**Natural antioxidants as food and feed additives to promote health benefits and
quality of meat products: A review**

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Abstract

Fresh and processed meats offer numerous nutritional and health benefits and provide unique eating satisfaction in the lifestyle of the modern society. However, consumption of red meat including processed products is subjected to increasing scrutiny due to the health risks associated with cytotoxins that potentially could be generated during meat preparation. Evidence from recent studies suggests free radical pathways as a plausible mechanism for toxin formation, and antioxidants have shown promise to mitigate process-generated chemical hazards. The present review discusses the involvements of lipid and protein oxidation in meat quality, nutrition, safety, and organoleptic properties; animal production and meat processing strategies which incorporate natural antioxidants to enhance the nutritional and health benefits of meat; and the application of mixed or purified natural antioxidants to eliminate or minimize the formation of carcinogens for chemical safety of cooked and processed meats.

Keywords: Meat products; meat processing; health; nutrition; toxins; oxidation; antioxidants

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1. Introduction

Meat is a highly nutritious source of food that provides high-quality proteins, minerals, vitamins, and many other micronutrients. Consumption of meat, particularly red meat (beef, pork, and lamb), is dated back to antiquity and remains to be a dominant lifestyle and usually a nutritionally indispensable form of life in the modern society. However, despite the overwhelming nutritional benefits, red meat consumption has been linked with coronary heart diseases and several types of cancer. A purported underlying mechanism is the generation of chemical toxins (carcinogens and mutagens) during processing operations, such as curing, smoking, fermentation, and heat treatment (McAfee, McSorley, Cuskelly, Moss, Wallace, Bonham, & Fearon, 2010). Therefore, processed red meat is subjected to particular scrutiny.

Processed meat encompasses a wide variety of products prepared through some degree of muscle structural alterations along with the application of various functional food ingredients for organoleptic and preservation purposes. Deli-style sliced ham, frankfurters, and fresh sausages are examples of common processed products. In spite of the re-creatable taste, food variety, convenience, and good nutritional value desired by the consumer, processed meats are often perceived to be less healthy than many other types of food. In October, 2015, the International Agency for Research on Cancer (IARC) under World Health Organization (WHO) issued a monograph classifying processed meat as carcinogen (Group I) and red meat as probable

carcinogen (Group 2A), based on the survey of published human and animal studies on meat consumption in relation to colorectal and other types of cancer.

While the IARC's claim remains disputable and the outweighing **nutritional** benefits of processed meats cannot be ignored, innovative processing and ingredient strategies must be developed to minimize the health concern and improve the products' overall organoleptic, nutritional, and health qualities. Much of the claim that processed meats are unhealthy stems from the ingredients that **are** added during processing as well as the processing condition itself (Jiménez-Colmenero, Carballo, & Cofrades, 2001; Vitaglione & Gogliano, 2004). On this, oxidation and associated deleterious changes often are viewed as a main causative factor. Due to the presence of added salt (NaCl), heme iron, and the relative abundance of endogenous phospholipids, processed muscle foods are very susceptible to oxidative reactions. Indeed, radical-induced lipid and protein oxidation occurring in high-temperature cooking contributes to the formation of potentially harmful health hazards. These include a variety of carbonyl-based cytotoxic and genotoxic compounds known as 'advanced lipid oxidation end products (ALEs)', such as 4-hydroxynonenal (4-HNE) and malonaldehyde (MDA) (Kanner, 2007; Negre-Salvayre, Coatrieux, Ingueneau, & Salvayre, 2008), mutagenic heterocyclic aromatic amines (HAAs) formed at high temperatures, such as 2-amino-1-methyl-6-phenylimidazo[4,5-b]pyridine (PhIP) and 2-Amino-3,8-dimethylimidazo[4,5-f]quinoxaline (8-MeIQx) (Shabbir, Raza, Anjum, Khan, & Suleria, 2015; Turesky, 2007), and carcinogenic nitrosamines in nitrite-cured products (Toldra, 2010).

Recent advances in antioxidant research have enabled meat scientists to think the possibility of mitigating chemical toxins in meat products through different strategies, for example, moderate thermal processing conditions to reduce the toxin formation, bio-accessibility restriction technology, and antioxidant interventions (Engel, Ratel, Bouhlef, Planche, & Meurillon, 2015). The latter is of particular interest because it is believed that many of the toxin-forming reactions involve free radicals in which reactive oxygen species (ROS) are particularly implicated. While synthetic antioxidants, such as butylated hydroxyanisole (BHA), butylated hydroxytoluene (BHT), propyl gallate (PG), and tertiary butylhydroquinone (TBHQ), have long been used to inhibit oxidation-induced deleterious changes in meat, they are under increasing scrutiny due to the potential genotoxic effects. Therefore, the current industrial trend has shifted toward natural antioxidants derived from various plant materials which are rich in radical-scavenging polyphenols (Shahidi, Janitha, & Wanasundara, 1992). ‘Nature-origin’ antioxidants have also been developed from enzymatic hydrolysis of protein (peptides) and cross-linking of small molecules into amphiphilic antioxidants suitable for the interface (in emulsions, foams, etc.) (Elias, Kellerby, & Decker, 2008; Jiang & Xiong, 2015; Xiong, 2010). While synthetic antioxidants at high dosage application levels can be carcinogenic, there is much less documented evidence indicating adverse effects of natural antioxidants. Not only are natural antioxidants capable of neutralizing ROS therefore reducing the probability of toxin formation when high temperatures are applied (Balogh, Gray, Goma, & Booren, 2000), but when used in the product formulation they could also augment existing antioxidant potential even if meat is

not subjected to extensive processing. This added health and nutritional benefit could be a distinctive advantage of natural antioxidants applied to meat processing.

In human bodies, the antioxidant defense system includes enzymes (e.g., superoxide dismutase, glutathione peroxidases, and catalase), iron and copper-binding extracellular proteins (e.g., albumin, transferrin, lactoferrin, haptoglobin, and ceruloplasmin), antioxidant vitamins (e.g., vitamin C, vitamin E, and β -carotene), and other cellular compounds (e.g., quinones, glutathione, uric acid, and bilirubin) (Krinsky, 1992). In addition, various exogenous phenolic compounds derived from dietary fruits, vegetables, legumes, or ingredients added to food, such as spices and herbs used in processed meats, contribute to the antioxidant pool. These dietary sources of antioxidants are essential when the body is exposed to a high degree of radical stress.

Antioxidants used to preserve raw and precooked meat have recently been reviewed. Karre, Lopez, and Getty (2013) analyzed the antioxidant effects of several fruit juice and plant extracts on meat and poultry; Shah, Bosco, and Mir (2014) reviewed the protective role of several plant extracts in the oxidative stability of meat; similarly, Kumar, Yadav, Ahmad, and Narsaiah (2015) described recent trends in the use of natural antioxidants for meat and meat product quality protection. In our present review, we describe the potential efficacy of several antioxidant strategies, including those applied to meat animal production to boost the antioxidant pool in muscle tissue and those directly added to meat product formulations, to improve the health and nutritional benefits of meat and meat products. Our focus is on the inhibition of toxin formation and the enhancement of nutritional status of meat products by natural antioxidants.

2. Lipid and protein oxidation in meat and meat products

Lipid peroxidation in meat products occurs primarily through the radical chain reaction mechanism although singlet oxygen may provide an alternative pathway (Min & Ahn, 2005). The high degree of susceptibility of animal fat to oxidation in such products is due to a variety of factors: the relatively high proportion of polyunsaturated fatty acids (PUFA) as constituents of membrane phospholipids, the deficiency of endogenous antioxidants, such as tocopherols, when compared with vegetable and other plant oils, yet, high concentrations of pro-oxidants and radical initiators, such as heme species, high concentrations of salt (NaCl) added, and the abundance of molecular oxygen that is usually incorporated into blended meats during processing operations (Kanner, Harel, & Salan, 1988). Salt has been found to reduce the activity of catalase, glutathione peroxidase, and superoxide dismutase (Lee, Mei, & Decker, 1997), which may be one of the reasons why salted fresh meat has poor oxidative stability.

During meat processing, oxygen can be converted to various reactive species (ROS), including hydroxyl radical ($\cdot\text{OH}$), superoxide anion ($\text{O}_2^{\cdot-}$), ferryl and perferryl species [$\text{Oxy-Fe(IV)}^{\cdot+}$], lipid peroxy radical ($\text{LOO}^\cdot$), alkoxy radical ($\text{LO}^\cdot$), and many others (Decker & Hultin, 1992; Kanner, et al., 1988). A variety of secondary products are generated in the process of lipid peroxidation, notably reactive carbonyl species, such as MDA and 4-HNE. Many of the

lipid oxidation end products (ALEs) are responsible for oxidative rancidity and can participate in health-hazardous compound formation through reaction with other meat components.

The advances in meat science research over the past two decades have led to a wealth of information indicating that muscle proteins are also susceptible to both radical and non-radical ROS, and, in some cases, even more labile to radicals than PUFA (Yang & Xiong, 2015). The mechanism of protein oxidation has been described in several comprehensive reviews (Stadtman, 2006; Xiong, 2000). Discussion of the specific impact of protein oxidation on the functionality and quality of meat has been presented by Xiong and Decker (1995) and Estevez (2011). In general, the same oxidants that initiate lipid oxidation have been found to cause and propagate protein oxidation, and carbonyl formation is a common reaction pathway found in the oxidation process. In addition, proteins can react with secondary products of lipid peroxidation, for example, aldehydes and ketones, to produce carbonyl derivatives and protein-protein and protein-lipid complexes (Butterfield & Stadtman, 1997). In muscle food systems, $\cdot\text{OH}$ is readily generated through the reaction of H_2O_2 or lipid peroxide with iron or copper and causes site-specific modification of amino acids, such as methionine and lysine (Park & Xiong, 2007).

The formation of protein radicals via reacting with ROS involves the abstraction of a hydrogen atom from methylene groups (α -carbon) next to the peptide bond (carboxamide). This is essentially similar to lipid oxidation where free radicals are formed initially by producing an

unpaired electron while abstracting a hydrogen from the methylene group adjacent to the double bond. Many amino acid residue side chains are readily modified by ROS. Amino acids with reactive side chains (sulfhydryl, thioether, amino group, imidazole ring, and indole ring) are most susceptible to oxidation initiated by oxidizing lipids and their products (Roubal & Tappel, 1966; Stadtman, 2006). Thus, cysteine, methionine, lysine, arginine, histidine and tryptophan residues are common targets of ROS generated via lipid peroxidation. Other susceptible amino acids include valine, serine and proline. Electron spin resonance (ESR) has been used to identify protein and amino acid radicals as direct evidence of protein oxidation (Lund, Luxford, Skibsted, & Davies, 2008).

Common consequences of protein oxidation in complex meat systems include increased susceptibility to proteolytic enzymes, protein polymerization which produces soluble aggregates that may promote gelation and emulsification, or insoluble aggregates that are impedimental to water binding and texture (Srinivasan & Hultin, 1997; Xiong, Blanchard, Ooizumi, & Ma, 2010; Xiong, Park, & Ooizumi, 2009). Because of their highly reactive nature, electron-deficient carbonyls (aldehydes and ketones) in oxidatively-stressed proteins can cross-link with free amino groups and other nucleophilic moieties to form heterogeneous polymers (Feeney, Blankenhorn, & Dixon, 1975) that not only impair the product quality and nutritional value but also generate health concerns due to the potential to modify cellular enzyme and genetic materials (Butterfield & Stadtman, 1997). Due to chemical modifications of amino acid side chain groups and aggregation or cross-linking of proteins, oxidation can change the digestibility of protein,

therefore, affect the nutritional quality. In general, mild oxidation does not influence proteolytic degradation of muscle proteins, but extensive oxidation can decrease proteolytic digestion (Liu & Xiong, 2000; Sante-Lhoutellier, Aubry, & Gatellier, 2007; Soladoye, Juarez, Aalhus, Shand, & Estevez, 2015).

3. Variety of natural antioxidants

3.1. General consideration

Natural antioxidants are produced in living cells to maintain a delicate oxidation-reduction balance in the process of nutrient metabolism and immune function. Upon oxidative stress, antioxidants will react with radical and non-radical species to initiate defense mechanisms for the protection of both intracellular and extracellular components. The plant kingdom is the most abundant source of antioxidants, which are richly present in spices (seeds), herbs, and essential oils used in meat products for organoleptic purposes. Certain fruits and vegetables are also good sources of antioxidants and other phytochemicals. Many tree leaves, although not used for flavoring, are also good sources of phenolic compounds, and tea is an excellent example of this plant antioxidant family. Some minerals and vitamins function as co-factors of antioxidant enzymes, therefore, are also considered natural antioxidants. Nature has also produced a number of multi-functional short peptides that are capable of neutralizing free radicals and chelating pro-oxidative metal ions. The latter has led to the preparation of ‘natural’ antioxidant peptides

through enzymatic hydrolysis of proteins (Table 1). When used as antioxidants for product quality preservation, these natural compounds may also be regarded as nutraceutical ingredients or supplements for health promotion. Indeed, plant-derived antioxidants provide meat processors with the flexibility to develop novel products with enhanced nutritional value and health benefits, an improved shelf-life, and an attractive overall quality profile.

3.2. Herbs, spices, extracts, and active compounds

Antioxidant activity is widely observed in spices and herbs, for example, oregano, rosemary, thyme, cinnamon, pepper, nutmeg, licorice, aniseed, cassia bark, fennel, prickly ash, round cardamom, basil, garlic, coriander, and ginger (Kong, Zhang, & Xiong, 2010; Velioglu, Mazza, Gao, & Oomah, 1998; Yoo, Lee, Lee, Moon, & Lee, 2008). The activity is attributed to various phenolic compounds, which are structurally related but differ in quantity and type, depending on the specific source. The major phenolic constituents in spices and herbs are phenolic acids (e.g., gallic acid, caffeic acid, and rosmarinic acid), phenolic diterpenes (e.g., carnosic acid and carnosol), flavonoids (e.g., catechin, quercetin, apigenin, kaempferol, naringenin, and hesperetin), and volatile oils (e.g., eugenol, carvacrol, thymol, menthol) (Brewer, 2011). Other active compounds have also been isolated, for example, carotenoids. Among the most widely studied phenolic acids are gallic acid, carnosic acid, caffeic acid, and chlorogenic acid.

A common property of these phenolic compounds is the ability to break free radical chain reactions by the donation of hydrogen and electrons (Shahidi et al., 1992). Of particular note are

231 rosemary extract, licorice extract, oregano, black pepper, and clove oil; they have received
232 considerable attention for use as flavoring agents in processed meats. Rosemary extract, a potent
233 antioxidant, is one of the most widely used natural ingredient in the meat industry. Its antioxidant
234 activity has been associated with the presence of several phenolic diterpenes, such as carnosic
235 acid, carnosol, rosmanol, rosmariquinone, and rosmaridiphenol (Aruoma, Halliwell, Aeschbach,
236 & Löligers, 1992). For licorice, triterpene saponins and flavonoids are major active compounds,
237 along with several phenolic acids in minor quantities, of which, liquiritigenin, liquiritin,
238 isoliquiritigenin, isoliquiritin, glabridin, glabrene, licochalcone, and glycycomarin are prevalent
239 (Zhang & Ye, 2009). Oregano extracts contain high concentrations of phenolics, especially
240 rosmarinic acid.

241 Green tea extracts as nutraceutical supplements have been used as natural antioxidant,
242 antibacterial, and antiviral agents. They have been reported to exhibit anticarcinogenic and
243 antimutagenic activity (Yang & Landau, 2000). The well-known antioxidant power of tea is due
244 to the high content of catechins, tannin, and other flavonoids. The primary catechin polyphenol
245 constituents include epigallocatechin gallate (EGCG), epicatechin gallate (ECG),
246 epigallocatechin (EGC), and epicatechin (EC) (Bronner & Beecher, 1998). Aside from potent
247 radical scavenging ability, these flavonoids are also capable of binding iron to further enhance
248 their antioxidant potential in the cell (Shahidi et al., 1992). Cocoa leaves are typically discarded
249 during tree pruning, but are a good source of catechins (Hassan & Fan, 2005).

3.3. Fruits

Fruits in general are good sources of antioxidants. Apples, blueberries, plums, grapes, cranberries, pomegranates, and bearberries contain relatively high concentrations of flavonoids (Brewer, 2011; Shahidi et al., 1992). Purees and extracts have been prepared from these fruits for industry uses, and their antioxidant activity has been well documented (Karre, Lopez, & Getty, 2013). Grape seed proanthocyanidin extract was reported to provide significantly greater protection against free radicals and free radical-induced lipid peroxidation and DNA damage than vitamins C, E and β -carotene (Bagchi, Garg, Krohn, Bagchi, Tran, & Stohs, 1997; Balogh et al., 2000). The powerful antioxidant potential is attributed to the extremely high concentrations of polyphenols, such as gallic acid, the monomeric flavan-3-ols catechin, epicatechin, gallocatechin, epigallocatechin, epicatechin 3-O-gallate, resveratrol, and procyanidin dimers, trimers, and more highly polymerized procyanidins (Shi, Yu, Pohorly, & Kakuda, 2003). According to the study of Zheng and Wang (2003), phenolic constituents and contents among different berries varied considerably. Anthocyanins were found to be the main components in blueberry, cranberry, and chokeberry; chlorogenic acid in blueberry, quercetin glycosides in cranberry and lingonberry, and caffeic acid and its derivative in chokeberry were also present in relatively high concentrations. These phenolic acids, along with peonidin 3-galactoside, cyanidin 3-galactoside, and cyanidin 3-galactoside, were the most important antioxidants in these berries. Phenolics such as quercetin and cyanidin, with 3',4'-dihydroxy substituents in the B ring and conjugation between the A and B rings, have highly effective radical scavenging structures.

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272 *3.4. Vitamins and minerals*

273 Vitamins are widely distributed in plant sources and are incorporated into foods either in the
274 pure form or as components within food additives. For example, when vegetable oils and tree
275 nuts are used as ingredients in reduced-fat meat products, a considerable amount of tocopherols
276 are introduced. Likewise, when apple pomace is added to meat product formulations, the product
277 would be enriched with ascorbic acid. Several minerals (as co-factors of antioxidant enzymes)
278 and vitamins are antioxidative, and their roles in protecting the cell and muscle tissue from
279 radical-mediated structural damage are well established ([Hercberg et al., 1998](#)). For this reason,
280 antioxidant vitamins and minerals have been used as nutritional and functional additives in
281 animal feed ([Radecki, Juhl, & Miller, 1988](#); [Wenk, 2000](#)).

282 Numerous basic and clinical studies have pointed to the role of ROS, particularly free
283 radicals, in many pathologic processes, and indicated the protective effect of antioxidant
284 vitamins, such as vitamin A (β -carotene as precursor), vitamin C (ascorbic acid), and vitamin E
285 (α -tocopherol), and minerals, notably selenium and zinc, for cardiovascular health and cancer
286 prevention ([Diplock, 1991](#)). In the SU.VI.MAX trial study that comprised 5,141 men
287 randomized to take either a placebo or a supplementation with nutritional doses of vitamin C,
288 vitamin E, β -carotene, selenium, and zinc daily for 8 years, it was found that these antioxidant
289 supplements lowered the incidence of prostate cancer ([Meyer et al., 2005](#)). The same study also
290 led to the conclusion that low-dose antioxidant supplementation lowered total cancer incidence

and all-cause mortality in men but not in women ([Hercberg et al., 2004](#)). Supplementation may be effective in men only because of their lower baseline status of certain antioxidants, especially of beta carotene. The findings supported the hypothesis that chemoprevention of prostate cancer can be achieved with nutritional doses of antioxidant vitamins and minerals. On the basis of convincing clinical evidence and the fact that regular diets may not provide adequate antioxidant supply, it is strongly advised that people at the midlife age take antioxidant vitamin and mineral supplements to achieve an optimum health ([Kesse-Guyot et al., 2011](#)).

Vitamin E (α -tocopherol) is one of the four isomers (the others are β -, γ -, δ -tocopherols) of the tocopherol family. In the food industry, mixed tocopherols, which also include α -, β -, γ -, and δ -tocotrienols, are commonly used as natural antioxidants. Aside from their direct antioxidant role to neutralize of radicals through electron donation ($\cdot\text{H}$), in biological systems, vitamin C has been shown to scavenge aqueous hydroxyl ($\cdot\text{OH}$) and superoxide ($\text{O}_2^{\cdot-}$) radicals, and act as a chain-breaker in lipid peroxidations ([Rock, Jacob, & Bowen, 1996](#)). Ascorbic acid may also act indirectly in protecting lipid membranes by regeneration of the active form of membrane-bound vitamin E. The ability to stabilize carcinogens or block carcinogenic processes and enhance immune functions has been suggested to be the possible anticarcinogenic mechanism of vitamin C.

3.5. Peptides and protein hydrolysates

Hydrolyzed protein has long been used for flavor and water binding in meat products. However, it was not fully recognized until recently that many peptides present in protein hydrolysates exhibit powerful radical scavenging and metal ion-binding capacity, therefore, can be treated as antioxidants for the inhibition of unwanted oxidative processes. Indeed, a myriad of peptides and peptide mixtures prepared from enzymatic hydrolysis of plant proteins of soy, corn, potato, and buckwheat (Chen, Muramoto, Yamauchi, Fujimoto, & Nokihara, 1998; Cheng, Chen, & Xiong, 2014; Li, Han, & Chen, 2008; Ma, Xiong, Zhai, Zhu, & Dziubla, 2010; Pihlanto, Akkanen, & Korhonen, 2008) and animal-derived proteins, such as whey (Elias, Bridgewater, Vachet, Waraho, McClements, & Decker, 2006; Peña-Ramos & Xiong, 2001), casein (Kim, Jang, & Kim, 2007), gelatin (Mendis, Rajapakse, & Kim, 2005), egg (Dávalos, Miguel, Bartolomé, & López-Fandiño, 2004; Xu, Shangguan, Wang, & Chen, 2007), and muscle (Raghavan & Kristinsson, 2008; Saiga, Tanabe, & Nishimura, 2003; Thiansilakul, Benjakul, & Shahidi, 2007).

The existence of antioxidant peptide segments within a protein may help explain why dietary protein intake can promote health beyond the normal nutritional benefits. For example, feeding rats the extract of Douchi (a traditional Chinese fermented soybean product that contains numerous antioxidant peptides) was found to enhance the superoxide dismutase activity in liver and kidney, catalase activity in liver, and glutathione peroxidase activity in kidney (Wang et al., 2008). Not surprisingly, the extract also lowered lipid peroxidation in liver. Antioxidant peptides have also been isolated from *in vitro* digests of proteins. A 16-amino acid peptide (1.8 kDa) showing strong antioxidant activity was isolated from peptic hydrolysate of hoki frame protein

(Kim, Je, & Kim, 2007). The protein hydrolysate inhibited lipid peroxidation more effectively than α -tocopherol, and efficiently quenched different free radicals, including $\cdot\text{OH}$ and $\text{O}_2^{\cdot-}$. It also reduced peroxide-induced cytotoxicity on human embryonic lung fibroblasts as well as protected DNA from radical damage. Our recent study also showed that 0.1–2.8 kDa antioxidative peptides isolated from whey protein hydrolysate were strongly protective of lung fibroblast MRC-5 cells against hydrogen peroxide-induced oxidative damage (Kong, Peng, Xiong, & Zhao, 2012).

4. Antioxidant feed additive strategies

The addition of antioxidants as nutritional supplements in animal diets is a common practice to improve animal performance, health, and welfare. For meat animals, natural antioxidants added to feed not only can improve the oxidative stability and organoleptic properties of meat but they also can enhance the nutritional value and the health benefit of meat products (Kasapidou, Wood, Richardson, Sinclair, Wilkinson, & Enser, 2012; Lynch, Kerry, Buckley, Faustman, & Morrissey, 1999; Phillips, Faustman, Lynch, Govoni, Hoagland, & Zinn, 2001). Recently, there has been a growing interest in supplementing animal feeds with plant antioxidant extracts or raw antioxidant plant materials to boost the nutritional value of meat for consumers' health benefits. For example, radical-scavenging rosemary leaves (Nieto, Estrada, Jordán, Garrido, & Bañón, 2011), grape seed extract (Jerónimo et al., 2012), and licorice extract (Zhang,

Luo, Liu, Jia, Chen, & Wang, 2015) as animal feed additives have been shown to decrease lipid oxidation and improve quality of lamb meat. Lamb fed distilled rosemary or thyme in the diet for several months showed a higher antioxidant stability of the meat, a higher concentration of polyphenolic antioxidants, and a delayed color deterioration in the meat (Nieto, Diaz, Banon, & Garrido, 2010; Serrano, Jordan, & Banon, 2014).

α -Tocopherol as the most traditional feed additive up to about 500 mg/kg feed supplementation levels could maintain the redness of fresh beef on retail display, and this protective effect is exerted via the delayed oxidation of oxymyoglobin and the inhibition of PUFA oxidation (Faustman, Chan, Schaefer, & Havens, 1998). Similar findings have been documented for lamb (González-Calvo, Ripoll, Molino, Calvo, & Joy, 2015) as well as poultry meat (King, Uijttenboogaart, & Devries, 1995). Moreover, there has been a continuing effort to manipulate the fatty acid composition of meat through feed regimens. The goal of the livestock producer is to produce nutritionally balanced or enhanced meat that contains appropriate amounts of n-3 PUFA (from α -linolenic acid) versus n-6 PUFA formed from linoleic acid (18:2) (Williams, 2000). n-3 Fatty acids, especially long chain n-3 PUFA, are known to reduce the risk of many diseases, such as arteriosclerosis, coronary heart disease, inflammatory diseases, and possibly behavioral disorders (Connor, 2000). Feeding pigs dried distillers grain with solubles (DDGS) has been shown to increase PUFA iodine value (Soladoye, Shand, Aalhus, Gariepy, & Juarez, 2015). However, an excessive amount of PUFA deposition could compromise the textural quality of pork belly (softness) intended for bacon. Because of the increased

susceptibility to oxidation, PUFA-enriched meat may have a reduced shelf-life, therefore, a high-PUFA diet should include an antioxidant supplement as well.

Organic minerals as co-factors of antioxidant enzymes offer another dietary strategy to improve the quality and nutrition of meat. In a recent study conducted in the authors' lab, cross-bred pigs were fed a basal diet supplemented with 0.3 mg/kg sodium selenite as control, 0.3 mg/kg organic selenium (Sel-Plex), or 0.3 mg/kg Sel-Plex plus 1.5% linseed oil (rich in n-3 PUFA) during growing-finishing periods. Pork from both Sel-Plex diets contained 38.1% more Se than pork from the control diet, indicating more efficient absorption of organic minerals. Pork from the Sel-Plex with linseed oil treatment group also had twice the amount of n-3 fatty acids found in other two groups. Apart from the improved nutritional value, drip loss of stored meat (4 °C up to 6 days) was reduced up to 48% by the dietary Sel-Plex supplement, coinciding with greater glutathione peroxidase activity. The 0.3 mg/kg Sel-Plex plus linseed oil treatment also produced the most tender pork. Feeding pigs with mixed antioxidant organic minerals (Bio-Plex) also produced further evidence supporting the nutritional and organoleptic benefits. Many of the micronutrients present in Bioplex® are co-factors for muscle tissue cellular antioxidant enzymes (Se for glutathione peroxidase; Zn/Cu or Mn/Fe for superoxide dismutase). Free Fe and Cu can act as prooxidants in meat, but this may not be necessarily true for organic minerals. Indeed, cooked pork loin from the Bio-Plex group exhibited an increased oxidative stability when stored at 4 °C, compared with the inorganic mineral group.

Aromatic herbs and essential oils have been used in animal feed to improve the flavor and palatability of meat. Essential oil plants and essential oils are known for their antioxidant potency which is mainly attributed to phenolic compounds in the oil or in other phytochemical fractions. Some nonphenolic substances also exhibit antioxidant activity, for example, caryophyllene, careen, and terpinene (Franz, Baser, & Windisch, 2010). Such substances contribute to the protection of feed lipids from oxidative damage, since the antioxidant status of the feed can have a profound impact on the quality and oxidative shelf-life of meat (Delles, Xiong, True, Ao, & Dawson, 2014). A dietary supply of thyme oil and thymol to aging rats showed a beneficial effect on the antioxidant enzymes superoxide dismutase and glutathione peroxidase (Youdim & Deans, 2000). In chicken, oregano added in doses of 50–100 mg/kg to the broiler diet exerted an antioxidant effect in the muscle tissue (Youdim & Deans, 2000). Meat and membrane phospholipids from broilers fed 500 mg/kg rosemary and sage extracts exhibited a significantly lower oxidation rate than those fed 200 mg/kg α -tocopherol and the control after 9 days of refrigerated storage (Govaris, Florou-Paneri, Botsoglou, Giannenas, Amvrosiadis, & Botsoglou, 2007). Feeding green tea to livestock has mixed results. Zembayashi, Lunt, and Smith (1999) reported that feeding cattle green tea (0.5 kg/d) reduced the iron content, redness, and intramuscular lipid content of the muscle tissue. While feeding cattle tea catechins and rosemary extract did not improve lipid or color stability, direct addition (1000 mg/kg) can improve color stability of loin slices held in a high O₂ (80%) modified atmosphere under refrigerated storage conditions (O'Grady, Maher, Troy, Moloney, & Kerry, 2006).

5. Antioxidant food ingredient strategies

5.1. Product quality consideration

The demonstrated efficacy of natural antioxidants, in the form of either a pure extract, a blend of active components, or a powder of the original seeds, leaves, etc., to retard lipid oxidation and flavor deterioration in meat products has stimulated a broad interest within the meat industry to explore nontraditional food ingredient strategies. The attention to natural antioxidants is heightened by the recent global trend to gradually phase out synthetic food additives that have traditionally be utilized in the food chain. Existing and potential natural antioxidant technologies applied to meat for shelf-life protection are focused on plant-derived compounds that target primarily on fresh or freshly prepared meat (for review, see [Karre et al., 2013](#); [Kumar et al., 2015](#); [Shah et al., 2014](#)). In comparison, the application of natural antioxidants in ‘further processed’ meats, which are subjected to considerable muscle structure alteration, protein extraction, treatment with functional ingredients such as salt and phosphate, and different thermal processes, has been much less investigated.

[Jayathilakan, Sharma, Radhakrishna, and Bawa \(2007\)](#) applied ascorbic acid (5 mg/kg), cloves (25 mg/kg), and cinnamon (25 mg/kg) to treat precooked sheep, beef and pork, and reported that after storage at 6 °C for 6 days, the production of warmed-over-flavor (WOF, expressed as n-hexanal formation) was suppressed by more than 50%, and the inhibition was

highly correlated with antioxidant potential of these plant extracts. [Colindres and Brewer \(2011\)](#) evaluated the effect of three natural (grape seed extract, oleoresin rosemary, and oregano extract) and three synthetic (PG, BHA, and BHT) antioxidants on sensory, color and oxidative stability of cooked (71 °C), frozen (−18 °C), then reheated ground beef patties, showing the effectiveness of the antioxidants in the order of PG~grape seed extract > oleoresin rosemary > BHA > oregano extract ~ BHT > control in 6 months of storage. There are many similar and related studies reporting effective protection of cooked meat quality by antioxidant-rich spices, herbs, plant phenol extracts, tocopherols, and some fruits and vegetable ([Ahn, Grün, & Mustapha, 2007](#); [Han & Rhee, 2005](#); [Juntachote, Berghofer, Siebenhandl, & Bauer, 2006](#); [Thongtan, Toma, Reiboldt, & Daoud, 2005](#)). Furthermore, essential oils applied to raw and cooked burgers can effectively prevent oxidative rancidity ([Loizzo, Tundis, Menichini, & Duthie, 2015](#); [Sharafati-Chaleshtori, Rokni, Rafieian-Kopaei, Drees, & Salehi, 2015](#)).

Natural antioxidants have also been shown to provide strong protection for processed meats. [Sebranek, Sewalt, Robbins, and Houser \(2005\)](#) evaluated a commercial rosemary extract for antioxidant effectiveness at concentrations of 1,500 and 2,500 mg/kg in precooked then frozen pork sausage (2.6% salt; cooked to 71 °C then stored at −20 °C). The rosemary extract was found equally effective to BHA/BHT in maintaining low TBARS values of the precooked sausage. In a more recent study ([Kong et al., 2010](#)), we compared 13 common spice extracts for their antioxidant efficacy and found that clove, rosemary, and cassia bark extracts (5 mg/kg), all having a high polyphenol content, were remarkably effective in inhibiting lipid peroxidation in

cooked (73 °C), breakfast pork sausage patties (containing 1.5% salt) during refrigerated storage (4 °C). As expected, sensory panel analysis detected significantly less off-flavor in these treated products than untreated. Similarly, we noted substantial suppression of lipid oxidation in precooked pork sausage patties (20% fat) containing 1.5% salt and various concentrations of licorice and rosemary extracts during refrigerated (2 °C up to 14 days) and frozen (−20 °C up to 6 months) storage (Jiang, Zhang, True, Zhou, & Xiong, 2013). Sausage treated with 0.1% of the spice extracts showed the same TBARS-inhibitory capacity as 0.01% BHA (fat basis). Sensory panel evaluation confirmed strong inhibition of rancidity and WOF-type off-flavor development by licorice extract, corroborating its remarkable anti-radical activity due to the presence of multiple phenolics, including liquiritigenin, glabrene, glabridin, glabrol, isoliquiritin, liquiritin apioside, isoliquiritin apioside, licorice glycoside A, which were most abundantly detected (Jiang et al., 2013). It is of interest that the efficacy of licorice phenolic extract was synergistically enhanced by the presence of antioxidant peptides prepared from hydrolyzed pea protein (Zhang, Xiong, Chen, & Zhou, 2014). Similarly, *Ginkgo biloba* extract was used as a natural antioxidant to inhibit lipid oxidation in dumplings (Kobus-Cisowska, Flaczyk, & Jeszka, 2010) and meatballs (Kobus-Cisowska, Flaczyk, Rudzińska, & Kmiecik, 2014), and the products' shelf-life was reported to be excellent. Flavonoid extracts from fruits, such as cloudberry and beetroot, were shown to be effective as well to reduce lipid oxidation in cooked pork patties (Rey, Hopia, Kivikari, & Kahkonen, 2005).

The incorporation of protein hydrolysates in meat and meat products for the protection against lipid oxidation is a recent trend. In an exploration study, we developed antioxidant hydrolysates by controlled Alcalase hydrolysis of potato protein. Cooked beef patties formulated with 1.5% salt and 5% protein hydrolysate, which showed potent radical-scavenging and metal ion-binding potential, exhibited 80-90% reductions in lipid peroxide and TBARS formation over a 7 day storage period at 4 °C. In a subsequent investigation, we showed that addition of 2.5% antioxidant potato protein hydrolysate significantly improved emulsion stability and decreased cooking losses, and had a significant inhibitory effect on lipid oxidation, in nitrite-free cooked frankfurters with 15 and 30% fat (Nieto, Castillo, Xiong, Alvarez, Payne, & Garrido, 2009). These results suggest that mixed peptides have both antioxidant and emulsifying properties which may be of potential suitability for meat emulsion manufacturing. Addition of casein peptides (20 mg/mL), obtained by the proteolytic enzymes alcalase and flavourzyme, was shown to completely inhibit lipid oxidation in ground beef homogenates (Rossini, Noreña, Cladera-Olivera, & Brandelli, 2009). Antioxidant peptides can also protect muscle proteins from oxidation changes, therefore, are able to modify the functionality of salt-soluble myofibrillar proteins in the process of comminuted meat products (Wang & Xiong, 2008).

Several studies have also shown efficacy of natural antioxidants for preventing protein oxidation under meat processing conditions. Jia, Kong, Liu, Diao, and Xia (2012) applied polyphenol-rich black current extract at 5, 10 and 20 g/kg application levels to raw pork patties with 2% salt, recording a dose-dependent significant prevention of TBARS and protein carbonyl

formation and loss of protein sulfhydryls during refrigerated storage. [Ganhão, Morcuende, and Estévez \(2010\)](#) added flavonoid and polyphenol-rich fruit extracts (30 g/kg) from arbutus berry, hawthorn, dog rose, and elm-leaf blackberry into emulsified cooked burger patties, noticing significant inhibition of protein oxidation (carbonyls) in the patties when stored at 2 °C. In addition to donating hydrogen to inhibit thiol group oxidation, antioxidant phenolic compounds can form quinone-thiol adducts via quinones and this has been demonstrated in the mixture of oxidized 4-methylcatechol and isolated myofibrillar protein ([Jongberg, Lund, Waterhouse, & Skibsted, 2011](#)). The blockage of the thiol groups inhibits disulfide bond formation, thus, prevents excessive covalent aggregation and insolubilization of proteins which may be detrimental to processed meat quality. Similarly, using MALDI-TOF/TOF MS, [Tang Zhang, Dai, Li, Xu, and Zhou \(2015\)](#) detected adducts formed between quinones (derived from rosmarinic acid) and thiols from peptides of a myosin digest under meat processing conditions, and the amount of adducts increased with the cooking temperature.

The concentration of phenolics used in meat processing must be carefully controlled in order to obtain the targeted benefit. For example, when studying dose-dependent effects of chlorogenic acid on the gelation of pork myofibrillar under meat processing conditions (0.6 M NaCl, pH 6.2) in the presence of ROS, [Cao and Xiong \(2015\)](#) noted that at 6 and 30 $\mu\text{mol/g}$ application levels, chlorogenic acid, which modified the structure of protein, increased the protein gel network strength by as much as 40%, while treatment of the protein with 150 $\mu\text{mol/g}$ chlorogenic acid greatly depressed the gelling capacity. The result was explained by the fact that low and

intermediate concentrations of the phenolic acid allowed the production of soluble myosin aggregates that were conducive to gel networks, and the high concentrations, the phenolic promoted the formation of excessive amounts of disulfide linkages leading to protein insolubilization. Dose-dependent effects of green tea extract on the textural and oxidative stability of meat emulsions has also been studied. [Jongberg, Terkelsen, Miklos, and Lund \(2015\)](#) reported that green tea at 100, 500, and 1,500 mg/kg levels all inhibited formation of TBARS (lipid) as well as thiol oxidation (protein) and myosin cross-linking. However, only the 100 mg/kg green tea extract showed no negative effect on the textural stability of meat emulsion; increasing concentrations of the extract resulted in the disruption of meat emulsion properties leading to reduced water-holding capacity and textural stability.

5.2. Nutritional and health benefits of antioxidants

5.2.1. Health promotion

Apart from improving shelf-life and organoleptic qualities, the use of plant-derived nutraceuticals rich in antioxidant flavonoids and phenolics may allow meat processors to develop novel products with enhanced nutritional and health benefits ([Table 2](#)). For example, incorporation of **vegetable food ingredients**, such as rice bran and walnut extract that are rich in vitamin E, vitamin B, and polyphenols, into vegetable oil-substituted sausage, restructured beef, and other processed meats improved the oxidative stability, textural properties, and nutritional value of the products ([Álvarez, Delles, Xiong, Castillo, Payne, & Laencina, 2011; Álvarez,](#)

Xiong, Castillo, Payne, & Garrido, 2012; Cofrades, Serrano, Ayo, Solas, Carballo, & Jiménez-Colmenero, 2004; Jiménez-Colmenero, Sánchez-Muniz, & Olmedilla-Alonso, 2010). Improvement in color, texture, and vitamin A content of beef patties by the addition of cooked carrot and sweet potato has been reported (Saleh & Ahmed, 1998). Likewise, Csapo, Incze, Kovacs, Zelenak, and Zsigo (2006) developed a variety of meat products with added lutein to enrich the pro-vitamin A content thereby promoting the eye health. Similarly, apple pomace as a polyphenol-rich by-product of apple juice production can be a valuable source of nutraceuticals with antioxidants for processed meats (Hyson, 2011; Rather, Akhter, Masoodi, Gani, & Wani, 2015). The presence of dietary fibers in fruit and vegetable ingredients impart additional benefits to meat products.

When incorporated into meat processing, many of the antioxidant compounds present in plant extracts are also of therapeutic functions, and their diverse roles in promoting human health and inhibiting various physiological disorders and pathological conditions have been well documented. Consumption of meat products rich in natural antioxidants has been shown to reinforce the endogenous antioxidant efficacy against oxidative stress and ROS-induced tissue damage and degenerative diseases (Valenzuela, Sanhueza, & Nieto, 2003). While natural phenolic antioxidants as food ingredients are of general effectiveness in promoting the overall health, the protection of the gastrointestinal tract health seems to be most obvious because absorption is not required (Halliwell, Rafter, & Jenner, 2005). Unlike most non-protein antioxidants that have the exclusive role of stabilizing free radicals and inhibiting radical

propagation, antioxidant peptides may exert other biological functionalities, for example, antihypertensive, anticancer, antimicrobial, immunomodulatory, and opioid activities (Mine, Li-Chan, & Jiang, 2010). Thus, naturally occurring antioxidant peptides and those derived from protein hydrolysis are now considered as novel and potential food ingredients to promote human health.

5.2.2. Mitigation of chemical toxicity

The formation of cytotoxic compounds in cooked and processed meats may involve free radicals. Chen, Pearson, and Gray (1990) reported that heterocyclic aromatic amines (HAA) MeIOx and imidazoquinoxaline (IQ), which have been linked to cancer and other health conditions, were formed in frying ground beef as a result of reaction between creatinine and radicals of alkylpyridine. Hence, it is conceivable that cooking and processing meat with antioxidant-rich spice, herb, and other plant extracts could reduce the formation of such toxic compounds. The natural antioxidant approach is a relatively new and interesting concept which may prove valuable as an alternative method to promote meat product health.

Indeed, a growing number of studies have provided preliminary evidence supporting the hypothesis of inhibiting carcinogenic toxin formation in meat by natural antioxidants (Vitagoline & Fogliano, 2004). Balogh et al. (2000) investigated the effect of α -tocopherol (vitamin E) and oleoresin rosemary on HAA formation in fried (175, 200, and 225 °C) ground beef patties. At the concentrations of 1 and 10% (fat-basis), α -tocopherol added to the ground beef patties reduced

the concentration of HAAs, including PhIP, the principal HAA in cooked muscle foods, in cooked patties by 69% and 72%, respectively. Oleoresin rosemary, when used at the same two concentrations (1 and 10%), reduced PhIP formation by 44%. The same research group also showed that the concentration of PhIP was reduced 93 and 87% by Montmorency and Balaton cherry tissue, respectively (Britt, Goma, Gray, & Booren, 1998). Puangsombat, Jirapakkul, and Smith (2011) also reported that in fried (204 °C) beef patties, the addition of 0.2% rosemary, turmeric, fingerroot, and galangal lowered the content of HAAs (MeIQx and PhIP) by 43.5, 39.2, 33.5, and 18.4%, respectively.

The degree of HAA inhibition was significantly correlated to the total phenolic content and the scavenging activity of spices, indicating the antioxidative protection. Fig. 1 presents a proposed mechanism by which phenolic antioxidants inhibit the formation of HAAs in heated and processed meats. Based on the report of Zamora, Alcon, and Hidalgo (2014), it can be suggested that antioxidants can stop reaction 1 by diverting to pathway 1' via binding to the precursor (e.g., creatinine) or reaction 2 via stabilization of radicals (pathway 2') since both reactions are thought to be oxidant-driven.

In high-fat meatballs fried at three different frying temperatures (175, 200, and 225 °C), the presence of added black pepper drastically reduced the production of HAAs, including IQ, MeIQx, PhIP, and several others (Oz & Kaya, 2011). The highest total amount of HAAs, 37.8 ng/g, was found in control group meatballs fried at 225 °C (31.8 ng/g of which belonging to

PhIP), but no PhIP was detected in meatballs with black pepper. It appears that natural phenolic compounds present in black pepper provided the protection.

Antioxidant sulfuro derivatives contained in garlic and onion were also found to have an inhibitory effect on HAA formation (Shin, Strasburg, & Gray, 2002). The catechin derivative EGCG contained in green tea had a potent inhibitory activity against PhIP, reducing its formation by 70% in pan-fried beef as reported by Melo, Viegas, Petisca, Pinho, and Ferreira (2008). Some more recent studies have confirmed that natural antioxidants, for example, ginkgo biloba extract, can inhibit the formation of oxidized cholesterol derivatives, reduce the production and absorption of MDA and HAAs in cooked meat (Kobus-Cisowska et al., 2014). Moreover, Vitaglione, Monti, Ambrosino, Skog, and Fogliano (2002) found that tomatoes significantly inhibited the production of HAAs, especially imidazo quinolines (IQ) and MeIQx, in cooked bovine meat (juice). The antioxidant activity of carotenoids in tomatoes (e.g., lycopene) and flavonoids (e.g., quercetin) were credited for the HAA inhibition.

The inhibitory effects of natural antioxidants on advanced lipid oxidation end products (ALEs) have also been demonstrated in several studies. Carnosine, a dipeptide of β -alanine and histidine that is naturally present in muscle tissue, is a strong cellular antioxidant and carbonyl scavenger. When used as a food antioxidant, carnosine shows a potent inhibition of ALEs such as MDA in cooked meat. According to Decker and Crum (1991, 1993), carnosine (0.5 and 1.5%) strongly inhibited formation of MDA in cooked salted and unsalted ground pork, and the degree of inhibition by 1.5% carnosine was superior to sodium tripolyphosphate (0.5%), α -tocopherol,

and BHT (0.02% of fat content). Carnosine was also the most effective at preventing oxidative rancidity and color changes as determined by a sensory panel, in salted ground pork after 1 month of frozen storage (-15°C). These data suggested that carnosine could be used as a promising natural antioxidant to inhibit the formation of cytotoxic ALEs in thermally processed meat.

In *in vitro* model systems, carnosine was shown to block the formation of MDA from lipid peroxidation (Hipkiss, Preston, Himsworth, Worthington, & Abbot, 1997). Moreover, it protected cultured human fibroblasts and rat brain endothelial cells against the toxic effects of MDA and advanced glycation end products (AGEs). Although there has been very limited experimental evidence for the inhibition of HAAs, ALEs, and other toxic compound formation in processed meats by peptides obtained from specific enzymatic hydrolysis of proteins, Petersen and Doorn (2004) did observe a high reactivity of the tripeptide glutathione (Glu–Cys–Gly) for 4-HNE and its essential role in maintaining α -tocopherol in an active state for protecting the cell against ROS-mediated oxidative stress. As many short peptides present in protein hydrolysates used in meat product formulations are potent radical scavengers (Xiong, 2000), research is warranted to explore this potential source for the inhibition of toxin formation in processed meats. Resveratrol, a polyphenol from red wine, is highly inhibitory of lipid peroxidation and ALE formation in experimental models for numerous diseases, including atherosclerosis, diabetes, and Alzheimer diseases (Aldini et al., 2013).

The effect of antioxidants on the formation of *N*-nitrosodiethylamine (NDEA) in a protein oxidation pathway was investigated in a recent study (Yang, Meng, Xiong, Ma, Wang, & Zhu, 2013). Fresh minced pork was untreated (control) or treated with 700 mg/kg α -tocopherol or 300 mg/kg tea polyphenol extract, packaged in a high-oxygen atmosphere (78.8% O₂), then stored at refrigerator temperature for 10 days. Myofibrillar and sarcoplasmic proteins extracted from stored meat were reacted with 43 μ M sodium nitrite at 80 °C for 1 h. Lipid oxidation was found to be completely inhibited by tea polyphenols but increased in control and tocopherol samples after 10 days. There was significant protein oxidation (loss of sulfhydryls, formation of protein carbonyls) in control meat and the heated protein-nitrite solution produced 182 ng/mL NDEA, compared to 120 and 88 ng/mL in samples treated with tocopherol and tea polyphenol extract. Therefore, nitrosamine formation in cured meats can be inhibited by the presence of natural antioxidants.

6. Conclusions

The preparation of palatable and nutritious meat and meat products, especially from mammalian species, with negligible generation of potentially health-impact chemical by-products is a great challenge to meat and food scientists. Nevertheless, recent exploratory research has demonstrated the feasibility to reduce such health risks to a practical minimum through natural antioxidant ingredient approaches. The ability of antioxidant ingredients to

inhibit the formation of chemical toxins in cooked meat is in addition to the nutritional benefits that they can impart as well as the flavor and shelf-life that these functional materials can contribute. In continuing the effort to identify the most effective natural antioxidants from spices, herbs, fruits, and other natural sources for this purpose, it is important to investigate the concerted effects of processing, and this should include the specific temperature, pH, the ionic strength (salt concentration), and the presence unsaturated lipids and reducing sugars because the processing environment can profoundly affect the efficacy of natural antioxidants. It would also be interesting to monitor the fate of natural antioxidants used in cooked and processed meats, namely, their own chemical changes and impact on meat quality. Finally, while there is little doubt that dietary intake of meat products rich in natural antioxidants can reinforce the endogenous antioxidant power against oxidative stress, it is still not clear what percentage of antioxidants is actually absorbed into the plasma because evidence of *in vivo* and *in situ* antioxidant effects of most natural antioxidants is still scant. It is almost certain, however, that dietary natural antioxidants will have a significant protective effect on endothelial cells within the gastrointestinal tract because of the high concentrations present. Further research is warranted to determine the amount and type(s) of natural antioxidants that are required to meaningfully reduce or totally inhibit the formation of harmful compounds in processed meats based on the necessary formulation ingredients and processing schemes specific for each product.

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1085 **Table 1**

1086 Natural antioxidants used to inhibit oxidation in processed meat products

Antioxidant category	Main active compound	Example	Mode of action	Treated meat product	Reference
Spices, herbs, and extracts	Phenolic acids, terpenoids	Gallic acid, rosmarinic acid, canosic acid, caffeic acid, glabrene	Radical scavenger, metal ion chelator	Breakfast sausage, precooked pork	Jiang et al. (2013); Kong et al. (2010)
Fruits, leaves, and extracts	Flavonoids, water-soluble vitamins	Procyanidins, quercetin, catechin	Radical scavenger	Cooked burger patties, raw and cooked pork patties	Ganhão et al. (2010); Jo et al. (2003)
Nuts, seeds, and extracts	Tocopherols, tocotrienols	α -, β -, γ -, and δ -Tocopherols	Radical scavenger	Restructured steaks, frankfurters	Cofrades et al. (2004); Jiménez-Colmenero et al. (2010)
Essential oils	Polyphenols, terpenoids	Eugenol	Radical scavenger	Turkey meat patties, beef burgers	Loizzo et al. (2015); Sharafati-Chaleshtori et al. (2015)
Peptides and protein hydrolysates	Short peptides	Carnosine, Tyr-Phe-Glu, Tyr-Ser-Thr-Ala	Radical scavenger, metal ion chelator	Cooked beef, meat patties, meat emulsions, frankfurters	Cheng et al. (2010); Decker & Crum (1992); Nieto et al. (2009); Sun & Xiong (2015); Wang & Xiong (2005)

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1093 **Table 2**

1094 Natural antioxidants that inhibit toxin formation in cooked and processed meat

Meat product	Toxin formed	Inhibitory antioxidant	Responsible agent	Reference
Fried beef patties	HAAs (MeIQx and PhIP)	rosemary, turmeric, fingerroot, galangal, cherry, vitamin E	polyphenols	Balogh et al. (2000); Britt et al. (1998); Puangsombat et al. (2011)
Fried meatballs	HAAs (IQ, MeIQx, PhIP)	Black pepper	polyphenols	Oz & Kaya (2011)
Pan fried beef	PhIP	Green tea extract	EGCG	Melo et al. (2008)
Beef juice	HAAs (IQ, MeIQx)	Tomato	Carotenoid Quercetin	Vitaglione et al. (2002)
Cooked meat	ALEs (MDA) oxidized cholesterol	ginkgo biloba extract	polyphenols	Kobus-Cisowska et al. (2014)
Cooked salted pork patties	MDA	Carnosine	Carnosine	Decker and Crum (1992, 1993)
Cooked cured meat protein extracts	Nitrosamine (NDEA)	α -Tocopherol, green tea extract	Phenolics	Yang et al. (2013)

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Fig. 1. Proposed mechanism for the inhibition of HAA formation in cooked meat by phenolic antioxidants. For illustration, gallic acid and 2-amino-1-methyl-6-phenylimidazo[4,5-b]pyridine (PhIP) are used. The information is partially deduced from [Zamora et al. \(2014\)](#).