Drivers and barriers for commercial uptake of edible coatings for fresh fruits and vegetables industry- A review

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ABSTRACT

As the world population is expected to rise to nearly eleven billion by 2050, a concomitant rise in the demand for fresh fruits and vegetables (FFV) is expected. FFV are highly perishable and constitute 20% of the global food wastage with nearly 30% of the losses occurring at the post-harvest (PH) phase. This represents a challenge to ensure food and nutrition security for future generations. A proposed solution is the use of edible coatings incorporating natural ingredients that have the potential to reduce PH losses. Rising consumer demands for healthy, safe and sustainable food have translated to a greater acceptance of natural edible coatings. Edible coatings are hydrocolloid-based layers often applied to the surface of FFV to confer physical protection as well as extending shelf-life and consumer attraction. Although there has been extensive research on edible coatings, their widespread use has been limited due to a number of challenges such as a lack of standards and regulations, limited market research on consumer opinion and purchase intent, difficulties in scaling-up for industrial application and environmental sustainability concerns. This article attempts to shed light on the drivers fostering, as well as barriers impeding, commercial uptake of edible coatings in the FFV industry.

Key words: Edible coating/ Regulation/ Consumer/ Cost / Environment /Drivers/ Barriers

Introduction

The Food and Agriculture Organization of the United Nations (FAO) estimates that by 2050 the world population will reach approximately nine billion.[1] This will cause an increase of 3.2 and 1.6 percent per year in the demand for fresh vegetables and fruits, respectively.[1] However, due to a number of factors namely, climate change, urbanization and a lack of investment, the agricultural sector will not be able to produce enough fresh fruit and vegetables (FFV) to ensure global food and nutrition security by 2050.[2] According to Yahaya & Mardiyya[3], it might not be necessary to step up the production of FFV to cater for the growing demand if the associated post-harvest losses (PHL) are reduced substantially.[3] The author postulated that the cost of preventing PHL is generally less than that of producing a similar additional amount of fruit and vegetable crop of the same quality.[3]

After harvesting, FFV generally become highly perishable due to their soft texture, nutrient composition and high moisture content.[4] They become even more prone to damage and deterioration during the postharvest (PH) management operations such as handling, packaging, transportation, and storage.[3] Major losses occur due to respiration, transpiration, microbes and insects.[5,6] Postharvest losses (PHL) in nutritional quality, can be substantial and are enhanced by physical damage, extended storage periods, high temperatures, low relative humidity, and chilling injuries.[7] Eventually, the cumulative effect of these changes reaches a point where consumers reject the product, because their sensory expectations and perceptions of the product are no longer met. The marketability of FFV is therefore highly dependent on the quality factors of the FFV.[3] Therefore, it is important to develop effective procedures and innovative technologies such as the application of edible coatings to FFV, for maintaining their nutritional quality to meet the increasing consumer demands.[7]

Edible coatings are promising novel systems that can be applied to improve the quality, safety, shelf-life and freshness of FFV.[8] Edible coatings are a thin layer of material applied onto the surface of food which provides a barrier to oxygen, microbes of external sources, moisture and solute movement for food[9]. The application of edible coatings can potentially gain higher interest than conventional food packaging given several unique characteristics.[10] For example, the edibility and biodegradability of natural coatings may cause a reduction in the overall use of synthetic materials as they appeal better to eco-conscious consumers.[11,12] Edible coatings thus have an important role in safeguarding product quality across the supply chain. However, they have to fulfil several requirements to be effectively and economically integrated within the food supply chain.[13]

Edible coatings are produced from a variety of natural biopolymers that are biodegradable such as polysaccharides, protein and lipids.[13,14] Biopolymers are ideal building blocks for edible coatings as they possess the capacity to act as carriers and provide controlled release of substances of active substances such as antioxidants[15,16,17], antimicrobial agents[18,19], nutritional or aromatic compounds[20,21,22] into their polymer matrix.[23] FFV that are coated with edible coatings can stay fresh for extended periods, thus rendering them more acceptable to consumers.[13] In addition, changing consumer demands and needs for convenient foods, that are natural and minimally processed whilst being safe and stable, are driving the global market.[24] Consumers are also more conscious about the negative effects of non-biodegradable packaging on the environment.[13,25] Taken together these above factors can create new opportunities for the application of edible coatings in the FFV industry.

This review starts with a description of the major and minor ingredients of edible coatings and subsequently discusses the limitations standing in the way of industrial application of edible coatings on FFV, such as the difficulty in obtaining regulatory clearance, ensuring consumer acceptance and engineering aspects to ensure consistency in the application of products. The opportunities for creation of specific niche markets for FFV treated with edible coatings are also discussed.

Major and minor components of Edible coatings

Edible coating ingredients can be classified as major or minor. Major ingredients are also called carriers and make up the greatest portion of the edible coating formulation. Minor ingredients are incorporated into edible coatings and provide a specific function. According to Pavlath and Orts[26], edible coatings are made up of different types of materials for application onto various fruits and vegetables to extend their shelf life, and are eaten together with the foods.

The major components that form edible coatings can be classified into several classes according to their structure.[27] These are (i) hydrocolloids e.g., polysaccharides, proteins and alginate, (ii) lipids e.g., fatty acids, acryl glycerides and waxes and (iii) composites or a combination of both groups e.g., protein/protein, polysaccharides/protein, lipid/polysaccharides.[9, 28, 29, 30] It is worth mentioning that lipid-based coatings such as wax can originate from different chemicals and while some are edible such as beeswax, carnauba wax, candelilla wax or sugarcane wax, others such as paraffin wax coatings and polyethylene are non-edible.[31] Synthetic coatings are mainly polyethylene-based and they are a petroleum by-product. As they are manufactured from a limited supply of fossil fuels[32], they are considered non-renewable. Moreover, these are becoming increasingly unpopular and restricted in us as consumer trends lean more towards natural products.[33] Edible coatings made from natural waxes, resins and polysaccharides represent an environmentally ideal preservation treatment for FFV since they are biodegradable, can be consumed with the coated product and the main ingredients are produced from renewable resources provided that the adequate barrier requirements are met.[31] Wax-based coatings that are considered edible must be approved as 'Food Grade' by competent authorities of the respective countries and certified for use on fruits.[34]

Table 1 shows the major components/carrier ingredients of edible coatings currently being used for the preservation of fresh fruit and vegetables as well as the shelf life extension period.

Table 1. Summary of research on the application of different classes of edible coatings on fruits and vegetables.

Class of edible coating	Major components	Produce used for application	Shelf life extension	References
Hydrocolloids (Polysaccharides)	Alginate	Ber fruit	**6-7 days**	[180]
		Blueberry	**ND**	[181]
		Carrot	**5-7 days**	[182]
		Cherry	**8 days**	[183]
		Mango	**ND**	[184]
		Peach	**6-9 days**	[185]
		Pear	**ND**	[186]
		Pineapple	**ND**	[151]
		Plums	**2-3 weeks**	[187]
		Raspberry	**ND**	[123]
		Tomato	**4–6 days**	[188]
	Aloe vera gel (AVG)	Strawberries	**ND**	[189]
	Arabic gum	Banana	**ND**	[190]
		Guava	**2 weeks**	[191]
		Mango	**ND**	[192]
		Papaya	**ND**	[190]
		Sweet cherry	**15 days**	[193]
		Tomato	**20 days**	[194]
	Basil seed gum	Apricot	**ND**	[195]
	Carboxymethyl cellulose (CMC)	Rambutan fruit	**ND**	[196]
	Carrageenan	Strawberry	**ND**	[197]
		Longan fruits	**ND**	[198]
	Chitosan	Apricot	**ND**	[199]
		Grapes	**24 days**	[200]
		Guava	**ND**	[201]
		Orange	**ND**	[202]
		Papaya	**10 days**	[203]
		Red kiwifruit berries	**ND**	[204]

		Strawberry	**ND**	[205]
		Sweet peppers	**ND**	[206]
	Gellan gum	Apple	**ND**	[207]
	Guar gum	Orange	**ND**	[208]
		Sweet cherry	**8 days**	[209]
	Locust bean gum	Mandarin	**ND**	[210]
	Methyl cellulose	Strawberry	**ND**	[211]
		Peaches	**ND**	[185]
		Green peppers	**ND**	[212]
	Pectin	Avocados	**1 month**	[213]
		Mango	**2 weeks**	[214]
		Nectarine	**7 days**	[215]
		Raspberry	**ND**	[123]
		Strawberries	**9 days**	[216]
	Pullulan	Kiwifruit	**4 days**	[217]
		Strawberry	**10 days**	[218]
	Starch	Apple	**12 days**	[108]
		Cucumber, Grape, Green Banana, Guava, Orange, Strawberry, Tomato,	**ND**	[108]
	Xanthan gum	Melon	**21 days**	[21]
		Pears	**4-8 days**	[219]
Hydrocolloids (Proteins)	Soy Protein isolate (SPI)	Apples & Potatoes	**ND**	[220]
	Wheat-Gluten	Strawberries	**6-7 days**	[221]
	Whey protein concentrate	Kiwi fruit	**ND**	[222]
	Zein	Apple	**ND**	[223]
		Tomato	**4–6 days**	[188]
			ND	
Lipids	Beeswax	Lemon	**ND**	[206]
		Mango	**15 days**	[224]
		Strawberries & Apricots	**5-10 days**	[225]
	Candelilla	Apple	**ND**	[226]
	Carnauba	Guava	**ND**	[227]
		Mango	**ND**	[228]
		Passion fruit	**ND**	[229]
	Polyvinyl acetate (PVA)	Tomato	**ND**	[230]
	Shellac	Mango	**10 days**	[231]
Composites & Bilayers	Beeswax & Chitosan	Strawberry	**7 days**	[232]
	Chitosan & Locust bean gum	Orange	**ND**	[233]

Chitosan & Pectin	Papaya	**10 days**	[234]
CMC & AVG	Banana, custard apple, and dragon fruit.	**ND**	[235]
Hydroxypropyl Methylcellulose-Beeswax	Plums	**ND**	[236]
	Cherry tomatoes	**ND**	[237]
Shellac, gelatin and Persian gum	Orange	**ND**	[238]

ND – Not determined, The shelf-life extension period was not clearly stated in the paper.

Besides the major ingredients which make up the bulk of the coating formulation, minor ingredients or additives are usually incorporated into the polymer matrix to perform a certain function. For instance, fatty acids and other surfactants are often used to emulsify waxes and lower surface tension to improve spread.[26] Plasticizers, which are small molecules such as glycerol, propylene glycol, or polyethylene glycol, are used to control viscosity of the liquid formulation, add flexibility and tensile strength, and control surface tension.[27] However, these ingredients can affect coating performance adversely by altering gas permeability or affecting characteristics like shine or gloss, as is shown when adding propylene glycol to a zein coating.[32] Ammonia and morpholine are used to solubilize and disperse fatty acids, waxes, and polymers.[35] Alcohol is used as a solvent and to decrease microbial growth during storage of the liquid coating and also to hasten drying after application to the product.[26] Finally, the bulk of a coating is made up of a solvent, often water or aqueous alcohol.[32] Other minor ingredients besides surfactants and plasticizers include proteins, antifoaming agents, as well as useful additives such as anti-browning, antioxidant or antimicrobial agents.[32]

Regulatory aspects of edible coatings

Edible coatings applied on FFV are intended to be consumed and therefore regulations pertaining to edible coatings should be congruent with those dealing with food additives or ingredients themselves in order to maintain edibility. [32,36,37] In fact, both major and minor components of edible coatings need to meet all the legal requirements.[38] According to the European Union (EU) regulation (Regulation EC 1331/2008 and Regulation EC 1333/2008) and United States (US) regulators (FDA, 2006), the major film-forming components must be food-grade and have a Generally Recognized As Safe (GRAS) status [39] In other words, they (a) shall not be dangerous to human health, (b) shall not alter the conformation of the food in an undesirable way, (c) shall not alter the texture, taste or odour of the food, and (d) shall adhere to the cGMP (EC/1935/2004). Additionally, all processes related to their preparation and application on foodstuffs should be in accordance with high hygiene requirements.[40,41]

This section of the review presents the regulatory aspects of edible coatings intended for use on FFV and focuses on prevailing legislations in the US, EU, the Codex Alimentarius Commission (CAC) and other countries. To our knowledge, there are currently no regulations for edible coatings in Mauritius other than the requirement that all products coated with edible coatings should adhere to GMPs.[42]

Regulations concerning the major components in edible coatings

US Regulation

In the US, the FDA provides a list of substances that are allowed to be used as major components in edible coatings either under the category of “Food additives permitted for direct addition to food for human consumption” (172.5 to 172.898) [DFA] or “Secondary direct food additives permitted in food for human consumption" (173.5 to 173.405) [SDFA][43,44]. For major components that are polysaccharide-based, most are approved under DFA as general use additives, including carrageenan, furcelleran and their corresponding salts, gellan, xanthan, and locust bean gums[40] (21 CFR 172).[43] These additives have important film-forming properties which can be exploited during coating of FFV. On the other hand, additives such as Polyvinylpyrrolidone, Sodium polyacrylate and Sorbitan monooleate are classified as SDFA under the "polymer substances and polymer adjuvants for food treatment" (21 CFR 173).[44]

As mentioned earlier, all components of an edible coating should be GRAS and be used for the specified purposes.[40] Major components that have already been given GRAS status and fall under Part 184 (Direct food substances affirmed as GRAS) Subpart B (Listing of Specific substances affirmed as GRAS) include pectin, wheat gluten, candelilla and carnauba wax.[45] If the edible coating polymer is not GRAS, but the manufacturer can provide evidence that it is safe, then a petition for GRAS affirmation can be filed to the Food and Drug Administration (FDA) or products can be marketed without FDA endorsement.[46] In addition, according to the Federal Food, Drug and Cosmetics Act (FD&C), all ingredients used for the construction of edible coatings must be declared on the label (21 USC 343).[47] Moreover, the application of edible coatings on FFV requires that only the necessary amount of coating components and final coating necessary to accomplish the intended effect are used (21 CFR 172).[43] If a substance has the potential to migrate from the coating to the food, it also becomes a component of the food and thus must be regulated as a food additive.[48]

Major components which fall under the list of "prior sanctioned substances" are exempted from classification as a food additive and thus excluded from the regulation.[42] Prior-sanctioned substances are those whose use in or on food were approved for a specific use mentioned in, Regulation 21 CFR 181. However these substances still need to adhere to the FD&C Act (21 CFR 180.1 (c)). However, their pre-sanctioned status can be revoked if they are adulterated or misleading[46]. To market edible coatings incorporating a new food additive or an already approved additive which had not previously been approved for use in coatings, a manufacturer or other sponsor must first petition the FDA for approval of the edible coating formulation and present evidence that the substance is safe for the manner in which it will be utilized (21 CFR 172).[43, 46] If clearance is obtained, the regulation will need to specify the type of foods that it can be used for, the maximum amount allowed to be used and how it should be identified on the label.[47]

It is also worth mentioning that for an edible coating to be certified "organic" or for coating applications on organic produce, the major components must be ingredients featuring on the "The National List of Allowed and Prohibited Substances" [48] developed by the National Organic Program (NOP) of the USDA.[32]

EU Regulation

The European Union (EU) legislation defines an edible coating as a substance not normally consumed as a food in itself or used as a distinctive component of food but is intentionally added to food to serve a technological purpose.[49] According to EU regulation (EC/1333/2008), the use of edible coatings should meet all legal requirements, that is, they should be permissible and not toxic. In fact, the European Directive (95/2/EC) states that edible coatings can be classified as: "food products, food ingredients, food additives, food contact substances, or food packaging materials."[50,51] Therefore, only additives which have been demonstrated to comply with Regulation 1333/2008, Article 5, i.e., feature on their positive list, are eligible to be placed on the market. Moreover, they also have to comply with Article 4 requirements which state that (i) there should be no safety concerns for consumer health at the proposed level of use, (ii) they should not deceive the consumer and (iii) they have to fulfil a technological need, such as shelf-life extension, that cannot be reasonably achieved through other means.[35, 41,52] In addition, deliberate usage of food additives in the edible coating formulation must be labelled on the packaging in accordance with the specific functional category with either their name or E-number (EC/1333/2008)[32,53]. Major components of edible coatings that are allowed include gums of acacia (E414), xanthan (E415) and karaya (E416), pectins (E440), shellac (E904) as well as wax of bees (E901), candelilla (E902) and carnauba (E903), and lately new ingredients such as fatty acids (E470- E479) and fatty acid salts, lecithin (E322) and polysorbates (E432-E436).[39,53] These new ingredients are of importance in food application principally as emulsifiers, anti-spattering agents and as synergists for antioxidants.[32,53] In all cases, these additives should be used whilst observing the *quantum satis* principle.[32,41] *Quantum satis* implies that when no maximum numerical level is specified, only the necessary amount to achieve the intended purpose shall be used in accordance with good manufacturing practice (Regulation (EC) No 1333/2008).[49]

Codex Alimentarius Commission Guidelines

Compared to the US and EU regulations, the polymer matrix of edible coatings are also regarded as food additives or composite food additives according to the Codex Alimentarius Commission CAC.[32] With reference to the CAC, only the substances listed under the "Food additives guidelines section" (Codex STAN 192-1995) are recognized as suitable for use in edible coatings in accordance with cGMP.[32,54] Major components of edible coatings that are listed for surface-treated FFV include, beeswax, candelilla and carnauba wax as well as shellac (Codex 192-1995)[55]. It is also worth mentioning that the use of the edible coating material is only justified when the utilization presents an advantage and serves one or more unique technological functions set out by Codex.[56]

The regulatory status for the US and EU as well as the CODEX guidelines pertaining to the major components of edible coatings are summarized in Table 2.

Regulations concerning minor components of edible coatings

Minor components comprise of a variety of functional ingredients or food additives that include antimicrobials, antioxidants, emulsifiers and plasticizers[32], and there are also provisions in the US and EU regulations and the CAC concerning minor components intended for application on FFV. For obtaining regulatory approval, these incorporated compounds should also be (i) GRAS, (ii) subjected to limitation of maximum use levels or restricted technical function[39,46] and (iii) mentioned on the ingredient label of the products itself.[36,41]

US Regulation

The FDA legislation regulates the minor components of edible coatings under different sections of the Code of Federal Regulations (CFR). For instance, substances such as Butylated hydroxyanisole (BHA), Butylated hydroxytoluene (BHT) and Tertiary butylhydroquinone (TBHQ) are subject to 21 CFR 172 ("Food additives permitted for direct addition to food for human consumption")[43] while essential oils, natural extracts, chemical preservatives such

Table 2. Regulations and standards for selected major components used for coating fresh fruit and vegetables.

Major components/ Carriers	Categories	Regulatory status		Standards
		US	**EU**	**CODEX**
Alginate	Emulsifier, Humectant, Stabilizer, Thickener	GRAS (21CFR 184.1011)	*quantum satis* (E400-E404)	GMP (INS no. 400)
Beeswax	Emulsifier Glazing agent Stabilizer Thickener	GRAS, GMP (21CFR 184.1973, 582.1973)	*quantum satis* (E901)	GMP (INS no. 901)
Candelilla wax	Emulsifier Glazing agent Thickener	GRAS, GMP (21CFR 184.1976)	*quantum satis* (E902)	GMP (INS no. 902)
Carnauba wax	Emulsifier, Stabiliser or thickener	GRAS, GMP (21CFR 184.1978, 582.1978)	130 000 mg/kg in the preparation, 1200 mg/kg in final product from all sources (E903)	400mg/kg (INS no. 903)
Carrageenan	Emulsifier, Humectant, Stabilizer, Thickener	20 percent to 40 percent on a dry-weight basis (21CFR172.620)	*quantum satis* (E407)	GMP (INS no. 407)
Cellulose	Anticaking agent, Emulsifier	N/A	*quantum satis* (E460)	GMP (INS no 460 (ii))
Gum Arabic (Acacia gum)	Emulsifier, Stabilizer, Thickener	GRAS, GMP (21CFR184.1330, 582.7330)	*quantum satis* (E414)	GMP (INS no. 414)
Pectin	Emulsifier, Stabiliser and Thickener	GRAS, GMP (21CFR184.1588)	*quantum satis* (E440)	GMP (INS no. 440)
Xanthan gum	Emulsifier, Stabilizer, Thickener	FDA-approved (21CFR172.695)	*quantum satis* (E415)	GMP (INS no. 415)

N/A – Not available

GRAS: Generally recognized as safe. Substances in this category are by definition, under Sec. 201(s) of the FD&C Act, not food additives. Most GRAS substances have no quantitative restrictions as to use, although their use must conform to good manufacturing practices. **GMP:** Major coating ingredient may be used in the following foods under the conditions of good manufacturing practices (GMP) as outlined in the Preamble of the Codex GSFA.[32]

'*quantum satis*' shall mean that no maximum numerical level is specified and substances shall be used in accordance with good manufacturing practice, at a level not higher than is necessary to achieve the intended purpose and provided the consumer is not misled (EC No1333/2008).

E-number: A number used in the European Union to identify permitted food additives. An E number means that an additive has passed safety tests and has been approved for use.

INS: The International Numbering System for Food Additives used by CODEX.

CFR: Code of Federal regulations for the US.

ascorbic acid, potassium sorbate and sodium benzoate amongst others, as well as emulsifying agents such as oleic acid, potassium oleate and sorbitan monostearate are subjected to the 21CFR 182 “Substances Generally recognised as safe.”[45]

EU Regulation

With regards to EU regulations, minor components of edible coatings such as Ascorbic acid (E300), Benzoic acid (E210), Sodium benzoate (E211), Potassium sorbate (E202), Sulphur dioxide and Sulphites (E220 – E228) which have a role in FFV preservation are regulated under Annex III “ Union list of food additives including carriers approved for use in food additives, food enzymes, food flavourings, nutrients and their conditions of use”.[53] Similarly, other minor components such as lecithins (E322), polysorbate (E 432 – R436) and sorbitan esters (E491 – E 495) which are approved glazing agents for fruits, are also listed in Annex III.[53] Minor components with antimicrobial function that are approved for use on FFV such as nisin and natamycin are regulated under Annex II “Union list of food additives approved for use in foods and conditions of use” under E-numbers E 234 and E235 respectively.[53]

Codex Alimentarius Commission Guidelines

As far as the CAC is concerned, minor components of edible coatings listed for surface treatment of FFV include sulphites (INS 220-225 227, 228, 539), sucroglycerides (INS 474), polyethylene glycol (INS 1521) and polyvinylpyrrolidone (INS 1201).[54] All food additives should adhere to the GMP [32,54] and be used within limits wherever stated.

Table 3. Regulations and standards for selected minor components used for coating fresh fruit and vegetables

Minor components	Categories	Regulatory status		Standards
		US	EU	CODEX
Antimicrobials				
Benzoic acid	Preservative	GRAS (21CFR184.1021)	1 500 mg/kg singly or in combination in the preparation 15 mg/kg in the final product expressed as the free acid E210	1,500 mg/kg (INS No. 210)
Clove bud oil	Essential oil	GRAS (21CFR 184.1257)	N/A	N/A
Potassium sorbate	Preservative	GRAS/FS (21CFR 182.3640)	1 500 mg/kg singly or in combination in the preparation 15 mg/kg in the final product expressed as the free acid (E200-E202)	1,500 mg/kg (INS No. 202)
Propionic acid	Preservative	GRAS/FS, GMP (21CFR 184.1081)	1000 mg/l (E280-283)	GMP (INS No. 280)
Sodium benzoate	Preservative for fruit jellies and citrus juices	GRAS/FS, GMP (21CFR 150.141, 150.161, 184.1733)	1 500 mg/kg singly or in combination in the preparation 15 mg/kg in the final product expressed as the free acid (E211)	1,500 mg/kg (INS No. 211)
Sorbic acid	Preservative	GRAS, GMP (21CFR 182.3089)	2 500 mg/kg in the preparation (E200)	1,500 mg/kg (INS No. 200)
Antioxidants				
Ascorbic acid	Antioxidant, preservative, colour stabilizer	GRAS, GMP (21CFR 182.3013)	*quantum satis* (E300)	GMP (INS No. L-300)
Ascorbyl palmitate	Antioxidant, preservative, colour stabilizer	GRAS (21CFR 182.3149)	*quantum satis* (E304 (i))	500 mg/kg (INS No. 304)
BHA (Butylated hydroxyanisole)	Antioxidant	GRAS, FS (21CFR 172.110)	20 mg/kg singly or in combination (expressed on fat) in the preparation, 0,4 mg/kg in final product (singly or in combination) (E320)	400mg/kg (INS No. 320)
BHT (Butylated hydroxytoluene)	Antioxidant	GRAS, REG, FS (21CFR 137.350, 172.115)	20 mg/kg singly or in combination (expressed on fat) in the preparation, 0,4 mg/kg in final product (singly or in combination) (E321)	400mg/kg (INS No. 321)

Citric acid	Sequestrant, buffer and neutralizing agent	GRAS/FS, GMP (21CFR 182.1033, 182.6033)	*quantum satis* (E330)	GMP (INS No. 330)
Propyl gallate	Antioxidant	GRAS (21CFR 184.1660)	1 000 mg/kg (propyl gallate, TBHQ and BHA, individually or in combination) in the essential oils (E310)	1,000 mg/kg (INS No. 310)
TBHQ (Tertiary butylhydroquinone)	Antioxidant	REG (21CFR 172.185)	1 000 mg/kg (propyl gallate, TBHQ and BHA, individually or in combination) in the essential oils (E319)	400 mg/kg (INS No. 319)
Tocopherols	Preservative, dietary supplement, nutrient	GRAS, GMP (21CFR 182.3890, 184.1890, 182.8890)	*quantum satis* (E306-E309)	GMP (INS No. 307)
Emulsifiers				
Acetylated monoglycerides	Emulsifier, coating agent, stabilizer	REG, GMP (21CFR 172.828)	N/A	GMP (INS no. 472a)
Glycerol monostearate	Coating agent, emulsifier	GRAS/FS, GMP (21CFR 184.1432)	N/A	N/A
Lecithin	Emulsifier, antioxidant	REG, GMP (21CFR 172.814)	*quantum satis* (E322)	GMP (INS No. 322(i))
Oleic acid	Emulsifier, binder, lubricant, coating for citrus fruits	REG, GMP (21CFR 172.840, 172.860, 172.863, 172.210)	N/A	GMP (INS no. 470(ii))
Sodium oleate	Packaging coating, emulsifier, anti-caking agent	REG (21CFR 172.863)	N/A	GMP (INS No. 470 (ii))
Sorbitan monostearate	Emulsifier, defoamer, stabiliser, coating fresh fruit	REG, GMP (21CFR 172.842)	*quantum satis* (E491)	5,000 mg/kg (INS No. 491)
Stearic acid	Emulsifier	GRAS,GMP (21CFR 184.1090)	N/A	GMP (INS no. 470(i))
Sucrose stearate	Emulsifier, texturizer and component of fruit coatings	REG,GMP (21CFR 172.859)	N/A	1,500 mg/kg (INS No. 473)
Miscellaneous additives				
Calcium chloride	Antimicrobial agent, firming agent	GRAS/FS (21CFR184.1193)	*quantum satis* (E509)	GMP (INS No. 509)
Carotene (β-carotene)	Nutrient, dietary supplement, colouring agent	GRAS, GMP (21CFR182.5245, 182.8245)	*quantum satis* (E160)	GMP (INS No. 160 (ii))
Essential oils	Natural flavourings	GRAS (21CFR 182.20)	N/A	N/A

Silicon dioxide	Anticaking agent, component of microcapsules for flavouring oils	REG, GMP (21CFR 172.480, 172.230)	*quantum satis* (E551)	GMP (INS No. 551)
Plasticizers				
Acetylated monoglycerides	Emulsifiers, coating component	GMP, REG (21CFR 172.828)	N/A	GMP (INS no. 472a)
Glycerol	Plasticizer, food flavoring	GRAS/FS, GMP (21CFR 182.1320)	quantum satis (E422)	GMP (INS no. 422)
Lauric acid	Coating for fresh fruits	REG (21CFR 172.210)	N/A	N/A
Oleic acid	Lubricant, binder, defoaming agent, and as excipient of other food-grade additives	GMP, REG (21CFR 172.840)	N/A	GMP (INS no. 470(ii))
Palmitic acid	Lubricant, binder, defoaming agent, and as excipient of other food-grade additives; coating for fresh citrus fruits; antifoaming in food processing	GMP, REG (21CFR 172.860, 172.210,173.340)	N/A	GMP (INS no. 470(i))
Polyethylene glycol	Coating component on fresh citrus fruits, binder, plasticizer, lubricant, resinous/polymeric coatings	GMP, REG (21CFR 172.210)	*quantum satis* (E1521)	GMP (INS no. 1521)
Propylene glycol	Plasticizer, component of resinous and polymeric coatings	GRAS/FS (21CFR 184.1666)	1 000 mg/kg in final food (as carry-over) (E1520)	2,000 mg/kg (INS no. 1520)
Sorbitol	Plasticizer, component of resinous and polymeric coatings	GRAS, GMP, REG (21CFR 184.1835)	*quantum satis* (E420)	GMP (INS no. 420(i))
Stearic acid	Lubricant	GRAS, GMP, REG (21CFR 172.860, 184.1090)	N/A	GMP (INS no. 470(i))
Sucrose	Nutritive sweetener	GRAS, GMP (21CFR 184.1854)	*quantum satis* (E473)	N/A

N/A – Not available

GRAS: Generally recognized as safe. Substances in this category are by definition, under Sec. 201(s) of the FD&C Act, not food additives. Most GRAS substances have no quantitative restrictions as to use, although their use must conform to good manufacturing practices. **GRAS/FS**: Substances generally recognized as safe in foods but limited in standardized foods where the standard provides for its use. GMP: Good manufacturing practices. **REG**: Food additive for which a petition has been filed and a regulation issued.[32]

‘***quantum satis***’ shall mean that no maximum numerical level is specified and substances shall be used in accordance with good manufacturing practice, at a level not higher than is necessary to achieve the intended purpose and provided the consumer is not misled (EC No1333/2008).

E-number: A number used in the European Union to identify permitted food additives. An E number means that an additive has passed safety tests and has been approved for use.

INS: The International Numbering System for Food Additives

CFR: Code of Federal regulations for the US.

The regulatory status for the US and EU as well as the CODEX guidelines pertaining to the minor components of edible coatings are summarized in Table 3. [Table 3 near here]

Edible coating regulations in other countries

Edible coating regulation in Japan

In Japan, the Food Sanitation Act is concerned with standards and specifications for food and food additives amongst others.[57] According to the Japan Food Chemical Research Foundation, major components of edible coatings, such as alginate, are approved for use in all foods, including FFV, in any form.[58] However, no specific mention is made for use of alginate as a carrier or coating. Although there are standards governing the use of food additives for FFV, such as diphenyl as an anti-fungal agent for citrus fruits, these are not mentioned for use in edible coatings.[58] It is also worth mentioning that in spite of extensive provisions in the Japanese regulation concerning food packaging materials [32,41,59], to our knowledge, there is no specific mention of edible coatings.

Edible coating regulations in Canada

In Canada, fresh fruits and vegetables are not subject to the "Food and Drug Regulation of Canada C.R.C., c. 870."[32] Therefore, fruits and vegetables are classified as "unstandardized foods".[32] Moreover, components of fruit and vegetable coatings are not regulated as food additives with the exceptions of mineral oil, paraffin wax, and petrolatum.[60] In fact FFV, with the exception of turnips, can be coated with paraffin wax and petrolatum at a level not exceeding 0.3% in conjunction with GMPs.[61] All other food additives permitted for use on unstandardized foods can be applied to fruits and vegetables unless mentioned otherwise.[61] Other protective coatings, such as vegetable oil, are not currently regulated as food additives as they have traditionally been used as food ingredients.[41] Waxy substances such as beeswax can be used as an anti-sticking agent for unstandardized foods such as FFV at a level not exceeding 0.4%.[61] According to the Canadian Food Inspection Agency (CFIA), growers, packers, distributors and food importers should take it upon themselves to consult the list of permissible ingredients to be included in FFV coating or waxing, and its technical specifications before commercial application.[62] Even if a wax and coating product is GRAS for food contact application in the exporting country, the product must still comply with the prevailing regulatory requirements of Canada.[32] Moreover, any substances incorporated in the coatings should meet the standards for food additives used in edible coatings as listed in the Food and Drug Regulations (C.R.C., c.870).[32,60] It is worthy to note that under the "Food and Drugs Regulations Act", coating manufacturers are not required to submit their coating formulation for review to Health Canada's Bureau of Chemical safety (BCS), but this can be voluntarily done at the discretion of the manufacturer.[32] Moreover, although the current legislation does not require the industry to declare any coating or wax components applied on coated FFV, film-forming materials which are potentially allergenic should be mentioned on the label and this greatly limits their use on FFV.[60] Ultimately, coating manufacturers and importers are compelled under Section 4(a) of the Food and Drugs Act Regulations to ensure that their coating formulation applied on FFV poses no health risk to consumers.[32,62]

Australia and New-Zealand

Australia and New Zealand have an integrated food regulatory system and established the Food Standards Australia New Zealand Code (FSANZ)[63] as an independent statutory agency for the two countries and they have provisions concerning components of edible coatings intended for FFV application. Major components of edible coatings such as beeswax (INS 901), carnauba wax

(INS 903), shellac (INS 904) are allowed for use in conjunction with GMPs.[32] In addition, minor components such as ammonium phosphate (INS 342) and sucrose esters of fatty acids (INS 473) have also been approved for use in coatings as potential antifungal agent or to enhance the barrier properties respectively.[32]

Gaps in the Regulation

Regulations pertaining to edible coatings intended for FFV application differ from country to country. Moreover, every country has different coating practices and therefore, some additives approved for FFV coatings in one country may not be approved in another.[32] For example, oxidized polyethylene is not approved for use in Japan while it is allowed in the US and EU.[32] Another example is that fresh fruit processed in the European Union (EU), cannot be coated with morpholine-containing fruit coatings, although such coatings are routinely used in the United States.[32] Morpholine has limited approval, because like other amines, it can react to form carcinogens.[35,64] Attempts to make morpholine-free coatings in the United States are in fact underway.[35,65] Another important issue is the labelling requirement for edible coatings which contain constituents such as milk protein (whey and casein), wheat protein (gluten), soy, peanut or walnut protein which are allergenic. As various authors [36,37] have indicated, it is extremely important that the presence of specific allergens be clearly and accurately indicated on the product label[47].

Industrial application and Cost feasibility

Cost feasibility and industrial applicability of edible coatings

Rapidly expanding knowledge on the related health benefits of FFV has increased global awareness and concurrently propelled international vegetable and fruit trade. For instance, in the fruit industry, Ecuador exported approximately 6 million tons of bananas and 89 thousand tons of pineapples in 2019, Costa Rica exported approximately 2 million **tons** of pineapples, and Chile exported about 65 thousand tons of grapes .[66] In 2015, 55% of the global population, representing 81 countries, achieved the WHO target for a minimum of 400 g of fruit per person per day.[67] With a view to meet WHO recommendations, it is expected that fruit trade will substantially increase in the near future. The increased recognition of the potential of vegetables as an affordable source of vitamins and minerals has boosted demand and fuelled trade.[68] Approximately 1 million tons of tomatoes was exported from Mexico in 2019, about 2 million tons of potatoes were exported from France and 39 thousand tons of cauliflowers and broccoli were exported from Spain.[66] However, both fruits and vegetables are highly perishable in nature and easily undergo postharvest damages, which account for a loss of 18–28%. Postharvest losses increase through the trading process, particularly during long distance distribution. The concept of "food miles" has been coined to provide an estimate of the number of miles or kilometres food items travel from the point of production to the point of consumption.[69] Fresh fruits exported from Chile to China travel approximately 19,000 km; citrus exported to China from South Africa travel a distance of approximately 11,000 km; and apples exported to India from the United States travel a distance of approximately 12,000 km.[70] Moreover, global fruit and vegetable trade has its own set challenges, such as, retaining the quality and freshness of fruits and vegetables travelling long distances, and ensuring safety and swift movement of fresh fruits and vegetables through the supply chain.[71]

Application of edible coatings might therefore be considered as an interesting strategy to preserve the freshness and extend the shelf-life of fresh fruits and vegetables during long distance trading, thereby enhancing profitability and growth of fruit and vegetable trade sectors. Considering the significant share of international fruit and vegetable trade as well as the aforementioned challenges, the cost feasibility and industrial applicability of edible coating application on fresh fruits and vegetables will be discussed in this section.

Exportation of FFV involves a number of actors and complex logistics. In general, actors involved in the FFV global value chain include producers, packaging centres, exporters, importers, warehousing facilities, distributors, wholesalers, retailers, and consumers. Figure 1 shows three different value chains of FFV in Uganda, South Africa, and Malaysia. As in the case of pineapples, mangoes, and avocados exportation in Uganda, fresh fruits come from different producers (Figure 1A) and are channelled towards the international exporters. Likewise, fruit and vegetable exporter companies in South Africa collect fruits and vegetables from small, medium, and large farms. The duration of this process depends on logistics and other conditions, such as road infrastructures. Packed fruits and vegetables are then exported by air or sea freight. Land transportation is also involved in FFV exportation, for example, from warehouses to freight forwarder and from importer to supermarket. Time is a crucial factor in the exportation of FFV due to high perishability. Figure 1C presents the value chain for jackfruit exportation from Malaysia to Dubai by air freight. Interestingly, the authors showed the timeline from harvesting of jackfruits to the consumers in Dubai. Considering that the jackfruits travelled a distance of approximately 5591 km[70]; the jackfruits reached the supermarket shelves 3 days after harvesting. However, it has been noted that the timeline was not reported for other value chains.

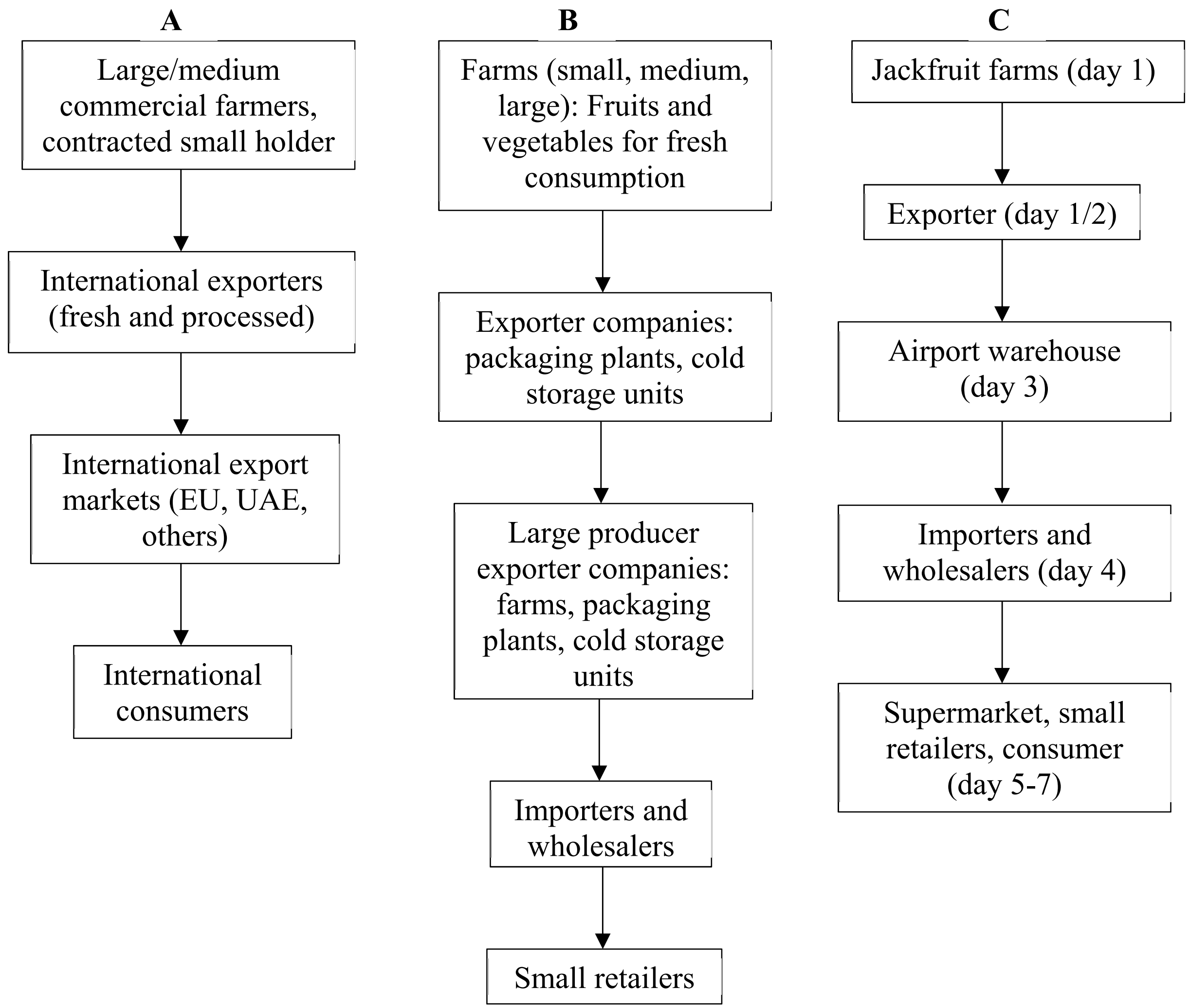

Figure 1. A. Pineapples, mangoes, and avocados value chain in Uganda[239] **B**. Fruits and vegetables value chain in South Africa[240]; **C**. Jackfruit value chain from Malaysia to Dubai by air freight[177].

Edible coating can be applied on the fruits and vegetables at different levels in the supply chain. Multiple scenarios are possible, for instance, edible coating application might occur at the level of the producer before collection or at the level of the packer before exportation. The application of the coating before exportation might be beneficial in terms of less spoilage during transit. If exportation is relatively short and quick and does not represent high risk for post-harvest damage, the coating might be applied at the level of the retailer to ensure an extended shelf-life of the product. Dipping, brushing, spraying, and electrostatic spraying are the different coating application techniques (Figure 2).[72] Table 4 summarizes the basic principle of the various techniques used for edible coating application on fruits and vegetables, as well as their advantages and limitations. Investment in the application technology greatly depends on the processing level, i.e., large or semi-industrial scale, while scaling-up edible coating application at industrial level involves a number of challenges which must be addressed. For example, washing fruits in water containing detergent before coating might remove the natural protective layer present on the surface of some fruits; and surface dehydration and moisture loss might happen during drying.[73] Assessing the advantages and limitations of the different coating techniques is crucial. A comprehensive review recently published by Maringgal and colleagues[74] reported that dipping was the most commonly used technique for the application of edible coatings. However, at commercial level the spraying method is regularly used. Scientific studies play a pivotal role in the assessment of edible coatings application during scaling up. It can be argued that there is a lack of scientific information regarding the use of spraying methods for the application of edible coatings on fruits and vegetables, representing a research gap.

A number of biopolymers, namely, polysaccharides, proteins, and lipids, have received scientific consideration for the development of edible coating.[75] The successful commercial

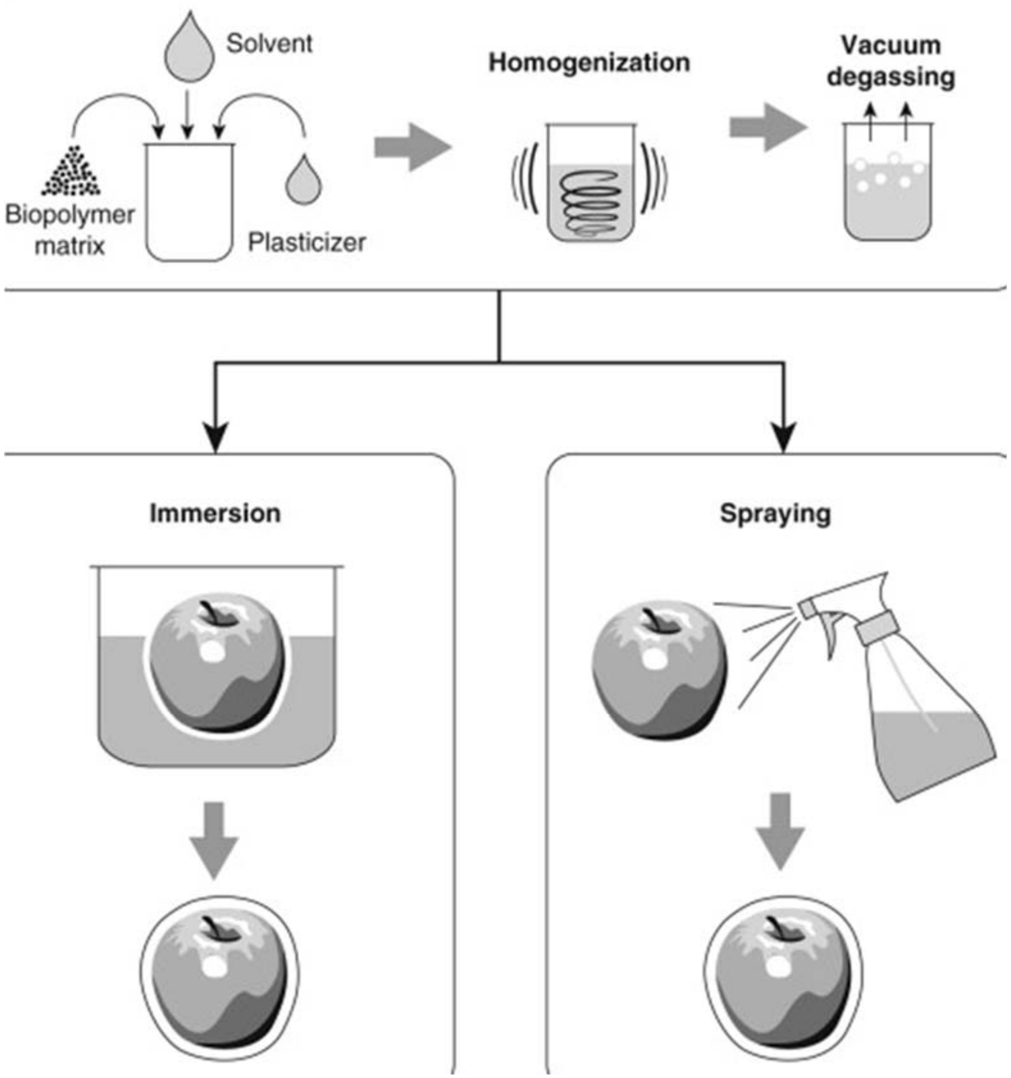

Figure 2. Preparation of edible coating solution and schematic representation of coating application techniques.[241,242]

Table 4. Methods of edible coating application.

Application method	Basic principle	Advantages	Limitations	References
Dipping	Immersion, dwelling to ensure complete interaction (5–30 sec), deposition to develop thin layers on the surface of fruit, draining, evaporation using heating and drying procedure	Simple, low cost, completely coat product surface, ensures good uniformity across rough and complex shape, **higher thickness of the coating material on the surface of food products**	Dilution of coating, waste or dirt accumulation, development of microbes in the dipping vat, dilution of the external layer and degradation of its functionality	[25, 243]
Spraying	Form droplets by dispensing via nozzles, three types of spraying techniques are used in the food industries edible coating application, namely, air spray atomization, air assisted airless atomization, pressure atomization	Uniform thickness coating, possibility for multilayer applications, no contamination, temperature control of the coating solution, and continuous production flow	Highly viscous solution cannot be easily sprayed	[25, 243]
Brushing	Application of coating using brushing equipment	Simple, unexpensive, automated, continuous production flow	Irregular coating	[71]

application of edible coatings to fruits has been reported in Table 5. Moreover, several companies providing post-harvest solutions, such as Fomesa Fruitech and Decco, are launching new edible coatings. For example, GreenSeal, Naturcover, and GreenGard-LE, based on biopolymers, hydrocolloids, edible emulsifiers, fatty acids, and natural waxes, have been commercialized. [76,77] GreenSeal-VG, a carnauba-based edible coating developed specially for vegans, was marketed by Fomesa Fruitech.[77]

The cost of production of biopolymer depends on a number of factors, including the source of biopolymer. For example, beeswax and shellac are produced by insects while pectin and cellulose occur in the cell wall of higher plants and are recovered by extraction. Extraction using conventional methods, such as, heat treatment under acidic conditions in the case of pectin, produce large streams of effluents and has low efficiency, limiting large-scale extraction.[78] New extraction methods, namely, microwave-assisted extraction, ultrasonication-assisted extraction, have been reported to considerably improve extraction yield, reduce extraction time, and energy use as compared to conventional methods.[79] Lately, microwave-assisted extraction has shown great potential for industrialization. The excellent performances of microwaves in the extraction of pectin have been extensively reported in the literature.[80-84] Ciriminna and colleagues[88] evaluated the industrial feasibility of pectin extraction from citrus peel using microwave technology at pilot scale. The plant produced up to 55 kg of high-quality pectin in 7 hours/one working day, consuming 840 kWh of energy. Based on the price of 346.5 EUR per kilo of pectin, the plant would produce an equivalent of 19,000 EUR in one day.[78] Even though the application of microwave is technically feasible for the recovery of pectin at industrial scale, associated high initial investment and maintenance costs could be a hurdle to its implementation.[85] Additionally, Ciriminna and colleagues[78] pointed out that the largest influence on the final manufacturing costs

Table 5. Commercial edible coatings.

Trade name	Composition	Examples of fruits coated	Purpose	Biopolymer present in formulation	Source of biopolymer	Main manufacturers	References
Tal Pro-long™	Sucrose polyesters of fatty acids and sodium salt of carboxymethyl cellulose	Plantains	Retard ripening of fruits, extend shelf life	Carboxymethyl cellulose, chemically modified-cellulose	Plant, algae and bacteria Main source: wood and cotton	NA	[244]
Prolong	Sucrose polyesters of fatty acids and sodium salt of carboxymethyl cellulose	Mango, pear	Retard ripening, reduce weight loss and chlorophyll loss	Carboxymethyl cellulose, chemically modified-cellulose	Plant, algae and bacteria Main source: wood and cotton	NA	[88]
Freshseel™	Sucrose esters	Melon	Extend shelf life	NA	NA	AgriCoat Nature Seal Ltd	[244]
Semperfresh™	Sucrose esters based	Stone fruit, pineapple, melon, avocadoes, citrus fruit, pears, apples, sweet cherries, and other tropical fruits	Retard moisture loss, ripening and spoilage	NA	NA	Pace International[239] LLC, AgriCoat Nature Seal Ltd	[191,245]
Nature-seal™	Blend of vitamins and minerals	Apples, pears, stone fruit, avocado, carrot	Extend storage and shelf life	NA	NA	NatureSeal, Inc.	[246]
Apeel™		**Avocados, limes, mandarins, apples, cucumbers**	**Extend shelf life**	**Highly polymerized esters of fatty acids**	**Plant**	**Apeel Sciences**	**[247]**

was the cost of electricity as well as operational labour cost, which, nonetheless can be limited. Other factors, such as, supply, storage, and drying of raw materials and standardization of the biopolymer might affect the cost of production.[86]

Benefits of uncoated *versus* coated fruits or vegetables are fundamental to ensure sustainable growth and demand. The ability of edible coating to preserve the sensory integrity, freshness, and nutritional value of the fruits, as well as, extending the shelf life, thus causing less wastage are decisive factors which must be considered, and consumer awareness of these benefits is a requisite to drive the demand for edible coated fruits.[87,88] Considering consumers' opinion is crucial for the successful marketing of new products and price is one of the factors affecting consumers' intent to purchase.[89] Most consumers would choose to buy the less expensive product, if the coated and uncoated products had the same qualities and benefits. However, if consumers perceive that coated fruits are value added products, they might pay a higher price for the coated products if the benefits are obvious.[90] A survey conducted amongst 611 participants, revealed that 70.97% of the respondents were expecting to pay the same price for coated and uncoated fresh-cut fruits and vegetables, 16.78% were willing to pay higher price, while 12.25% expected a lower price.[90]

Currently the most commonly used coating for fruits, vegetables and meats is the dipping method. With this method the commodity is directly dipped into the composite coating formulations (in aqueous medium), removed and allowed to air dry, whereby a thin membranous film is formed over the commodity surface. However, continuous dipping leads to a build-up of decay organisms, soil and trash in the dipping solution, which needs to be removed for better performance characteristics and consumer acceptance.[91]

Consumer acceptance

Consumer acceptance is crucial to the development of successful food products and is a major driving force of the global food market.[92] Understanding why consumers choose to buy and consume a product is important for assessing their motivation for doing so and allows for the determination of any barriers to consumption.[93]

Consumers' attitudes and motivations are largely influenced by factors such as quality or value, however there are numerous other complex factors that can also impact on consumers' perception.[94] **These factors may be either internal to the person (e.g., skills, abilities, power of will, compulsion) or external to the person (e.g., time, opportunity, dependence on others).[94]** For these reasons, product sensory evaluation is extremely important in relation to new technologies especially, to obtain the consumers' perspective and for food chain innovation.

Over the last decade, the healthy eating trend of nutrition-conscious consumers has boosted the demand for more natural, high-quality, safe foods that can stay fresh for extended periods of time.[95,96] Consumers are also becoming more conscious about the environment and the growing rate of waste from fossil-based packaging materials, and are demanding alternative food packages that are edible, recyclable and biodegradable and are prepared with renewable and sustainable processes that do not increase pollution.[97,98] Consequently, extensive research has been done by companies and researchers to focus on developing environmentally friendly, biodegradable, and edible packaging materials. This has given rise to the concept of active packaging, a type of packaging that is coordinated to maintain or even improve conditions surrounding the food thus enhancing the productivity, sensory properties, quality, freshness, safety and extend the shelf life of fresh fruits and vegetables.[4,7,12,75,98,99]

Edible coatings are an ideal alternative to conventional synthetic/plastic packaging material as they are produced from biopolymers they possess the advantages of biodegradability, process simplicity and an aptitude to be combined with other materials [17,88, 99-105] ; to reduce food waste and PHL of FFV.[106] Research has shown that edible coatings can protect food products against various microbial organisms[107], enhance their shelf life[108-110], reduce deterioration effect[111], minimize lipid oxidation[112], and- control moisture transfer[113] and gas exchange.[114] Edible coatings are already being used commercially in the food processing sector to preserve the integrity, quality and shelf life of a broad range of fruits including pears, bananas, mango, citrus, apples, kiwi and pineapples[13,115,116,117] without causing the loss of nutritional and sensory attributes.[118]

Consumer attitudes towards edible coatings

Research has shown that consumers will only approve of edible coatings if they feel they are safe. According to numerous studies, edible coatings can be consumed with the contained food; however, only a small number of these investigations has strong evidence supporting the safety of edible coatings.[119] **Such** lack of information and awareness on the safety of edible coatings coupled with limited marketing efforts to promote their benefits greatly influence consumer acceptance.[120] A study by Pashova and colleagues[37] examined consumer attitudes towards the use of edible coatings in various sectors of the food industry and towards choosing, buying and consuming food covered with edible coatings. Thirty-four percent of the participants said they would choose foods coated with edible coatings over processed foods if the price did not differ substantially**; however** nearly sixty percent of them have not had the chance to choose or consume foods with edible coatings.[37] Moreover, this study also demonstrated that quality and appearance are two of the factors that consumers identify as critical in their choice of coated and uncoated foods. In today's thriving technological environment, the improvement of these attributes is possible with the development of suitable edible coatings that are safe for consumer health.[37]

Lastly, consumers are hesitant to accept edible films fearing for the presence of food allergens. By appropriately labelling all possible allergens, consumers are more likely to accept edible coatings since they will be aware of any potential health threats. It is extremely important for regulatory bodies to emphasize the labelling requirements for food producers to ensure the required information about allergens and the presence of animal derived materials are communicated to customers.[88] For example, shellac coatings are primarily constructed using insect exudates which have made them unappealing to some consumers.[75] According to a study by Sonti[98], on the consumer perception of edible coatings on FFV, only 54.6% of the 611 consumers surveyed had heard of edible coatings. However, after the advantages of edible coatings were described to the consumers, a 7% increase in purchase intent was observed. However, four of the respondents still said they would peel/wash off the edible coating before consumption and a few stated that they would not buy coated fruit if the coating materials were of animal origins.[98] Majority of the respondents (79.3%) said they would buy coated FFV with edible coating if the latter was approved by the FDA[98].

Utilization of edible coatings to improve consumer acceptability of fresh fruit and vegetables

Consumers judge the quality of a product based on its appearance and freshness at the time of purchase.[121] Although quality is subjective to different types of consumers[122], the latter still rely on certain factors during their decision-making process to decide whether to buy a product or not and which one to choose. These factors, include characteristics such as the absence of defects, visual appearance, state of maturity, nutritional value, texture, size, flavour, taste and safety.[123,124] The stage of maturity has a considerable influence on consumer acceptability of FFV as it is an indicator of the degree of ripeness and freshness.[125]. Not only is the eating quality affected by the stage of maturity, but the shelf life of the product can also be seriously restricted by physiological stresses as a result of processing operations causing an acceleration of the senescence process.[126,127]

The marketing of FFV is also strongly influenced by colour changes due to enzymatic reactions of phenolic compounds.[128]

The post-harvest life of FFV based on flavour and nutritional quality is shorter than that based on appearance and textural quality.[122] The end of flavour life results from losses in sugars, acids, and aroma volatiles (especially esters) and/or development of off-flavours due to fermentative metabolism or transfer of undesirable odours, such as those caused by sulphurous compounds, from fungi or other sources.[122] This causes the FFV to be undesirable to consumers. Flavour is influenced by genetics, preharvest, harvesting and postharvest procedures, packing operations and storage conditions which provides opportunities for retention of flavour by edible coating application.[122]. These critical factors serve as precursors for ester formation and are critical in determining the level of volatile esters in fresh and stored fruits and vegetables. Preharvest factors such as climatic conditions (temperature, light, rain, wind) and cultural practices (planting density, tree pruning, fruit thinning, nutrient and water quantities; control of weeds, diseases, and insects) that result in high yield often result in less than optimal flavour quality.[122] Environmental and physiological factors affect the volatile composition of FFV during postharvest handling and through- out the entire distribution chain.[98,122] Edible coatings provide a sufficient gas barrier for controlling gas exchange and restricting the exchange of volatile compounds between the fresh product and its surrounding atmosphere[123]. Thus, effectively delaying ethylene biosynthesis, reducing the respiration rate and slowing down deterioration as well as preventing both the loss of natural volatile flavour compounds and colour components from fresh FFV and the acquisition of different odours.[123]

The gas-barrier function also retards enzymatic oxidation and **protects** the fresh product from browning discoloration and texture softening during storage.[123] Edible coatings slowed the ripening rate and delayed colour change in comparison to the uncoated tissues.[129] This allows the vegetables to be aesthetically acceptable to consumers for longer. For example, in a study done by Abebe [130], chitosan coating delayed the colour change in tomatoes when compared to the controls by slowing down the respiration rate. According to a study done by Chauhan and colleagues[131] on the effect of Aloe vera gel edible coating on green grapes, the coating showed beneficial effects in terms of delaying rachis browning and maintaining the visual aspects of the grapes without any adverse effect on aroma, taste or flavours.

Nonetheless, even if edible coatings are the solution, to ensure consumer acceptance of edible coatings, it is important that all ingredients used for the coating formulation have a negligible effect on the sensory quality of the coated produce in terms of colour, shine, taste (bitterness, sourness, and sweetness), smell, and firmness.[124] Indeed, unusual colours and odours are often associated with lower quality and consumer rejection.[132] Thus, it is important that the use of edible coatings does not alter the attractive natural appearance and aroma of FFV. It is important that consumer hedonic studies are incorporated during the development of edible coatings, at different stages of the shelf-life period of the coated FFV. The sensory properties of the coatings should be evaluated, through the external appearance (colour, brightness, opacity etc.) and flavour of the products once coated and over the product shelf-life.[37]

This is important since coated FFV can possibly become less fragrant, similar to the observation made by Vargas et al [133] in the case of strawberries.

FFV are also highly susceptible to weight loss, wilting and shrivelling caused by vapor pressure gradient and respiration, resulting in low-market value and acceptability by consumers.[124,129] Edible coatings reduce moisture loss by acting as a barrier for water loss to the atmosphere by maintaining the high relative humidity of the tissue atmosphere and improving the appearance by conferring a shiny surface to FFV.[116]. In addition to the sensory qualities, consumers are concerned about the microbiological quality of FFV. Many types of microorganisms can cause the spoilage of FFV including Gram- positive and Gram- negative bacteria and fungi.[134] The growth of these spoilage microorganisms can be slowed down by the incorporation of antimicrobial agents into the edible coating matrix.[135] The use of edible coatings to slow down the degradation of fruit caused by fungal decay has been thoroughly reviewed.[136,137] There are numerous antimicrobial agents that can be used, however antimicrobial agents from plant sources are recommended to increase consumer acceptance.[138]

Consumer attitudes toward incorporation of active ingredients into edible coatings

Edible coatings can be effectively used as a carrier for active ingredients such as anti- browning agents, colorants, flavourings, nutrients, spices and antimicrobial compounds that can extend product shelf- life and reduce the risk of microbial growth on food surfaces.[139] Currently the trend in food packaging is the use of natural bioactive compounds against microorganisms due to the indiscriminate use of synthetic chemicals in food, prompting consumers to avoid such substances.[13] Thus, natural plant extracts, and essential oils (EO) from herbs, such as rosemary[140], oregano[141] and tea[142] are of great interest. These plant extracts and EO provide an added bonus to edible coatings due to their antimicrobial and antioxidant properties.[95,143-146] According to a study by Asensio & Nepote[147], the incorporation of a natural phenolic extract (Ethyl acetate-soluble polyphenols (EAP)) in a walnut protein-based coating used on walnuts showed an equal or better preservation effect in comparison to the synthetic antioxidant alternative, namely butylated hydroxytoluene. Also, consumer acceptance of the product was not negatively affected by EAP (colour, flavour, and overall acceptance). Thus, the study concluded that it is feasible for natural antioxidants to replace harmful synthetic antioxidants which are known to be detrimental to consumers' health.

The use of EOs has been rigorously investigated for several fruits and vegetables[39] and their activity as well as their active constituents have been studied against numerous microorganisms.[124,148-151] For example, incorporating cinnamon leaf essential oil into a pectin edible coating, resulted in effective antimicrobial activity and enhanced antioxidant status of fresh-cut peaches as well as satisfactory consumer acceptance.[152] However, the direct use of EO in edible coatings is still limited due to the strong flavour they impart as well as their impact on organoleptic food properties and their variable activity in foods due to interactions with the food components.[124,153] These ingredients have a naturally bitter/ off-flavour[154] which is an important aspect, since it can lead to consumers rejecting the product.[155,156] Usually active ingredients are encapsulated in a proper edible matrix, and their controlled release is stimulated by certain external environment such as changes in pH, temperature or pressure.[22] By encapsulating the EO in an edible coating[154], better physical and chemical stability can be obtained, which provides more fresh-keeping advantages for food.[18,157,158] It was found that citrus EO preserved the quality of fresh-cut fruit salads without affecting the consumers acceptance of the product.[159] Moreover, since the chemical composition of EO is naturally inconsistent and may involve many compounds, the best approach for utilization would be using purified single compounds instead of crude extracts to obtain an edible coating with constant characteristics as required by the market.[160]

Bio-packaging still represents a niche market because of the cost and poor overall performance of biodegradable coatings when compared to those of traditional packaging materials.[161] There is a great research effort focused on developing new edible coating materials incorporating natural bio-actives. In addition, new and improved processing systems are being[154] trialled in order to ensure optimal composition, functional properties and low costs of edible coatings.[99] However, it is crucial to gradually implement this new technology in the production of various foodstuffs, in order to meet the high consumer expectations and gradually introduce such foods into the daily life and diet of the various consumer groups.[37] Consumers look onto the film properties from firstly a personal point of view and then environmental or industrial benefits come into play. Hence, marketing and product development should mainly focus on the edible films from the consumers' point of view and should improve the film properties accordingly.[162]

Environmental Sustainability

Between 1950 to 2015, a colossal increase in the global production of plastic, corresponding to an escalation from 1.7×103 Kt to 3.35×105 Kt, has been registered.[163] This upsurge has been fuelled by the inordinate vast physico-chemical properties of plastic making it suitable for a wide range of application at a relatively low cost.[164] However, the excessive use of plastic as well as the inability to effectively manage plastic waste have led to an unprecedented pollution crisis.[163] Plastic pollution is almost everywhere, from landfills to residential areas, from rivers to oceans. One key example is the burning issue of marine plastic pollution. As such, it has been advocated that between 4.8 and 12.7 million tons of plastic waste enters our oceans annually.[165] Besides, the issue of the possible accumulation of microplastic in marine organisms which might ultimately reach human food chains has been the focus of intense discussion.

In an attempt to reduce plastic pollution, considerable effort has been devoted in the development of biodegradable food packaging and this concept is continually being honed and adjusted to meet environmental and societal requirements. Over the past decades, zero-waste alternatives have been the focus of intense research. Numerous researchers and companies have thus concentrated on developing coatings that are sustainable and biodegradable.[7] Indeed, the development of completely biodegradable and even edible packaging material is considered to be a real and viable solution to eradicate pollution caused by food packaging and to mitigate waste management issues.[166] The realm of natural polymers offers a platform compatible with the eco-friendly paradigm towards a green and sustainable world.[167] Besides, the recovery of biopolymers, such as polysaccharides, from agro-industrial waste is in line with sustainable development goals (SDGs) which advocates for recycling and waste recovery.

Biopolymers are considered as alternatives to petroleum based plastics, since they are non-toxic, environmentally friendly, and can be isolated from sustainable raw materials, such as agro-industrial waste. The recovery of biopolymers from agro-industrial waste contributes in recycling waste, and thereby promoting sustainable development and an eco-friendly environment.[168] Inherent functional properties of biopolymers, including, barrier properties, transparency, flexibility, economic profitability, and environment compatibility, underpin the successful development and application of edible coatings.[93]Three basic types of biopolymer, namely, proteins, lipids, polysaccharides, as well as their possible amalgamations, have been considered for the formulation of edible coating matrices. Moreover, biopolymer-based edible coatings serve as vehicles for natural antimicrobial agents. As shown in Table 3, enrichment of biopolymer-based edible coatings with natural antimicrobial agents has been presented as a promising technique to preserve wholesome fruits and vegetables. It was found that biopolymer-based edible coatings with natural antimicrobial agents were more effective than direct application, since the antimicrobial compounds migrated within the food system, thereby decreasing the agent load and activity.[169] Moreover, in comparison to direct application which might alter the organoleptic properties of the produce, the incorporation of antimicrobial agents to the biopolymer-based edible coating imparts a highly localized function.[170] A number of patents relating to the development of biopolymer-based edible coatings enriched with natural antimicrobials have already been filed and granted.[171-173]

The success of an edible coating in extending the shelf life and enhancing the quality of FFV depends on its barrier properties to moisture, oxygen, and carbon dioxide which in turn depends on nature of the major component of the edible coating. However, edible coatings also have certain limitations as indicated by other researchers. For instance, the application of edible coating on FFV leads to the modification of internal atmosphere which might adversely affect quality, favour spoilage, and retard desirable ripening.[174] Besides, the modification of internal atmosphere is related to the development of physiological disorders, such as, the formation of off-flavours and ethanol, as a result of anaerobic respiration related to the inhibition of oxygen and carbon dioxide exchange, core flush, and flesh breakdown.[175,176] For instance, the application of edible coating on FFV leads to the modification of internal atmosphere which is related to the development of physiological disorders, such as, the formation of off-flavours and ethanol, as a result of anaerobic respiration related to the inhibition of oxygen and carbon dioxide exchange, core flush, and flesh breakdown.[175,176] Wax-based edible coatings were reported to inhibited normal ripening and respiration, thereby contributing to the development of alcoholic flavours due to anaerobic fermentation.[175] Moreover, coatings made of sucrose fatty acid ester increased the incidence of core flush in apples while zein-based edible coatings were reported to favour the production of alcohol and off flavours of coated tomatoes which were related to low oxygen level and high carbon dioxide level.[175]

The choice of material with appropriate permeability might to some extent address problems related to the modification of internal atmosphere condition.[177] Moreover, the recovery of some biopolymers might be tedious and might necessitate the use of harsh chemicals, as is the case for the extraction and purification of cellulose and pectin. The development of new extraction methods based on the principle of Green Chemistry and Technology, including ultrasonication, microwave-assisted extraction, the use of deep eutectic solvents, etc., is receiving intense focus to fit the example of SDGs.

The FFV sector uses a lot of plastic to meet the demand for convenient fresh products with a longer shelf life. Edible coatings are useful as postharvest treatments to preserve the quality of FFV, with the additional benefit of reducing the volume of non-biodegradable packaging materials.[178] Pioneering fruit companies have already taken a step towards fully compostable packaging or laser labelling in order to reduce the volume of non-biodegradable packaging. However, the absence of primary packaging favours mechanical damage of FFV, resulting in higher food loss. The need for a second packing material in most cases for consumer health because edible coatings have lesser physical and chemical resistance compared to petroleum-derived materials.[179]

Conclusion

This review provides an overview of the various drivers and barriers for the commercialisation of edible coatings for the fresh fruits and vegetables industry. Barriers include global regulations, industrial application and cost feasibility, consumer acceptance as well as environmental sustainability. The drastic rise in consumption of FFV, in an endeavour to promote healthy eating habits and prevent the onset of nutritional disorders, has given rise to a concomitant rise in global food trade. The commercial importance of edible coating to decrease post-harvest losses, increase the shelf-life and foster consumer acceptability of FFV in the global FFV value chain is now more important than ever. By encouraging factors that drive the adoption of edible coatings and overcome adoption barriers, for the commercial uptake of edible coatings this can contribute to food and nutrition security for future generations.

As far as regulations pertaining to edible coatings and their application to FFV are concerned, this review has highlighted the wide disparity existing across different regions of the world. As a result, FFV exporters should take into account the regulations of the importing countries when determining the approved list of coating materials. When food manufacturers produce edible films or when packers apply coatings to FFV, it is also important that they state all the ingredients used for film formation on the labels of their food products. Taken together, this calls for a harmonization of the regulations of the different countries, especially of the Eastern and Western nations, in the interest of global food trade. The joint FAO-WHO food standards programme, with 194 member nations, is a step in the right direction, as a collection of harmonized international food standards to protect the health of consumers and ensure fair trade practices.

Although several methods have been developed for the industrial application of edible coatings mainly on produce such as apples; the industrial application and commercialization of edible coatings are not yet fully viable. There is a need for more studies to assess the applicability of edible coatings given the differing characteristics of food items, in terms of their acidity, texture, presence/absence of peel, amongst others. In addition, Moreover, to ensure optimal quality of FFV during transit and shipment, the application of edible coatings has been advocated in line with the zero-waste concept. However, edible coatings are not silver bullets on their own and quality FFV can only be ensured if a temperature-controlled supply chain with adequate logistics is in place. In addition, whether edible coatings should be applied in the importing rather than the exporting country is also a key research question. Edible coating thickness should also be considered as this will affect oxygen and water permeability as well as the release of active ingredients. Thicker coatings generally result in lower gas permeability (reference), but provide optimal water permeability (ref). However, if the gas permeability is too low, it can cause anaerobic respiration and lead to undesirable flavors (reference). Thicker coating can have slower release of active ingredients (ref), for example .... Thus, it is important to determine coating thickness as it affects the functional properties. Coating thickness can be determined by microscopy techniques for example SEM, and CLSM with specific dye for the coating materials.

Thus, a SWOT analysis of FFV treated with edible coatings should be undertaken to determine the step in the value chain where edible coating has the most value. However, the literature does not provide much information on the cost benefit analysis of the application of edible coatings on FFV for major actors in the value chain which makes it complex to evaluate the commercial attractiveness of edible coatings.

Consumer are one of the most important drivers to ensure the commercial uptake of edible coatings as they will be the ones buying the coated FFV. Edible coatings will only be commercialisable if consumers feel they are safe for consumption, cost effective, make use of sustainable processes and are aware of the positive effects on the environment. However a lack of awareness and fear about edible coatings can reduce their acceptance, that is why marketing strategies, such as conducting awareness programs, price discounts, advertising, attractive offers and highlighting the added value, could be helpful in attracting consumers. The customer acceptability of edible films not only depends on the functional properties, but also other factors, such as film appearance, organoleptic properties, marketing, cost etc. Edible films should not affect the sensory properties and nutritional values of the contained food. They should be transparent, odourless, tasteless and enhance the appearance of the fresh produce but not change it. Therefore, in-depth sensory analysis of all coated FFV should be done before attempting to commercialise it. Moreover, empirical data is required to ensure that novel edible coating formulations have no adverse effect on consumers' health in the long term.

Although the use of biopolymers is sustainable and environmentally friendly, the recovery of some biopolymers might be tedious and might necessitate the use of harsh chemicals, as is the case for the extraction and purification**.** This could lead to high costs that would discourage consumers from buying the coated FFV. However with further research, cheaper ways of performing these processes could lead to the development of product that is price competitive on the market.

Fresh produce companies should present the application of edible coatings on fresh fruits and vegetables to consumers as an eco-innovation that will contribute to the promotion of circular bioeconomy as well as a technological innovation that supports the creation of an ecological and waste-free environment.

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Nomenclature

FFV- Fresh fruits and vegetables

PH – Post- harvest

PHL- Post-harvest losses

FDA – Food and Drug Administration

US – United states

EU – European Union

CFR – Code of Federal regulations

USC – United States Code

GRAS – Generally Recognized As Safe

cGMP – current Good manufacturing practices

FDCA – Federal Food, Drug and Cosmetics Act

ED – European Directive

EC – European Commission

EFEMA – European Food Emulsifiers Manufacturers Association

UNCTAD – United Nations Conference on Trade and Development

FAO – Food and Agriculture Organization

FSL – Food Sanitation Law

WHO – World Health Organization

JMHLW – Japanese Ministry of Health, Labour, and Welfare

EO – Essential oil

SDG- Sustainable Development Goals

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