Encapsulation of Bioactive Phytochemicals

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Contributor: David McClements

Many consumers are switching to a plant-based diet because of their concerns about animal-derived foods on the environment, human health, and animal welfare. There has therefore been great interest in identifying, isolating, and characterizing functional ingredients from botanical sources, especially waste streams from food and agricultural production.

Keywords: plant-based foods ; encapsulation ; delivery systems ; nutraceuticals ; bioactive ingredients ; botanical extracts

1. Introduction

The food and agricultural industries have become increasingly interested in developing sustainable plant-based functional materials to replace synthetic or animal-based ones. This change in emphasis has been driven by growing consumer demands for a more ethical, healthy, and environmentally-friendly food supply to feed the expanding global population [1][2]. Scientists are therefore utilizing plant-derived constituents, such as proteins, polysaccharides, phospholipids, and lipids, to construct new materials for use in the food industry, including foods, beverages, packaging materials, coatings, and delivery systems [3][4][5][6]. In this article, we focus on the design, fabrication, and utilization of plant-based delivery systems for bioactive food ingredients, such as nutraceuticals, preservatives, colors, and flavors. As a specific example, we highlight the utility of these delivery systems for incorporating functional ingredients into traditional meat products. In recent decades, a great deal of research has focused on the isolation, characterization, and utilization of phytochemicals in the food industry [7][8][9][10]. As a specific example, they are being utilized as natural antioxidants and antimicrobials to inhibit chemical degradation and microbial growth in meat and meat products [11]. However, many plant-based bioactive agents cannot simply be applied to agricultural crops or incorporated into food products or packaging materials because of their poor solubility, their low chemical stability, or their adverse impacts on food quality (such as appearance, texture, or flavor). Consequently, it is important to encapsulate these components within colloidal particles that are specially designed to improve their water dispersibility, chemical stability, and matrix compatibility [4][5]. Moreover, encapsulation of these phytochemicals can improve food quality by masking off odors and flavors [12][13], while increasing their shelf-life. The particles may vary in their compositions, dimensions, shapes, electrical properties, and environmental sensitivities. As a result, it is important to select the most appropriate particle design for each specific application. As a representative example, we focus on the application of encapsulated phytochemicals for improving the quality, safety, and shelf-life of meat products in this manuscript.

This article reviews the main phytochemicals that can be used as functional additives in foods, highlights the various techniques that can be used to isolate them from botanical sources, and provides a brief overview of the different analytical instruments that can be used to establish their identity and concentration. Advanced encapsulation technologies that can be used to increase the handling, stability, and efficacy of phytochemicals are then discussed. Finally, the efficacy of encapsulated phytochemicals is highlighted by reviewing their potential applications in the meat industry.

2. Isolation of Bioactive Agents from Botanical Sources

In the last two decades, there has been increasing interest in the extraction of bioactive compounds from plant matrices due to their nutritional value, technological properties, and potential health benefits [14]. In addition, the valorization of agro-food by-products based on the extraction of high-value molecules and the development of functional products can lead to the more environmentally sustainable use of these resources and higher economic benefits for the food sector [10][15]. In general, bioactive compounds can be subdivided into two main groups: *lipophilic compounds* such as essential oils, oleoresins, curcuminoids, and carotenoids that are extracted with more non-polar solvents; and *hydrophilic compounds* such as polyphenols that are extracted using more polar solvents. A broad spectrum of different kinds of bioactive constituents are found in different plant sources [16] (**Figure 1**). As a result, crude extracts often contain a mixture of different phytochemicals that may have different biological activities, which may be additive, synergistic, or antagonistic.

As an example, hydrophobic extracts from botanical sources (such as tomatoes or turmeric) may contain a mixture of different hydrophobic phytochemicals, such as carotenoids (lutein, lycopene, α-carotene and β-carotene), xanthophylls (lutein, zeaxanthin, astaxanthin and canthaxanthin), fat-soluble vitamins and pro-vitamins (retinol and tocopherols), curcuminoids and alkaloids [10][17][18]. Similarly, essential oils isolated from different varieties of aromatic plants (such as *Asteraceae, Lamiaceae, Lauraceae, Myrtaceae, Rutaceae, Umbelliferae,* and *Zingiberaceae* families) contain a great variety of bioactive compounds, which can be grouped into two main groups; terpenoids and phenylpropanoids [8][19][20]. Similarly, hydrophilic extracts from plants may also contain many different components that different in their biological activities. For instance, there are numerous kinds of polyphenols in aqueous extracts [7][21], including flavonoids (rutin, naringenin, naringenin chalcone, kaempferol, rhamnetin, astragalin, rhamnocitrin, quercetin, catechin, gallocatechin, tanins, etc.) and phenolic acids (hydroxycinnamic, chlorogenic, rosmarinic, sinapic, p-coumaric, ferulic, syringic, vanillic, caffeic acids, etc.). Moreover, in berries (elderberry, blueberry, blackberry, blackcurrant, cloudberry, bearberry, strayberry, etc.) one of the largest groups of polyphenols are anthocyanins and anthocyanidins (malvidin, peonidin, petunidin, cyanidin-3-O-sambubioside, cyanidin-3-O-glucoside, cyanidin 3-(E)-p-coumaryl-sambubioside-5-glucoside, etc.) [14][22]. Many anthocyanins are widely used as natural pigments and antioxidants in foods. Similarly, betalains (such as betacyanins and betaxanthins) are also used as natural pigments and antioxidants [9][23][24][25].

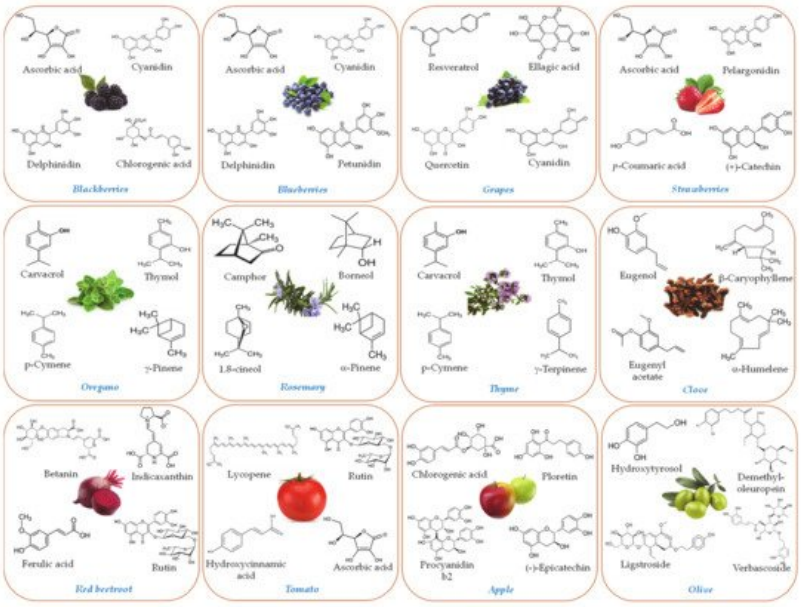

Figure 1. Examples of some important bioactive agents isolated from edible plant materials.

To extract these compounds, it is vital to choose a suitable extraction method. Ideally, this method should minimize the processing steps, time, and energy consumption involved, while increasing the quality and yield of the extract, and ensuring the safety of the final product. There are some common factors that affect the efficiency of extraction in both conventional or emerging assisted extractions, such as the solid/solvent ratio, the solvent concentration, particle size and the use of flow or batch mode [26]. Moreover, the solvent, extraction technique, and operating conditions used strongly influence extraction efficiency and the phytochemical composition of the extract obtained [19]. With this in mind, below is a description of the main methods used to obtain phytochemicals.

3. Characterization of Plant-Based Bioactive Agents

3.1. Conventional and Spectrophotometric Methodologies

Indirect measurement of phytochemicals has been carried out for decades. These indirect determinations are based on the measurement of the total antioxidant capacity, usually involving a redox reaction with the oxidant [27]. The measurement of antioxidant capacity permits determining the ability of certain molecules to eliminate free radicals or to transfer an electron to reduce an oxidant [28]. Generally, the methods for determining antioxidant properties of plant extracts can be divided according to the chemical reactions involved into hydrogen atom transfer-based, electron transfer-based and mixed mode techniques [29][30]. The most common techniques to determine the total antioxidant capacity are ferric reducing antioxidant power (FRAP) (using iron) and copper reduction (CUPRAC) (using cooper) assays, the 2,2′-azino-bis (3-ethylbenzothiazoline-6-sulphonic acid) (ABTS), Trolox equivalent antioxidant capacity, 2,2-diphenyl-1-picrylhydrazyl (DPPH), oxygen radical absorbance capacity (ORAC), total radical-trapping antioxidant parameter (TRAP), total oxyradical scavenging capacity (TOSC) and in vitro phosphomolybdenum assay. Although numerous tests are available to measure the antioxidant activity of phytochemicals, there is no single one that can reliably predict the in vivo

antioxidant capacity. In fact, the antioxidant activity of phytochemicals should usually be determined using a combination of complementary antioxidant tests that are most appropriate for the target substance [31]. The use of various antioxidant methods helps to understand which type or types of mechanisms are involved in the activity of plant extracts. However, the lack of standardization of the methods makes it difficult to compare the results of different studies. Furthermore, the variations within some methods, as well as the units in which the results are expressed, are significant drawbacks of the measurement of total antioxidant capacity. In fact, these drawbacks have not been solved after 25 years of research [32]. Despite their limitations, the DPPH, ABTS, ORAC, FRAP and phosphomolybdenum assays are widely used to assess the antioxidant capacity of botanical extracts [27][33][34][35]. Thus, the total antioxidant capacity (using the aforementioned methods) is normally assayed before the use of the plant extracts and phytochemicals, in order to know their functionally and technological aptitudes for food application [17][22].

Groups of phytochemicals can also be characterized directly using spectrophotometric techniques. For instance, the determination of the total content of phenolic compounds (TPC) [36], betalains [37][38], carotenoids [39], anthocyanins and chlorophylls [22] has been widely used for the characterization of plant extracts, although they have the disadvantage that it only gives general information, and it is not possible to determine the specific constituents of the extract. On the other hand, some compounds, such as betacyanins, betaxanthins, or some carotenoids such as β-carotene or lycopene can be determined using spectrophotometric techniques. However, there may be interferences in the determination since many other compounds can absorb in the same wavelength range, so the amount of these phytochemicals could be overestimated.

In the case of essential oils, some classical analytical techniques have been used to verify oil purity, including density and refractive index measurements, the determination of polar substances, and the measurement of melting and congealing points. Additionally, the aldehydes (bisulfide method) and ketones (neutral sulfide test) content or the solubility test in ethanol are also frequent analysis in essential oils characterization [40].

3.2. Chromatographic and Mass Spectrometric Methodologies

Although conventional methodologies are very useful for screening purposes and giving us a general idea of the properties of extracts obtained from plants, the use of chromatographic and mass spectrometric techniques is more appropriate for the more precise identification and quantification of bioactive molecules. This is because extracts are normally molecular complex mixtures containing several phytochemicals, thus, the use of selective, sensitive, and versatile analytical techniques is necessary [41].

Several methods using liquid chromatography with diode array detector (LC–DAD) have been used for the determination of phytochemicals, operating in reverse phase for hydrophilic compounds (for example, for the determination of betalains or polyphenols) or in normal phase for lipophilic compounds (for example, carotenoids or tocopherols). In this case, several advantages were observed in comparison with spectrophotometric methods, since chromatographic methodologies ensure the correct separation/resolution of specific compounds, and therefore, their correct identification and quantification. Moreover, the specific compounds/isomers can also be quantified. For example, the use of LC–DAD allows the quantification of different red betalains (amaranthine, isoamaranthine, probetanin, betanin, isobetanin, betanidin, and isobetanidin) that compose the betacyanins fraction of different plants, while the use of spectrophotometric techniques only allows the quantification of “total” betacyanins [37][38]. LC–DAD is one of the most used analytical techniques for the determination of polyphenols and polyphenol-rich extracts [42][43][44].

The use of liquid chromatography combined with mass spectrometry is the most convenient and powerful technique to characterize complex botanical extracts. For instance, LC–TOF/MS and LC–ESI–MS were able to identify more than 32 isomers in betalains [37][45], while DAD could not discriminate them all. Although LC–DAD is a relatively simple technique to determine polyphenols in botanical extracts, it mainly discriminates and identifies molecules based on their retention time (using reference standards) and UV spectra [41]. Thus, LC–MS and LC–MS/MS techniques have been increasing in order to more thoroughly characterize polyphenol-rich extracts. Several combinations were used in a comprehensive polyphenol identification and quantification, including liquid chromatography hybrid linear ion trap quadrupole-Orbitrap-mass spectrometry (LC–LTQ–Orbitrap–MS) [46] or LC–QTOF/MS [45]. Furthermore, in some cases, the use of a single quadrupole mass spectrometer is not selective enough, thus tandem mass spectrometry (MS/MS) is needed to achieve noise reduction and improve sensitivity by exploiting a multiple reaction monitoring (MRM) scan mode [41]. Several researchers have successfully used this technique [47][33][48]. Thus, LC–MS/MS is currently the most powerful technique for the correct identification and quantification of phytochemicals.

On the other hand, although both gas and liquid chromatography could be used for essential oil analysis, the gas chromatography technique is preferably due to the volatile nature of their constituents [49]. Gas chromatography (GC)

using non-polar fused silica capillary columns are suitable for chromatographic separation and resolution of these materials. Multiple kinds of detectors can be utilized to quantify the separated peaks, including flame ionization detector (FID) and mass spectrometer (MS). Among these detectors, the FID needs standards for the correct identification of the compounds (based on the retention time), while the use of mass spectrometry does not need any standards since the use of mass spectrum comparison with international spectrum libraries ensures correct identification of all essential oil constituents. This fact is a major advantage of MS compared to FID, since it even allows the identification of different isomers of the same compound, and using different tools (for example, deconvolution) allows separating compounds that coelute. Thus, gas chromatography coupled with mass a spectrometer (GC–MS) is the most common method currently used in the determination of essential oil composition. Several authors have used this powerful technique to determine the composition of complex mixtures of phenylpropanoid derivatives and terpenoids [50][51][52][53], which are the main constituents of essential oils [54][49] and responsible for their characteristic odor [55]. Furthermore, solid-phase microextraction (SPME) is a solvent-free isolation technique that allows the extraction and concentration of volatile compounds from vial headspaces. Therefore, the combination of SPME and GC–MS is a reliable and fast method to determine essential oil composition, since it improves the detection limits and resolution [55].

In general, methods involving chromatography coupled to mass spectrometry are currently the best options for the complete characterization of botanical extracts, but they are relatively expensive, which limits their utilization in some laboratories.

4. Encapsulation of Plant-Based Bioactive Agents

A diverse range of encapsulation technologies have been developed to encapsulate bioactive agents, which vary in the ingredients and processing methods used to assemble them. In this section, we review a number of the most important ones that can be used to encapsulate botanical bioactive substances[1].

4.1. Plant-based Micelles and Microemulsions

In general, micelles and microemulsions are colloidal particles comprised of surfactant molecules assembled into spheroid structures with the non-polar tails facing inwards (away from water) and the polar heads facing outwards (toward water). Typically, micelles are only formulated using surfactants, whereas microemulsions may also contain co-surfactants and oils. Micelles typically have diameters around 5 to 20 nm, whereas microemulsions have diameters around 20 to 100 nm. Hydrophobic bioactives are typically solubilized within the non-polar domains within the interior of these colloidal particles, *i.e.,* between the surfactant tails or within a central lipid core. Amphiphilic bioactives may also be solubilized between the surfactant tails. Micelles and microemulsions are thermodynamically stable because they have a lower free energy than the separated components (oil, water, and surfactant). It should be noted, however, that they are only thermodynamically stable over a certain compositional and environmental (pH, ionic strength, and temperature) range, and tend to breakdown if they move out of this range. In principle, micelles and microemulsions should form spontaneously when the different components are brought into contact because of the negative free energy associated with their assembly. In practice, it is often necessary to apply some form of external energy (such as mixing or shearing) to overcome activation energies associated with self-assembly of the surfactants in water.

Traditionally, micelles and microemulsions are formed from small molecule synthetic surfactants, such as Tweens and Spans. Nevertheless, they may also be formed from some plant-derived surfactants, such as the saponins derived from quillaja or tea trees. These surfactants have a hydrophilic part and a hydrophobic part, which allows them to self-assemble into micelles or microemulsions in aqueous solutions.

4.2. Plant-based Nanoliposomes and Liposomes

In general, liposomal systems consist of colloidal particles that are made up of one or more concentric phospholipid bilayers. Nanoliposomes (d < 100 nm) can be distinguished from liposomes (d > 100 nm) due to their smaller diameters. Nevertheless, both types of system are only metastable, *i.e.,*they tend to breakdown over time because the separated state has a lower free energy than the liposomal system. Even so, the formation of the phospholipid bilayers does occur spontaneously because of the hydrophobic effect. Liposomal systems can be used to encapsulate amphiphilic, hydrophilic, or lipophilic bioactive substances because they have regions with different polarities. Hydrophilic bioactives can be incorporated into the aqueous interior of liposomal systems or between the polar head groups of the phospholipids, whereas lipophilic and amphiphilic bioactives can be incorporated within the hydrophobic domains formed by the phospholipid tails. Liposomal systems can be further characterized by their tendency to form single (unilamellar) or multiple (multilamellar) phospholipid bilayers. The formation of these different structures is governed by the ingredient formulation and processing methods utilized in their assembly

Liposomal systems can be formulated entirely from plant-derived ingredients, such as soybean or sunflower lecithin, which means that they are suitable for application in plant-based foods and other functional materials. This kind of colloidal dispersion can be fabricated using a variety of approaches, which vary in their efficacy and suitable for large scale production. Some of the most commonly employed methods for producing liposomal systems are solvent evaporation/rehydration, solvent injection, and microfluidization methods. The main disadvantages of liposomal systems are that it is often challenging to incorporate high amounts of bioactive components, the encapsulation efficiency is relatively low, and they have a tendency to breakdown over time, particularly when exposed to extreme conditions, such as high salt concentrations, acidic conditions, and elevated temperatures.

4.3. Plant-based Nanoemulsions and Emulsions

Nanoemulsions and emulsions both consist of small droplets of one fluid (the “dispersed phase”) distributed throughout another immiscible fluid (the “continuous phase”). In the food industry, these two fluids are usually oil and water. An oil-in-water (O/W) system is formed when the oil phase forms the droplets, whereas a water-in-oil (W/O) system is formed when the water phases forms the droplets. Typically, the droplets are coated by a layer of emulsifier molecules to prevent them from aggregating with each other. The free energy of nanoemulsions and emulsions is higher than that of the separated phases, and so they are thermodynamically unfavorable. These systems must therefore be designed to ensure that they are metastable, *i.e.,* have a sufficiently long shelf life for the intended application. This usually involves controlling the droplet composition, concentration, and size, as well as by using suitable additives such as emulsifiers, thickeners, gelling agents, weighting agents, and ripening inhibitors. Conventionally, the mean diameter of the droplets in nanoemulsions is below 100 nm, whereas it is above this value for emulsions. The smaller dimensions of the droplets within nanoemulsions has some important consequences for their functional attributes, typically leading to greater optical transparency, improved resistance to aggregation and gravitational separation, and a higher bioavailability of any substances encapsulated within them.

Nanoemulsions and emulsions can be created using a broad spectrum of methods, which can be classified as high-energy or low-energy approaches. High-energy methods employ specially designed mechanical devices, such as high-shear mixers, colloid mills, microfluidizers, sonicators, or high pressure valve homogenizers, to generate intense disruptive forces that break up the oil and water phases. In contrast, low-energy methods rely on the spontaneous formation of small droplets when certain oil, water, and surfactant mixtures are treated in a specific manner, *e.g.,* their composition or temperature is changed. These latter methods include phase inversion temperature, spontaneous emulsification, and emulsion inversion point methods.

4.4. Plant-based Solid Lipid Nanoparticles and Nanostructured Lipid Carriers

Solid lipid nanoparticles (SLNs) and nanostructured lipid carriers (NLCs) have structures that are fairly similar to those found in O/W nanoemulsions, but the oil droplets are fully or partially crystallized, respectively. Indeed, these systems are often formed by creating an O/W nanoemulsion at a temperature above the melting point of the oil phase and then cooling it to crystallize the droplets. Like nanoemulsions, the lipid particles in SLNs and NLCs are stabilized by coating them with a suitable emulsifier. One of the advantages of SLNs and NLCs over nanoemulsions is that crystallizing the oil phase retards the diffusion of molecules inside the lipid particles, which can improve the retention of encapsulated substances, as well as protecting them from chemical degradation. It should be noted, however, that the oil phase must be carefully designed to achieve this. If the oil phase forms a crystalline structure that is too regular, then any encapsulated bioactive agents may be expelled because they cannot be accommodated within the crystals. In addition, the formation of a highly regular crystalline phase can cause lipid particles to undergo a transition from a spherical to an irregular shape, thereby increasing their oil-water surface area. Consequently, there may not be enough emulsifier molecules present to saturate the lipid particle surfaces, thereby promoting particle aggregation. SLNs are particularly prone to these problems because they contain fully crystalline nanoparticles. Conversely, NLCs are less prone because the lipid phase is selected to be only partially crystalline after it solidifies, thereby preventing the expulsion of encapsulated bioactive substances and inhibiting particle morphology changes.

4.5. Plant-based Biopolymer Nanoparticles and Microgels

Plant-based proteins and polysaccharides can be used to assemble biopolymer nanoparticle and micro-gels. Biopolymer nanoparticles mainly consist of tightly packed proteins and/or polysaccharide molecules, with only a little water. Conversely, biopolymer hydrogels consist of a protein and/or biopolymer network that traps large amounts of water. The biopolymer molecules in these particles are typically held together by physical or chemical bonds, including hydrogen bonding, hydrophobic attraction, electrostatic interactions, and disulfide bonds. The dimensions of these particles ranges from around 100 nm to 1000 mm depending on the ingredients and fabrication method used. There are a wide range of

different fabrication methods available to produce biopolymer nanoparticles and microgels, including antisolvent precipitation, injection-gelation, phase separation-gelation, emulsion templating, and molding methods. The composition, porosity, shape, and dimensions of biopolymer nanoparticles and microgels can be manipulated to provide desirable loading, retention, and release properties.

5. Application of Encapsulated Plant-Based Active Ingredients in the Meat Industry

There is great interest in using botanically-derived preservatives in the meat industry. Oxidative reactions and microbial growth are the two main degradation processes involved in the loss of quality in meat and meat products [11]. In addition to the nutritional quality loss (degradation of unsaturated fatty acids and vitamins), accumulation of toxic compounds derived from oxidation reactions and the reduction in sensory quality and consumer acceptance (rancid flavor and odor) [11], the changes in meat color are also important. The loss of the characteristic bright cherry-red color in meat and meat products is a consequence of myoglobin oxidation, which is directly related to the redox state of iron in the heme fraction of myoglobin molecule [56]. Similarly, microbial spoilage occurs in meat and meat products, which could promote the growth of pathogenic microorganisms and produce unpleasant odors, abnormal discoloration, and the presence of slime that limit the shelf-life of these products [56].

To inhibit these negative alterations in meat quality during storage, several additives are normally used by the meat industry. However, most of them are synthetic additives, which could exert negative effects on human health [19]. Moreover, the growing interest of the consumer in minimally processed food results in growing interest within the meat industry on replacing synthetic additives with natural antimicrobials and antioxidant agents [21][57]. Thus, researchers in academia and industry are carrying out studies to find new alternatives, including natural extracts (polyphenol-rich extracts, oleoresins, purified compounds, etc.) or essential oils from plant materials, which are added to the meat formulation [8][9][10][14][19][33][48] or to the packaging materials [6][56][58] to increase meat and meat products shelf-life [57]. In addition to the antioxidant and antimicrobial properties of these compounds, the use of certain extracts or phytochemicals, with a red color (anthocyanins, betalains, lycopene, etc.) could also be important to maintain sensory properties, since they also act as natural colorants [10], which increase the stability of the characteristic red color of meat and meat products. Essential oils can be also applied as natural flavors to meat products [40]. Moreover, a number of studies have also shown that pollen and pollen extracts as well as propolis can be utilized as effective preservatives in meat products [59]. In this regard, bee pollen was applied as a natural antioxidant to prevent the degradation of refrigerated sausages [60] and meatballs [61][62], while propolis extract was added to increase the shelf-life of beef and pork patties [63][64].

On the other hand, phytochemicals (phenolic compounds, betalains, carotenoids, terpenoids, etc.) are the major constituents of plant materials that contribute to their antioxidant and/or antimicrobial activity. Thus, several plant materials, including roots [9], berries/fruits [14], leaves [33], seeds [7][48] or also agro-food by-products [10][15] are potential sources of these important bioactive compounds that could be used as natural and promising additives in the meat industry. These bioactive compounds may be incorporated in meats as water-soluble extracts, water-insoluble extracts (oleoresins, essential oils, etc.) and powders [14]. Thus, phytochemical-based preservatives are gaining popularity in the meat industry since they are perceived by consumers as safe and are Generally Recognized as Safe [21]. In recent decades, several researchers have therefore studied the antimicrobial and antioxidant activity of plant extracts and essential oils in various meat products [7][8][19][20][21][56]. However, it is also important to highlight that these natural extracts should not negatively influence the sensory properties of meat products, and they should be active at low concentrations, inexpensive, and stable during the manufacturing process for industrial applications. Furthermore, prior to the incorporation of the phytochemicals in meat products, evaluating the toxicity of these compounds to human cells through in vivo studies and clinical trials to better understand their potential effects on consumer health should be carried out [57].

Some recent reviews make an in-depth analysis of the direct application of different extracts [7][9][10][14][16][21] and essential oils [8][19][20] in meat products, focusing on their antioxidant and/or antimicrobial function. However, most of these reviews have not considered the application of encapsulated phytochemicals within the meat industry. In this section, recent studies on the effects of encapsulated phytochemicals on the main degradative phenomena of meat and meat products are therefore reviewed.

Encapsulation of bioactive compounds usually increases their stability during storage and processing by increasing their resistance to environmental conditions, such as pH changes, high temperatures, light exposure, and oxidative conditions. They are also being explored for their ability to control the release of phytochemicals within meat products. These studies have shown that encapsulation technologies offer a promising strategy for improving the quality of meat products, increasing their nutritional properties, and limiting degradation processes (such as microbial contamination and oxidative

reactions) [12][13]. **Table 1** summarized some recent studies where encapsulated phytochemicals (either as extract or as essential oil) were incorporated into meat or meat products formulations to improve their quality, shelf-life or safety.

Table 1. Effects of the application of encapsulated plant-based active ingredients in meat industry.

Plant Extracts	Concentration	Meat/Meat Product	Main Effects			Ref.
			Antioxidant Effects	Antimicrobial Effects	Other Effects	
Rosemary extract	800–1600 ppm	Beef meat	Reduce primary (peroxide values) and secondary (TBARs values) lipid oxidation	Inhibit the growth of microorganisms (total viable counts) during refrigerated storage	Minimum changes in color parameters	[65]
Orange essential oil and cactus acid fruit extract	0–5%	Emulsified meat system	Increase antioxidant activity (DPPH; ABTS) and reduce lipid oxidation during storage (TBARs)	NR	Increase fat content (with bioactive compounds from orange essential oil) and increase the total phenol content	[66]
Radish, hibiscus and beetroot extracts	0.4–7.29 g/kg	Cooked ham	NR	NR	Cooked ham with hibiscus presented the best color (instrumental and visual aspect parameters). From beetroot, the unencapsulated extract showed the best results	[67]

Plant Extracts	Concentration	Meat/Meat Product	Main Effects			Ref.
			Antioxidant Effects	Antimicrobial Effects	Other Effects	
Lupulon–xanthohumol nanoliposome	50–200 ppm	Cooked beef sausage	Addition of liposome + nitrite successfully prevented lipid oxidation (TBARs)	Inhibit the growth of microorganisms (total viable counts and molds/yeast) (nitrite + nanoliposome combination presented the best results) during refrigerated storage. Nitrate + nanoliposome effectively inhibit the growth of *Clostridium perfringers* and coliforms	Liposome + nitrite successfully maintain the redness and did not produce changes in sensory properties of beef sausage (Customer acceptance)	[68]
Allium sativum essential oil	0.10%	Minced meat	NR	The essential oil microcapsules showed inhibitory effect (in essential oil concentration-dependent manner) against microorganisms growth (total aerobic mesophilic flora, sulfite-reducing anaerobes and *E. coli*)	NR	[69]
Thyme essential oil	1%	Hamburger-like meat products	NR	Inhibit the growth of thermotolerant coliforms and *E. coli*	NR	[70]
Prickly pear fruit extract	5%	Beef burger patties	NR	Samples treated with encapsulated prickly pear fruit extract showed lower values of mesophilic bacteria, *Enterobacteriaceae* and *Pseudomonas* spp.	Samples treated with encapsulated prickly pear fruit extract showed the smallest variations of color (redness) and texture. Maintain the pH values during storage, in contrast to control samples in which pH values increase progressively	[71]

Plant Extracts	Concentration	Meat/Meat Product	Main Effects			Ref.
			Antioxidant Effects	Antimicrobial Effects	Other Effects	
Olive leaves extract	100 mg oleuropein / kg	Meat systems (with healthy oil mixture)	Higher oxidative stability (peroxide and TBARs values) than meat systems without extract (5 days under accelerated oxidative conditions). High antioxidant activity (FRAP and DPPH)	NR	Improvement of binding properties and texture	[72]
Laurus nobilis leaf extract	1000–1500 ppm	Minced beef	Inhibit oxidative degradation (peroxide and TBARs values)	Samples with extract presented the lowest values of total viable count and psychotropic count. Also inhibit the growth of *Staphylococcus aureus* and *E. coli*	Nanoencapsulated extracts reducing spoilage processes (lipolysis and non-protein volatile nitrogen). The score of sensory properties (general acceptance) decreased with the inclusion of extract, although all treatments had sensory ratings approved by the evaluators	[73]
Quinoa peptide-loaded nanoliposomes	3–5 mg/mL	Burger	Reduce primary (peroxide values) and secondary (TBARs values) lipid oxidation	Reduce the total bacterial count and growth of *S. aureus*, mold, and yeast	Reduce proteolytic activity derived from enzyme and/or microbial spoilage	[74]

NR: Effects not reported or studied.

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