by full-text assessment, and information on wax type/source,

polymer matrix, concentration, preparation method, functional properties, and food applications was extracted and comparatively synthesised.

Overview of Natural Wax-Containing Edible Films and Coatings

Based on the reviewed literature obtained, natural waxes are increasingly being incorporated into biopolymer-based packaging systems in edible films and coatings in order to enhance functional performance. There has recently been substantial interest in employing natural lipids as ingredients in edible films in order to improve water resistance and barrier properties of hydrophilic films [16, 17].

The wax reviewed included commonly studied natural waxes such as beeswax, carnauba wax, and candelilla wax, while other plant-derived waxes, including rice bran wax, were also reported, particularly in direct applications to food surfaces such as fruits and vegetables [18, 19]. Waxes were incorporated into different film-forming matrices, including starch-based systems derived from various botanical sources, gelatin, whey proteins, and chitosan [16, 20]. Starch-based matrices were widely investigated because starch is abundant, biodegradable, and capable of forming films, although its hydrophilic nature limits its resistance to moisture and water vapour.

In addition to differences in wax type and polymer matrix, the reviewed studies employed different methods for

incorporating waxes into edible films and coatings. These included solvent casting, extrusion, and emulsion-based formulations for preparing wax-containing films, as well as direct application to food surfaces in coating formulations [18, 20]. Differences in incorporation methods can influence wax dispersion within the polymer matrix and consequently affect the functional characteristics of the resulting films and coatings.

Distribution of Reviewed Studies by Wax Type

Beeswax was one of the most extensively studied natural waxes incorporated into biopolymer films. Its strong hydrophobicity and suitability for food-related applications make it a favourable

candidate for incorporation into starch-, gelatin-, and other biopolymer-based film systems. Beeswax has been investigated as an edible barrier component and in combination with other functional additives. For example, beeswax incorporation into cassava starch-based films has been investigated for its effects on mechanical, thermal, and antimicrobial properties. Similarly, the incorporation of beeswax into breadfruit starch-based films was reported to decrease water-vapour permeability and modify the mechanical behaviour of the films [19, 20]. Beeswax incorporated into starch–gelatin matrices produced a hydrophobic surface and the lowest water-vapour permeability among the waxes investigated [21].

Table 1. Comparative summary of natural waxes investigated in edible films and coatings

Natural wax	Source	Reported matrix/application	Major reported effects	Reference(s)
Beeswax	Animal-derived	Cassava starch, breadfruit starch, starch–gelatin and other biopolymers	Increased hydrophobicity and water resistance; reduced water vapour permeability; modified mechanical and thermal properties	[19–21]
Carnauba wax	<i>Copernicia prunifera</i>	Starch–gelatin and other edible matrices	Improved water resistance and surface hydrophobicity; influenced crystallinity and barrier-related properties	[21]
Candelilla wax	<i>Euphorbia antisyphilitica</i>	Starch–gelatin and whey-protein matrices	Reduced permeability; increased hydrophobicity; modified mechanical properties	[21, 22]
Rice bran wax	Rice bran	Emulsion-based coatings for fresh produce	Extended reported storage life; influenced physiological weight loss and other quality parameter	[17]
Other plant-derived waxes	Various plant and fruit surfaces	Mainly direct coating systems	Reported roles in moisture/gas barrier formation and surface protection	[18]

The two waxes most prominently mentioned were carnauba wax and candelilla wax. These are both plant-derived waxes which have been tested in films and coatings, and are also highly hydrophobic. Although in some cases these waxes are interchangeable, studies suggest their impacts on film properties are not equivalent; the type of wax added to a starch/gelatin film impacted both water resistance and surface hydrophobicity, in addition to effects on the mechanisms governing the starch gelatinization and the final film mechanically [22]. Candelilla wax has been tested as part of whey-protein films to decrease permeability [22].

Another commonly investigated plant-derived wax is rice bran wax, which has particular relevance to postharvest applications involving fresh produce. Application of a 10% rice bran wax emulsion to tomatoes increased the reported storage period from 18 to 27 days under the study conditions [17]. Recent studies have also examined plant sources as potential sources of waxes or investigated waxes naturally present on fruits and vegetables, although these materials have received less attention than beeswax, carnauba wax, and candelilla wax [18].

Reported Effects of Natural Waxes on Edible-Film Properties

A common trend across the reviewed literature was an improvement in the moisture-barrier properties of edible films following the incorporation of natural waxes into hydrophilic polymer matrices, although the magnitude of improvement varied with wax type, concentration, and polymer system. Wax incorporation generally increased water resistance and surface hydrophobicity and, in several formulations, reduced water-vapour permeability [16, 21]. A comparative study of starch-gelatin films further demonstrated that the effects varied considerably among wax types. Beeswax produced the highest water contact angle (102.6°) and the lowest water-vapour permeability among the three waxes evaluated, although its incorporation was associated with reduced tensile strength [21]. These findings indicate that improvements in hydrophobicity and moisture resistance may be accompanied by changes in other film properties, highlighting the need to consider multiple functional characteristics when optimising wax-containing edible films.

Table 2. Reported effects of natural wax incorporation on edible-film and coating properties

Wax	Film/coating matrix	Property assessed	Reported effect	Reference(s)
Beeswax	Starch-gelatin	Contact angle	Increased surface hydrophobicity; contact angle reached 102.6° in the reported formulation	[21]

Beeswax	Starch-gelatin	Water-vapour permeability (WVP)	Produced the lowest WVP among the wax formulations investigated	[21]
Beeswax	Starch-gelatin	Tensile strength	Reduced tensile strength	[21]
Candelilla wax	Starch-gelatin	Water resistance	Increased water resistance and surface hydrophobicity	[21]
Candelilla wax	Whey protein	Water-vapour permeability (WVP)	Reduced film permeability	[22]
Beeswax	Breadfruit starch	Water-vapour permeability (WVP)	Decreased WVP	[20]
Beeswax propolis	+ Cassava starch	Antimicrobial activity	Reported inhibition of <i>A. niger</i> of up to 51% in the tested formulation	[19]
Rice bran wax	Tomato coating	Storage life	Extended reported storage life from 18 to 27 days under the study conditions	[17]

Similar effects on the mechanical and thermal properties of starch-wax systems have been reported in other studies. The tensile strength, elongation, and Young's modulus of cassava starch films containing beeswax varied significantly with composition, while interactions among starch, beeswax, and other components were evident from thermal analysis [19]. Incorporation of waxes into starch-gelatin films also influenced the degree of gelatinisation and shifted the thermal decomposition and gelation temperatures, with the magnitude of these changes varying according to wax type. Among beeswax, candelilla wax, and carnauba wax, beeswax produced the greatest reduction in thermal stability [21]. Other studies have reported a decrease in moisture content and an increase in thermal stability following the incorporation of lipids into starch films [16].

In addition to changes at the film level, wax-containing coatings have demonstrated potential for food applications. In a tomato-coating study, rice bran wax influenced physiological weight loss and increased the reported storage period from 18 to 27 days under the study conditions [17]. Overall, the reviewed findings indicate that natural wax incorporation can improve moisture-barrier properties and surface hydrophobicity, although its effects on mechanical, thermal, optical, and other functional properties vary according to wax type and concentration, polymer matrix, and processing conditions.

Functional Role of Natural Waxes in Edible Films and Coatings

In edible films and coatings, natural waxes can significantly alter functional behaviour by introducing a hydrophobic phase into hydrophilic biopolymer matrices. The functional effects of natural waxes as additives to biopolymer-based edible films

and coatings are not determined solely by their hydrophobicity but also by wax selection, preparation method, formulation, concentration, and the properties of the polymer system [16, 17]. The role of natural waxes in film performance is therefore better understood as a composition-dependent phenomenon in which changes in mechanical, optical, thermal, and gas-barrier properties may accompany improvements in moisture resistance and surface hydrophobicity.

Sources, Composition and Characteristics of Natural Waxes

Natural waxes are highly hydrophobic mixtures of complex compounds, predominantly wax esters, together with varying proportions of hydrocarbons, fatty acids, fatty alcohols, and other constituents. Their long hydrocarbon chains and esterified fatty components contribute to their low affinity for water, making them useful for improving the moisture resistance of edible packaging systems [23, 24]. Natural waxes occur in both plant and animal sources. Beeswax is a commonly used animal-derived wax, whereas carnauba, candelilla, and rice bran waxes are important examples of plant-derived waxes.

Naturally occurring waxes commonly form protective layers on plant surfaces, where they contribute to the cuticular barrier and help reduce transpirational water loss and water movement across plant tissues [18]. In food science, this natural barrier function makes fruit-surface waxes

particularly relevant to moisture-barrier films and coatings, as their inherent water-resistant properties may contribute to improved resistance to water transfer when incorporated into packaging systems.

While many waxes will share common characteristics due to similar functional group and hydrocarbon structures, there are significant variations among major naturally occurring waxes as indicated by the differences in composition and performance profile of wax based edible films presented earlier. Beeswax for example differs from carnauba wax in that it does not have high proportion of long chain esters and thus has relatively low melting point and candelilla wax consisted primarily of high molecular weight straight chained hydrocarbons. Both beeswax and carnauba wax consist largely of wax esters and other constituents, and the former consists of slightly larger amounts of alcohols and acids, has the lowest percentage of esters, and consequently lowest melting range while carnauba consists almost exclusively of diesters or triglycerides [23,24]. Rice bran waxes are also rich in complex esterified alcohols and fatty acids and is isolated as a by-product of the purification of crude rice bran oil [24].

The influence of wax composition on film properties is closely related to the interactions between the wax and polymer matrix, which can affect wax dispersion and phase separation. These structural features influence water interactions and may also affect mechanical strength, gas

permeability, and other functional properties. In the comparative study by Cheng et al. [21], beeswax, candelilla wax, and carnauba wax all increased surface hydrophobicity and influenced water-barrier properties, but their effects on mechanical, optical, and thermal characteristics differed. These findings indicate that wax selection should be based on the overall functional requirements of the film rather than on hydrophobicity alone.

Incorporation of Natural Waxes into Edible Film Matrices

Natural waxes can be incorporated in to films in number of ways, primarily blending directly in with the other film components, formulation as a dispersion in an emulsion or some other application. Direct blending seems the most practical method but often the process of melting can cause degradation of either the polymer or the wax while some organic compounds may dissolve to greater extent in less hydrophilic than in hydrophobic matrix. Regarding interaction between wax and biopolymer matrices such incompatibility gives the problem if dispersion and phase segregation is not controllable [16,17].

One approach to overcome wax incompatibility in film formation and a more controlled dispersed wax phase can be done with the incorporation of wax as a melt in a pre-emulsified biopolymer matrix and using homogenisation and emulsification techniques to obtain small

wax droplets within the dispersed wax system.

Wax droplet distribution impacts on the wax film matrix modification; fine distributed droplets contribute better to modification with increased surface area and narrower pore diameter leading to decreased WVP compared to larger accumulated domains [16,17]. This method can also apply to direct application of the emulsified waxes on to produce coat on a food item itself for quality assurance [18].

One of the major limiting aspects of applying waxes within edible films and coatings is wax-polymer compatibility. Highly hydrophilic biopolymer materials that readily interact with water will naturally interact weakly with hydrocarbons that comprise most waxes. In addition, it could lead to discrete crystalline lipid-rich domains within the polymer matrices of the films, and these domains can impart advantages by limiting diffusion paths for water movement through the film. Excessive phase separation can lead to structural defects and therefore weakening of films.

In case of starch/gelatin films, interactions between components in starch/gelatin film were weakened with incorporation of both bees, wax, and candelilla wax, and thus reduced the overall tensile strength, as opposed carnauba wax which exhibited less interaction with the film matrix [21]. Therefore, careful consideration needs to be given to the processing parameters, that include concentration, intensity of mixing,

homogenisation, drying conditions of product from such film matrix (such as air velocity over surface and temperature), because waxes must provide optimal domain size and structure for best film performance.

Moisture-Related Properties

Moisture properties are some of the most obvious areas where natural waxes can provide an improvement over a standard biopolymer film. Edible materials like starch and protein, which require a high level of interaction with water to form strong films, are often undesirable as film or coating material for high-moisture food products that require significant limitation of water diffusion through their packaging. Conversely, incorporation of an edible wax can dramatically affect these interactions by limiting the quantity and strength with which individual polymer chains interact with water and therefore reduce effective permeability to water [16,17].

Water uptake and by extrapolation moisture content and solubility can be significantly reduced by the inclusion of natural waxes. This has the potential for improvement in retention of high-moisture food products although completely limiting interaction to water is not always suitable for all edible packaging systems. Increased insolubility has potential advantage as the coating can retain its integrity in higher water environments, for example fresh products requiring good visual appearance, and decreased swelling ensures minimum impact to the material within a high-moisture environment. In both cases such

property depends on dispersion and concentration of waxes and if the wax is allowed to aggregate it would then lead to weak film integrity as has been mentioned before [16,17].

Water-vapour permeability is particularly significant as it represents how readily water-vapour travels across the film; in general food-preservation contexts, high WVP is associated with moisture loss from fresh produce, causing wilting, loss of firmness and weight loss, though the specific relationship in wax-containing films requires case-by-case evaluation [10,11] or condensation of moisture onto the food surface, causing microbial growth (e.g. Moulds and bacteria [10]) waxes create a hydrophobic region which lowers the affinity of films for water and thus increases barrier to water vapour transit. Some previous studies have investigated the effect of natural waxes such as bees wax, candelilla and carnauba waxes addition to starch and gelatin matrix showed significant increase in water-resistance and surface hydrophobicity. Among them beeswax showed a contact angle of about 102.6° and significantly reduced WVP [21] and similar results also reported for the breads fruit starch/beeswax films [20] and candelilla wax in Whey protein matrices [22].

Such reduction WVP of films does not only depend on the hydrophobic nature of the incorporated wax but also its properties and presence, structure (such as particle and droplets) formed during the processing of edible films, polymer matrices properties, and other processing

parameters used which thus means what form that wax is incorporated in is extremely important and needs to provide optimal wax content that does not deteriorate mechanical properties of the film.

Mechanical Properties

Mechanical properties are generally found to be less consistent than moisture-resistant properties in wax systems. The tensile strength and elongation of a film are mainly controlled by the interactions holding the polymer chains together and the coherence of the polymer matrix. Using a hydrophobic wax may interrupt polymer-polymer contacts and create discrete domains throughout the matrix which cause discontinuities, thereby reducing tensile strength [21]. This effect has been demonstrated for starch/gelatin films with beeswax and candelilla wax.

However, the level is influenced by formulation: adding some wax could increase rigidity or alter the flexible behaviour but too much wax could either become so aggregated, or its presence contribute in such way, to the film that mechanical strength is weakened due to these discontinuities and interfacial interactions. In addition to wax content the influence on the mechanical behaviour is likely to be dependent upon the plasticiser amount, type of polymer and also the conditions of film formulation and treatment. Consequently, it should not be assumed that a decrease in tensile strength is an immediate indication of a failed wax system-it simply represents another compromise for obtaining an

effective moisture resistance. The optimal formulation, one which provides adequate mechanical stability whilst achieving necessary barrier characteristics, should be sought out.

Optical Properties

The addition of any natural wax will either enhance or detract from clarity because many incorporate small particles which scatter incident light. This is therefore going to introduce either a greater or lesser transparency in the film: for some applications consumers need to see the product in the packaging but in other food applications, it can be desirable for light scattering within the films to prevent photodegradation of the food product itself. The level of light scattered by wax is proportional to the quantity of crystalline lipids in the films, thus making it less transparent when that is increased [16,17]. This represents another formulation trade-off, and this time depends upon factors such as amount of wax added, size of any wax crystals and optical properties of the polymer system.

Surface Properties and Hydrophobicity

Hydrophobicity is often an important measure of the influence on natural wax systems. The contact angle was used to measure the ability of the film to resist the dispersion of water droplets on its surface: at contact angles larger than 90° the drops 'beaded' up indicating an improvement in water resistance. The contact angle for starch/gelatin film incorporated with 3% beeswax found was 102.6° demonstrating the effectiveness of the waxes in increasing hydrophobicity of the surfaces [21].

Hydrophobicity on the surface means a reduced water interaction with the actual film thus helping the moisture resistance.

Micrographs showed a homogeneous distribution of waxes for low concentrations of wax. This indicates why contact angles will not completely give an indication to the moisture barrier; for instance, larger pores could compromise a high contact angle measured on the surface for high percentage wax added to increase water resistance. The two measurements complement each other to reflect the surface properties of the wax system.

Gas Barrier Properties

Since fresh produce continues to respire after harvest, gas-barrier properties are important for controlling the movement of oxygen and carbon dioxide through edible films and coatings. Effective control of gas exchange may help regulate the internal atmosphere surrounding packaged produce and consequently influence respiration and quality retention. However, oxygen and carbon dioxide have different transport characteristics, and the ability of a film to restrict one gas does not necessarily indicate equivalent performance for the other. Gas-barrier performance is influenced by factors such as wax type and concentration, polymer matrix, film thickness, moisture content, and processing conditions [16, 17]. Therefore, improved moisture resistance should not automatically be interpreted as evidence of equivalent oxygen or carbon-dioxide barrier performance.

Thermal Properties

In terms of thermal characteristics, natural waxes are expected to have a pronounced effect on film properties, mainly due to their specific thermal characteristics i.e. Transition temperature upon melting and cooling and also their interactions with the food matrix components: it appears that wax type significantly influenced the gelatinisation of starch as well as thermal characteristics: beeswax had more potent influence over final film stability and candelilla wax had strong crystalline behavior in post film production. This effect can be seen in the wax/starch/gelatin comparisons [21] however the effect has to be taken in correlation with type of natural wax used.

Antioxidant and Antimicrobial Potential

Wax can be a functional barrier, but in the context of adding any antimicrobial/antioxidant agent it must be considered the performance separately. Many applications have tried to make bifunctional products by incorporating additional anti-oxidants and antimicrobials, e.g. Polyphenols, essential oils, propolis or others in the system.

For example, cassava starch films containing beeswax and propolis demonstrated inhibition of *Aspergillus niger*, with the antimicrobial effect associated with the incorporated active components [19]. Natural waxes have also been incorporated with essential oils such as eugenol and botanical extracts such as Aloe vera in fruit coatings, providing barrier properties alongside antimicrobial or antioxidant functions [14]. These

findings indicate that waxes can serve as components of multifunctional packaging systems, although the specific contribution of the wax should be distinguished from that of the incorporated antimicrobial or antioxidant agents.

Effect of Wax Concentration on Film Performance

When considering barrier properties, the amount of wax is often crucial. At very low levels the hydrophobic nature may not be enough to alter the system; by incrementally increasing levels of wax into the system the overall level of hydrophobic material available to interrupt water sensitive pathways is raised, thus improving barrier performance. Higher amounts may initiate aggregate formation and thereby the formation of discrete hydrophobic domains which create a less coherent surface structure. At these levels, water would be less able to penetrate but a loss in physical properties might occur. It is probably for this reason that there seem to be conflicting results obtained concerning wax systems by using same lipids at different concentrations [16, 17]. Therefore, it is advisable that optimum wax concentration is evaluated experimentally.

Influence of the Film-Forming Polymer on Wax Performance

Similar to above, the type of film-forming polymer dictates the interaction the wax will have with the system. With hydrophilic starches there is great demand on developing an adequate moisture

barrier: proteins and polysaccharides like chitons have inherent differing characteristics on their film forming properties and interaction with water. Hence, it is impossible to present identical wax type of results with same polymer matrix to another. For example, the same series Beeswax/Candelilla wax/Carnauba wax have performed so differently in terms of Mechanical and Thermal Properties as well as WVP for starch/gelatin system [21]. One should therefore also consider the combined influence of polymer upon wax type rather than independent attributes only.

Applications of Wax-Containing Films and Coatings in Fresh-Produce Preservation

The ultimate value of wax-containing edible films and coatings lies in their ability to preserve food quality. By reducing moisture transfer, wax-based systems can decrease weight loss and help maintain firmness and visual quality. They may also modify gas exchange and provide a surface barrier against environmental and microbial deterioration [24].

Evidence from actual food applications supports this potential. Rice bran wax applied as a coating to tomatoes increased the observed shelf life from 18 to 27 days under the reported storage conditions and influenced physiological weight loss, firmness and respiration-related characteristics [17]. Similarly, wax-containing composite coatings have been investigated for citrus and other fruits, with reductions in weight loss and improvements in firmness reported under specific storage conditions [14]. The cited

tomato study [17] suggests that improvements in laboratory film properties may translate into measurable postharvest benefits, though the extent to which this holds across different commodities, coating formulations, and storage environments remains to be systematically established.

Current Limitations and Research Gaps

This review synthesises current knowledge on natural wax incorporation in edible films, comparing wax-specific effects across multiple functional properties and identifying formulation-dependent trade-offs that have not been comprehensively addressed in prior reviews. While the use of natural waxes as constituents in functional edible films has gained attention, several limitations and research gaps remain. Firstly, the different types of wax source, purification procedures (e.g., refining and melting methods), wax concentrations used, specific polymer matrices, plasticiser content, processing conditions, and test methods vary greatly across studies. Consequently, direct quantitative comparison across studies is not readily achievable, and the conclusions of this review are necessarily qualitative and context dependent. Secondly, while properties like hydrophobicity might benefit from additional wax loading, further changes in parameters might lead to negative impacts such as decreasing tensile strength, increasing film opacity or inducing a phase separation between wax and polymer [21].

Additionally, compared with the abundance of reports on common waxes (beeswax, candelilla, carnauba), few studies have examined commercially underutilised plant- and fruit-derived waxes. Consequently, this review's conclusions are disproportionately informed by the most-studied wax types, and the generalisability of findings to other natural waxes remains uncertain [19]. Evidence for underutilised plant- and fruit-derived wax remains limited, and conclusions regarding specific wax sources should therefore be supported by targeted literature searches. Further works are critically important to fully understand wax-polymer interfacial interactions, define standardised testing protocols, and assess scalability, food safety, and environmental impacts. It should also be noted that this review is limited by the absence of quantitative meta-analysis and formal quality assessment of included studies, which constrains the strength of evidence synthesis and the ability to identify publication bias [12].

Future Perspectives

Future research should focus on optimising wax concentration, improving the dispersion of hydrophobic phases within hydrophilic polymer matrices, and exploring emulsion-based or multilayer film systems. Combining natural waxes with antioxidants or antimicrobial agents may also provide multifunctional packaging while avoiding excessive wax incorporation. Greater attention should be given to lesser-known and non-

conventional plant-derived waxes, particularly those that are locally available and can be processed using environmentally sustainable approaches.

Multifunctional edible films incorporating natural waxes with other active ingredients, such as nanoparticles, antioxidants, or antimicrobial compounds, may provide enhanced barrier and preservation functions. However, future studies should evaluate not only film functionality but also food-contact safety, biodegradability, cost, scalability, and life-cycle impacts before widespread application. The development of wax-biopolymer composites from locally available plant sources may provide environmentally sustainable alternatives to fossil-based packaging materials.

CONCLUSION

Natural waxes have the potential to function as useful constituents of edible films and coatings in food packaging applications. Being predominantly hydrophobic, their incorporation can reduce water interaction, thereby decreasing water uptake and water-vapour transfer, which are major limitations of hydrophilic biopolymer-based films. The incorporation of natural waxes may also alter film surface hydrophobicity and modify mechanical, optical, and barrier properties. Studies have indicated that wax-containing films can reduce quality losses in fresh produce, retain certain quality attributes, and consequently extend the shelf life of fruits and vegetables under specific storage

conditions. However, the performance of natural waxes in edible films is highly dependent on wax type, source, concentration, polymer selection, plasticiser content, wax-polymer interactions, dispersion, and film-processing conditions. Wax concentration requires careful optimisation to achieve adequate dispersion and barrier development while avoiding aggregation, phase separation, and undesirable reductions in mechanical properties. Therefore, achieving an appropriate balance between moisture-barrier performance and mechanical properties, alongside other required film characteristics, remains essential for effective wax incorporation. Future research should focus on concentration optimisation, improved wax dispersion and wax-polymer interactions, exploration of lesser-known plant-based waxes, development of multifunctional films containing active components, and evaluation of food-contact safety, biodegradability, life-cycle impacts, and scalability to support the development of environmentally friendly alternatives to conventional petroleum-based packaging.

Author's Contribution

Hamsah R.U. was responsible for conceptualisation, supervision, and writing—review and editing. Madu C.C. contributed to the investigation, literature search and synthesis, methodology, writing—original draft, and writing—review and editing. Egwim E.C. was responsible for validation, critical review,

and writing—review and editing. Oyewole O.A., Umar M.B., Busari M.B., and Baba A.I. contributed to reviewing and editing of the manuscript. All authors reviewed and approved the final version of the manuscript.

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