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Recent Trends in the Use of Natural Antioxidants for Meat and Meat Products

Yogesh Kumar, Deep Narayan Yadav, Tanbir Ahmad, and Kairam Narsaiah

Abstract: Antioxidants are added to fresh and processed meat and meat products to prevent lipid oxidation, retard development of off-flavors, and improve color stability. In the food industry, they can be divided into natural and synthetic antioxidants. Synthetic antioxidants have been confirmed for their toxicological and carcinogenic effects. Thus, the food industry now chooses natural products over synthetic ones. This review provides an overview of the current trends in the use of antioxidants from natural sources, for potential applications in meat and meat products. These natural antioxidants contain some active compounds, which exert antioxidative potential in meat and meat products by different mechanisms of action. The efficient extraction of these antioxidants from their natural sources, along with establishing their *in vitro* and *in producto* antioxidant activity, has been a great challenge for researchers engaged in this field. Therefore, this review is focused on all these aspects, along with current studies related to this area, to provide in-depth information to readers.

Keywords: extraction, mechanism, meat, meat quality, natural antioxidants, synthetic antioxidants

Introduction

The quality attributes of meat products deteriorate due to the lipid oxidation during processing and storage. Lipid oxidation is responsible for development of primary and secondary oxidation products, reduction in nutritional quality, as well as changes in flavor (Maqsood and Benjakul 2011a), which can precipitate health hazards and economic losses in terms of inferior product quality (Naveena and others 2008). Lipid oxidation is a rather complex process whereby the unsaturated fatty acid fraction of membrane phospholipids is oxidized, and hydroperoxides are formed which are further susceptible to oxidation or decomposition to secondary oxidation products, such as short-chain aldehydes, ketones, and other oxidized compounds that may adversely affect the overall quality and acceptability of meat and meat products.

Antioxidants are compounds that are capable of donating hydrogen ($H^{\bullet}$) radicals (Masuda and others 2001; Saito and others 2004) for pairing with other available free radicals to prevent the propagation reaction during the oxidation process. This effectively minimizes rancidity, retards lipid oxidation, without any damage to the sensory or nutritional properties, resulting in maintaining quality and shelf-life of meat products. However, intrinsic factors are available in live muscle to prevent lipid oxidation. These factors are often lost after slaughtering during conversion of muscle to meat, primary/secondary processing, handling, or storage of meat products, necessitating further supplementation with extrinsic antioxidants.

For this reason, synthetic antioxidants, such as butylated hydroxytoluene (BHT), were extensively used to delay, retard, or prevent the lipid oxidation by scavenging chain-carrying peroxyl radicals or suppressing the formation of free radicals. However, because of the concern over the safety of these synthetic compounds, extensive work is being carried out to find novel and naturally occurring compounds to delay the oxidative degradation of lipids, improve quality, and maintain the nutritional value of foods (Johnston and others 2005; Ciriano and others 2009, 2010). Thus, natural antioxidants have greater application potential in the meat industry because of the consumers' acceptability over the synthetic antioxidants. However, the application of plant extracts, herbs, spices, and essential oils with antioxidant effects is still distant for the major reasons of limited data about their effects in different meat products.

Mechanism of Lipid Oxidation in Meat and Meat Products

Lipid oxidation is described as an oxygen-dependent, oxidative-deterioration of saturated and unsaturated fatty acids. This modification of fatty acid is principally carried out by an autocatalytic mechanism of free radicals, called auto-oxidation and consisting of 3 phases: initiation, propagation, and termination (Figure 1). In the 1st reaction, the presence of prooxidants (P_0), or reactive oxygen species (ROS), or any other oxidation-favorable condition, results in the loss of a hydrogen radical from unsaturated fatty acids. In the absence of such oxidation-favorable conditions, the reaction between fatty acids and oxygen molecules cannot occur

MS 20150895 Submitted 28/5/2015, Accepted 15/7/2015. *Authors Kumar and Ahmad are with Livestock Products Technology, Central Inst. of Post Harvest Engineering and Technology, Punjab Agricultural Univ., Ludhiana, India. Author Yadav is with Food Science and Technology, Central Inst. of Post Harvest Engineering and Technology, Punjab Agricultural Univ., Ludhiana, India. Author Narsaiah is with Agriculture Structure and Process Engineering, Central Inst. of Post Harvest Engineering and Technology, Punjab Agricultural Univ., Ludhiana, India. Direct inquiries to author Kumar (E-mail: ysomvanshi@gmail.com).*

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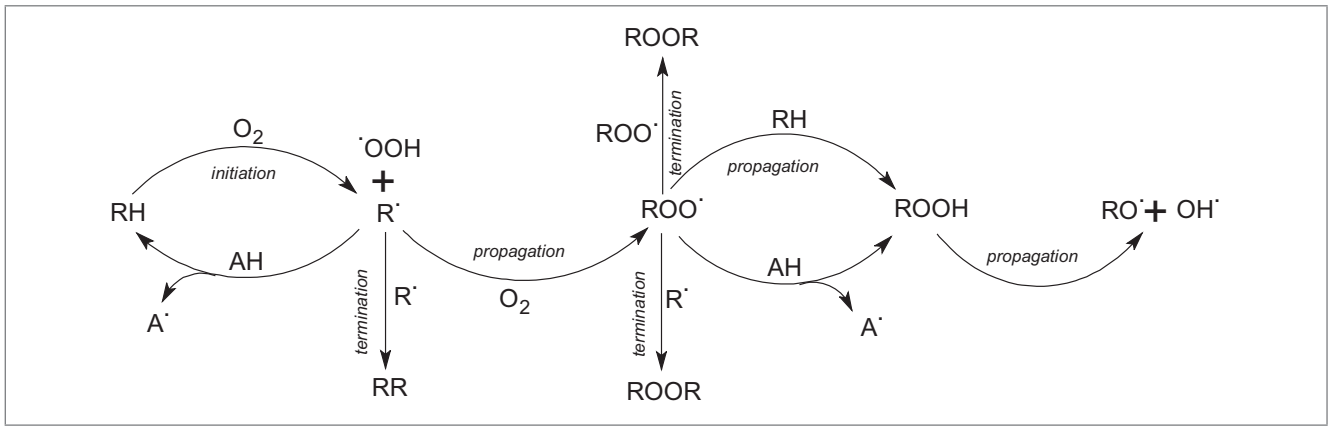

Figure 1–Mechanism of lipid oxidation; AH, antioxidant (free radical scavenger; chain breaking inhibitors); A·, scavenger radical (relatively very stable).

because of the unequal electronic state and spin barrier posed by these ground states. Thus, the ROS or other P_0, after thermal, redox, or light reaction can produce free radicals, and thus starts the primary reaction of lipid oxidation.

In the 2nd stage, molecular oxygen reacts with the alkyl radical of an unsaturated fatty acid and results in peroxide radical formation (Figure 1). In a subsequent reaction, the formation of hydroperoxides occurs. These are primary products of lipid oxidation and are relatively stable at moderate reaction conditions (low temperature/absence of pro-oxidative metal ions). However, because of the adverse conditions present in the muscle foods the hydroperoxides become susceptible to further free radical chain reactions, such as isomerization and decomposition. This produces the secondary products, including pentanal, hexanal, 4-hydroxynonenal, and malondialdehyde (MDA).

The last stage is known as termination reaction, during which the free radicals react in various combinations to form stable products (Masuda and others 2010). Other unstable compounds are also formed during the termination reaction, which also affect the quality of meat products and give rise to an unpleasant flavor (taste and odor).

Lipids and their derivative fatty acids are present in muscles as structural components of muscle membranes, as storage droplets of triacylglycerol between muscle fibers, and as adipose tissue. The form and nature of these fatty acids decide color stability, drip loss, and the development of oxidative rancidity, which ultimately decide the sensory and nutritional quality of meat products (Delgado-Pando and others 2010a, b; Baer and Dilger 2014; Berasategi and others 2014). The attractiveness of meat to the purchaser is mainly related to color and flavor, after perceived economic value (Bryhni and others 2002a, b). When meat ages it turns brown as the myoglobin is converted to metmyoglobin (MetMb: oxidized form). This is the main cause of rejection of meat and meat products by consumers. Lipid oxidation increases the rate of metmyoglobin formation; metmyoglobin acts as a catalyst for lipid oxidation, which further increases the rate of lipid oxidation, and deterioration of product color and flavor occurs. Lipid oxidation also depends upon: the degree of unsaturation of the fatty acids; the level of antioxidants (internal or external); and the presence of prooxidants (P_0), such as free iron (Morrissey and others 1998). The lipid oxidation rate is directly proportional to the unsaturation of fatty acids, which ultimately decides the color and oxidative stability of meat products (Gatellier and others 2010; Hallenstvedt and others 2012).

There are 3 stages where lipid oxidation can take place: at preslaughter (live muscle), during slaughtering (conversion of muscle to meat), and after slaughtering (processing and storage) (Figure 2). In live animals, intrinsic factors are available that can control the oxidation reaction in muscular tissues, such as enzymes (superoxide dismutase, catalase, and so on) and certain proteins and their mechanisms (transport proteins), or oxidative reaction-breaking antioxidants (vitamin E and C) (Thurnham 1990; Chan and others 1994). After slaughtering, these factors lose their antioxidative potential due to various post-slaughter conditions, such as anaerobic environment, presence of prooxidants (P_0), and lack of enzymatic antioxidative mechanisms (Carlsen and others 2005). Hemoglobin and myoglobin, which are also considered as prooxidants (Chan and others 1997; Richards and Hultin 2002; Maqsood and Benjakul 2011b; Maqsood and others 2012), along with other processing parameters, result in lipid oxidation during processing and storage of meat and meat products.

Antioxidants for Meat and Meat Products

Antioxidants are added to different meat products to prevent lipid oxidation, retard development of off-flavors, and improve color stability. In the food industry, they can be divided into natural and synthetic antioxidants. BHA (butylated hydroxyanisole), BHT, PG (propyl gallate), and TBHQ (tert-butylhydroquinone) are examples of synthetic antioxidants; while ingredients obtained from natural sources which exhibit antioxidative potential in a food model system are considered as natural antioxidants. These antioxidants play a very important role in the food industry. However, synthetic antioxidants have been identified as toxicological and carcinogenic agents in some studies (Abraham and others 1986; Ahmad and others 1995; Sarafian and others 2002; Faine and others 2006). Thus, the food industry now chooses natural products over synthetic ones. Consequently, the food market is demanding natural antioxidants, free of synthetic additives and still orientated to diminish the oxidation processes in high-fat meat and meat products.

Antioxidants vary widely in chemical structure and have varied mechanisms of action. The key mechanism is their reaction with free radicals to form relatively stable inactive products (Figure 3) (Yogesh and Ali 2014). Thus, antioxidants delay lipid oxidation by scavenging free radicals which are generated in the initiation phase, propagation phase, or during the breakdown of the hydroperoxides. The mechanism of lipid oxidation is illustrated in Figure 1. The level needed for such antioxidants to be effective

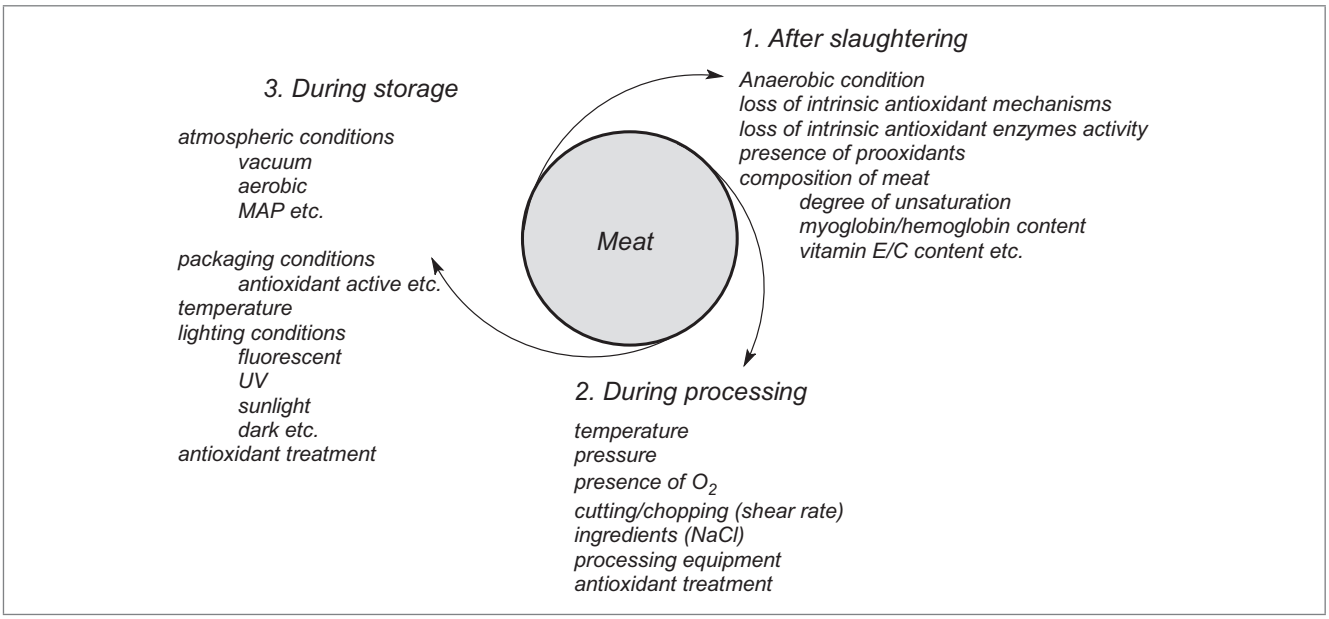

Figure 2–Factors affecting the oxidative stability of meat at various stages.

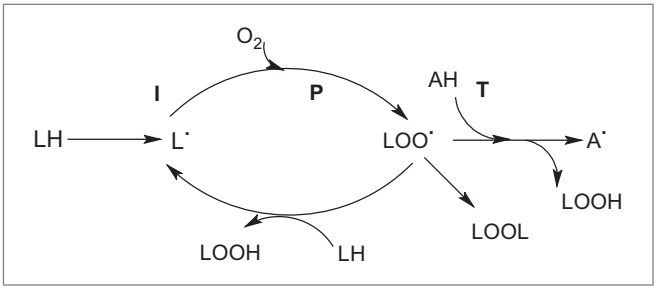

Figure 3–Auto-oxidation reactions and antioxidant action (I, P, and T = initiation, propagation, and termination, respectively) of polyunsaturated fatty acids; LH, unsaturated fatty acid; LOO·, peroxyl radicals; AH, antioxidant (free radical scavenger; chain breaking inhibitors); A·, scavenger radical (relatively very stable). [Polyphenols are very active in this respect and the radical-scavenging activities of gallates, nordihydroguairetic acid, and flavonoids arise from this process].

in a given product corresponds to the concentration necessary to inhibit all chain reactions started by the initiation process. As long as the concentration of the antioxidants is above this threshold level the total number of free radicals is kept at a constant low level. Subsequently, the antioxidant is gradually depleted and when its level is finally below the threshold level, radicals escape from the reaction with the antioxidant and the concentration of hydroperoxides increases. The high level of hydroperoxides further increases the concentration of radicals, and the remaining antioxidant molecules are used up completely. When all the antioxidants are consumed, the oxidative processes accelerate, and the increase in the production of secondary oxidation products leads to the progressing deterioration of the meat product. Based on their mode of action, antioxidants inhibit or prevent oxidation; they are again classified into 2 groups. The 1st group is primary antioxidants, which react directly with lipid radicals and convert them into relatively stable products; these are also called as chain-breaking antioxidative compounds. The 2nd group is secondary antioxidants, which can reduce the rate of oxidation by different mechanism of action. Most primary antioxidants act by donating a hydrogen atom ($H^{\cdot}$). Secondary antioxidants may act by binding metal ions (Fe^{2+}, Fe^{3+}, and Cu^{2+}) able to catalyze oxidative processes, by scavenging oxygen, by absorbing UV radiation, by inhibiting enzymes, or by decomposing hydroperoxides (Rice-Evans and others 1997). Some natural phenolic compounds function as both primary and secondary antioxidants.

Natural Antioxidants: Mechanism of Action

Much interest has been developed during the last few years for naturally occurring antioxidants because of the adverse attention received by synthetic antioxidants, and also because of the worldwide trend to avoid or minimize the use of artificial (synthetic) food additives. The research for natural antioxidants has also increased in recent years; these antioxidants may be found in any plant part, such as grains, fruits, nuts, seeds, leaves, roots, arils, and barks. The majority of natural antioxidants are phenolic compounds, and the most important are the tocopherols, flavonoids, and phenolic acids. All are generally common to all plant sources. They are added to an extensive variety of foods, in order to prevent or retard lipid oxidation.

The phenolics present in the natural antioxidants have strong $H^{\cdot}$-donating activity (Muchuweti and others 2007) or have high radical-absorbance capacity. The major antioxidative phenolics are: phenolic acids, phenolic diterpenes, flavonoids, and volatile oils. Some phenolics prevent the formation of free radicals and propagation of ROS, whereas other scavenge free radicals and chelate prooxidants (transition metals) (Ozsoy and others 2009). Phenolic acids trap free radicals; flavonoids scavenge free radicals and chelate metals (Fe^{2+}, Fe^{3+}, and Cu^{2+}) as well. The antioxidant potential of these natural compounds (phenolics) depends on their skeleton structure and pattern of functional groups on this skeleton (Wojdylo and others 2007). For instance, the number and location of free hydroxyl (–OH) groups on flavonoid skeleton decide the free radical-scavenging potential (Lupea and others 2008). Presence of multiple –OH groups and ortho-3,4-dihydroxy structures enhance the antioxidant potential of plant-based phenolics (Geldof and Engeseth 2002; Brown and Kelly 2007). Polymeric structures (containing more –OH groups)

possess more antioxidant potential (Ursini and others 2001), whereas glycosylation of functional groups (reduction of –OH groups) usually decreases antioxidant effectiveness. Plant-derived pigments (anthocyanins and their hydrolyzed products, anthocyanindins) also contain –OH groups, which can donate H· and thus possess antioxidant properties. Some phenolics also contain vicinal –OH groups attached to aromatic ring. These phenolics donate H· as well as vicinal –OH groups that can chelate metals, thus prevent oxidation via more than one method. This type of natural antioxidants (for example, carnosic acid) has several times the antioxidant activity as BHA and BHT because the latter do not have vicinal –OH groups, thus do not chelate metals and antioxidant properties depend only on H· donation mechanism.

Extraction Methods

Although the concept of using natural antioxidants to prevent lipid oxidation in meat and meat products is promising, safe, efficient, and economical procedures for extraction of these compounds from plant materials must be developed, in order to establish commercial sustainability. Researchers have employed a variety of extraction procedures. Because of the variations in these procedures, the extraction time ranges from a few seconds to many hours. These variations include different ratios of solvent volume to sample weight, as well as different physical parameters, such as application of pressure, temperature, and radiation. The fact that one single plant may contain up to several thousand secondary metabolites makes it necessary to develop high-performance and rapid-extraction methods. In general, extraction is being carried out using traditional methods, including Soxhlet extraction, solid–liquid, and liquid–liquid extraction (Table 1). These methods have been associated with higher solvent consumption, longer extraction time, and a higher risk of thermal degradation of labile components.

Extraction with organic solvents like ethanol, chloroform, acetone, diethyl ether, and methanol has been used by various researchers (Hernández-Hernández and others 2009; Lee and others 2010, 2011; Trindade and others 2010; Garrido and others 2011; Biswas and others, 2012; Selani and others 2011; Vaithiyanathan and others 2011). A combination of organic solvents has also successfully been used for extraction of antioxidants from various plant sources (Hernández-Hernández and others 2009; Trindade and others 2010; Vaithiyanathan and others 2011). The extraction efficacy of the organic solvent extraction method is better in many instances, but the main disadvantage is the problem of removal of residues of organic solvents from extracted materials. In general, these organic solvents are removed by various evaporative methods, but this could lead to economic imbalance, as well as health-related issues if not removed completely. On the other hand, hydrodistillation (Fasseas and others 2008), steam-distillation (Bozkurt 2006), and aqueous extraction methods (Huang and others 2011; Kanatt and others 2011; Biswas and others 2012; Yogesh and others 2012) have also been used for the efficient extraction of antioxidants from various natural sources. The main advantage of aqueous extraction is the safely edible product it produces because of the absence of the traces of organic solvents. However, it is a well-known fact that the solubility of different compounds is affected by various parameters, which can also affect the extractability of a compound of interest during various processing conditions.

Thus, alternative novel extraction procedures are described which can lower the extraction time and solvent consumption, increase sample throughput, and improve analyte recovery. Some of these novel methods include subcritical extraction (Kumar and others 2011; Aliakbarian and others 2012; He and others 2012; Veggi and others 2014), supercritical extraction (Gallo and others 2012; Marqués and others 2013; Pereira and others 2013; Vicente and others 2013), accelerated solvent extraction (Hossain and others 2011; Richter and Raynie 2012; Barros and others 2013), ultrasound-assisted extraction (González-Centeno and others 2014; Kulkarni and Rathod 2014; Orphanides and others 2014), and microwave-assisted extraction (Pavlović and others 2013; Zhang and others 2013a, b; Jiao and others 2014). Apart from these, some researchers have also identified other method for the efficient extraction of antioxidative compounds. For instance, Badr and Mahmoud (2011) used squeezing and evaporative concentration for antioxidant extraction from carrot juice. Ciriano and others (2009) showed the extraction of antioxidative compounds from borage (*Borago officinalis* L.) leaves by sonication. Enzymatic hydrolysis is another method recently applied for extracting these compounds (Sun and others 2010).

Use of Natural Antioxidants for Meat, Meat Products, and Meat Model Systems

Antioxidants from a natural source provide a good alternative to conventional antioxidants (Table 2) because of high phenolics and other active ingredients, which can effectively prevent initiation or propagation of lipid oxidation reactions, as described in earlier sections. The antioxidative activity of grape seed extract (Ahn and others 2002, 2007; Brannan 2008), pomegranate by-products (Shan and others 2009; Qin and others 2013; Keşkekoğlu and Üren 2014), rosemary (Mielnik and others 2003; Nissen and others 2004; Sebranek and others 2005; Rojas and Brewer 2007, 2008), oregano (Rojas and Brewer 2007, 2008), and various other spices (Lee and Shibamoto 2002; Murcia and others 2004; Du and Li 2008) in meat and poultry products has been well demonstrated. Some of these antioxidants have shown to exhibit stronger antioxidant properties than synthetic BHA/BHT. Various natural antioxidants have also been shown to exert a positive or negative effect on the color and sensory properties of the meat products.

Mariutti and others (2011) studied the effect of the addition of sage and garlic on lipid and cholesterol oxidation in chicken meat, in the presence of salt as prooxidant. These authors found that the content of unsaturated fatty acids did not change in the presence of sage; on the contrary, with garlic, the contents of these fatty acids were decreased after cooking and storage. The hexanal and pentanal contents were lower in chicken patties containing sage, and they were higher in patties with garlic. The 7-ketocholesterol was the cholesterol oxide, found in a higher amount in raw chicken on day 0, whereas the formation of 7β- and 7α-hydroxycholesterol was verified only from day 30. Sage was effective in controlling lipid and cholesterol oxidation, minimizing the prooxidant effects of salt, cooking, and storage.

The antioxidant effect of water and methanolic garlic extracts (WEFG and MEHG) in ground meat during refrigerated storage was evaluated by Park and Chin (2010). MEHG had a greater total phenolic content, 1,1-diphenyl-2-picrylhydrazyl (DPPH) radical-scavenging activity, and reducing power than WEFG, whereas the latter had a greater yield and iron-chelating ability than the former. The addition of garlic extracts (WEFG, MEHG, and their combinations) to pork patties decreased the pH, redness, and TBARS values.

Kong and others (2010) assessed the antioxidant efficacy of 13 common spice extracts in a liposome system, as well as in cooked pork patties. In the liposome system, the extract of licorice was distinctly the strongest inhibitor of TBARS production (by 70.9%).

Table 1–Active ingredients in natural antioxidants for meat and meat products.

Serial number	Natural source	Extraction methods	Active ingredients (analyzed)	Reference
1	Mustard (*Brassica juncea*) leaf kimchi extract	70% Ethanol	NA[a]	Lee and others (2010)
2	Oregano (*Origanum vulgare*) essential oils	Hydro-distillation	Thymol, *p*-cymene, gamma-terpinene, carvacrol	Fasseas and others (2008)
3	Sage (*Salvia officinalis*) essential oils	Hydro-distillation	Eucalyptol, camphor, α-pinene	Fasseas and others (2008)
4	Lotus (*Nelumbo nucifera*) rhizome knot and lotus leaf extract	Distilled water	Phenolics, tannins, flavonoids	Huang and others (2011)
5	Curry (*Murraya koenigii L.*) & mint leaves (*Mentha spicata*)	Ethanol, hot water, ethanol + hot water	Phenolics	Biswas and others (2012)
6	Carrot juice	Squeezing/evaporative concentration	Phenolics, carotenoids	Badr and Mahmoud (2011)
7	Mung bean (*Vigna radiata*), Bengal gram (*Cicer arietinum*), pigeon pea (*Cajanus cajan*) hulls	Distilled water/evaporative concentration	Phenolics, flavonoids	Kanatt and others (2011)
8	Rosemary (*Rosmarinus officinalis L.*) and oregano (*Origanum vulgare L.*) leaves extracts	Chloroform, ethanol, chloroform + ethanol	Phenolics, rosmarinic acid, carnosic acid, carnosol	Hernández-Hernández and others (2009)
9	Rosemary, sage, and thyme decoction	Decoction obtained after water vapor distillation	NA	Mielnik and others (2008)
10	Chitosan+mint (*Mentha spicata L.*) extract	Described elsewhere	NA	Kanatt and others (2008)
11	Pomegranate (*Punica granatum*, var-kabul) juice, pomegranate rind extract	Grinding and filtration boiled distilled water	Phenolics	Naveena and others (2008)
12	Grape (Vitis vinifera var. Cencibel) antioxidant dietary fiber (GADF)	Freeze drying, milling	Phenolics mainly tannins catechins, flavonols, anthocyanidins	Sáyago-Ayerdi and others (2009)
13	Pomegranate (*Punica granatum* var-kabul) fruit juice phenolics	70% Acetone and diethyl ether	Phenolics, pro-anthocyanidins, tannins	Vaithiyanathan and others (2011)
14	Various spices/Maillard reaction products (MRPs)	Spices-as wet paste MRPs[b]-Refluxing of glucose and lysine (60 mM)	NA	Jayathilakan and others (2007)
15	Different kimchi extracts	75% ethanol	Phenolics, flavonoids	Lee and others (2011)
16	Grape (*Vitis labrusca L.*) seeds and peels extract	80% ethanol	Phenolics	Selani and others (2011)
17	Green tea extract	Boiled water	NA	Bozkurt (2006)
	Thymbra spicata oil	steam distillation	NA	
18	Red grape pomace extract	Methanol, instantaneous pressure change	Total polyphenolics, total anthocyanins	Garrido and others (2011)
19	Sea buckthorn (*Hippophae rhamnoides*) berry residues	Ethanol	Polyphenols	Püssa and others (2008)
20	Oregano extract	Diethyl ether, ethyl alcohol, and distilled water	NA	Trindade and others (2010)
21	Borage (*Borago officinalis L.*) leaves extract	Preheated (96 °C) water, sonication	Phenolics	Ciriano and others (2009)
22	*Melissa officinalis L.* leaves extract	Preheated (100 °C) water, refluxing	Phenolics, rosmarinic acid	Ciriano and others (2010)
23	Arbutus-berries (*Arbutus unedo L.*), common hawthorns (*Crataegus monogyna L.*), dog roses (*Rosa canina L.*) elm-leaf blackberries (*Rubus ulmifolius Schott.*)	Absolute ethanol	NA	Ganhão and others (2010)
24	Maillard reaction products (MRPs) from MDCR hydrolysates	Enzymatic hydrolysis of MDCR	NA	Sun and others (2010)
25	Defatted canola (*Brassica napus*) meal	70% acetone	Sinapic, ferulic, *p*-hydroxybenzoic acids	Brettonnet and others (2010)
26	Thuza (*Thuja occidentalis*) cones extract	Boiled sterilized distilled water	Phenolics, flavonoids	Yogesh and Ali (2014)
27	Curry (*Murraya koenigii L.*) berry extract	Boiled sterilized distilled water	Phenolics, flavonoids	Yogesh and others (2012)

[a] Not analyzed.
[b] Maillard reaction products.

Table 2–Various sources used as natural antioxidants for meat and meat products.

Serial number	Natural material used	Meat/meat products	MCU[a]	Packaging	Temperature	SD[b]	Oxidation indices	Reference
1	Mustard (*Brassica juncea*) leaf kimchi extract	refrigerated raw ground pork meat	0.2%	Anaerobically PE[1] /nylon films	4 ± 1 °C	14	TBARs[2], FFA[3], conjugated dienes	Lee and others (2010)
2	Oregano (*Origanum vulgare*) essential oils	raw and cooked porcine/bovine meat	3% (w/w)	–	4 °C	12	TBARs	Fasseas and others (2008)
3	Sage (*Salvia officinalis*) essential oils	raw and cooked porcine/bovine meat	3% (w/w)	–	4 °C	12	TBARs	Fasseas and others (2008)
4	Lotus (*Nelumbo nucifera*) rhizome knot and leaves extract	raw and cooked porcine/bovine meat	3% (w/w)	PE films	4 °C	10	TBARs	Huang and others (2011)
5	Curry (*Murraya koenigii L.*) mint leaves (*Mentha spicata*)	raw ground pork meat	0.025%	LDPE[4]	4 ± 1 °C	12	TBARs	Biswas and others (2012)
6	Carrot juice (0%, 35%, and 60% concentrated)	irradiated beef sausage	19.843%	Aerobically/PE	4 ± 1 °C −18 °C	12 60	TBARs, PV[5] total carbonyl content	Badr and Mahmoud (2011)
7	Mung bean (*Vigna radiata*), Bengal gram (*Cicer arietinum*), pigeon pea (*Cajanus cajan*) hulls	irradiated minced chicken meat	0.1%	–	Chilled temperature	10	TBARs	Kanatt and others (2011)
8	Rosemary (*Rosmarinus officinalis L.*) and oregano (*Origanum vulgare L.*) leaves extracts	Raw pork batter	0.02% (w/w)	–	4 °C	3	TBARs	Hernández-Hernández and others (2009)
9	Rosemary, sage, and thyme decoction	Turkey thigh meat (marinated)	25% of meat (in 1 L marinade)	Dark room aerobically	4 °C	7	TBARs, volatiles	Mielnik and others (2008)
10	Chitosan+mint (*Mentha spicata L.*) extract	Pork cocktail salami	0.1% of 1% extract	–	0 to 3 °C	21	TBARs	Kanatt and others (2008)
11	Pomegranate (*Punica granatum*, var-kabul) juice, pomegranate rind extract	Cooked chicken patties	PJ 8% PR 1%	Aerobically LDPE	4 °C	15	TBARs	Naveena and others (2008)
12	Grape (*Vitis vinifera* var. Cencibel) antioxidant dietary fiber (GADF)	Raw and cooked chicken hamburger	2%	Nylon/PE, PVC[6]	4 °C	13 (raw) 5(cooked)	TBARs	Sáyago-Ayerdi and others (2009)
13	Pomegranate (*Punica granatum* var-kabul) fruit juice phenolics	Chicken breast meat (dipping at 25°C)	0.02%	Aerobically/LDPE	4 °C	28	TBARs	Vaithiyanathan and others (2011)
14	Various spices/Maillard reaction products (MRPs)	Freeze–thawed and fluidized bed dried mutton	–	PFP[7]	25 ± 2 °C	180	TBARs, total carbonyls	Jayathilakan and others (2007)
15	Different kimchi extracts	Cooked ground pork	0.1% of 10% extract	Anaerobically/PE/nylon films	4 ± 1 °C	14	TBARs, PV HC[8], CD[9]	Lee and others (2011)
16	Grape (*Vitis labrusca L.*) seeds and peels extract	Raw and cooked ground chicken	Equivalent to 60 mg PC[11]/kg meat	Vacuum/EVA[10]	−18 °C	270	TBARs	Selani and others (2011)

(*Continued*)

Table 2–Continued.

Serial number	Natural material used	Meat/meat products	MCU[a]	Packaging	Temperature	SD[b]	Oxidation indices	Reference
17	Green tea extract *Thymbra spicata* oil	Sucuk	Equivalent to 300 mg SS*/kg meat	Ripening	–	15	TBARs, BA[12]	Bozkurt (2006)
18	Red grape pomace extract	Pork burgers	0.06% of final products	PS trays with PP films[13]	4 °C	6	TBARs	Garrido and others (2011)
19	Sea buckthorn (*Hippophae rhamnoides*) berry residues	Raw and cooked MDCM[14] raw and cooked MDTM[14]	4%	–	6 °C	6	TBARs	Püssa and others (2008)
20	Oregano extract	Irradiated beef burgers	400 ppm	Aerobically/PE	−20 °C	90	TBARs	Trindade and others (2010)
21	Borage (*Borago officinalis L.*) leaves extract	Dry fermented sausages enriched with x-3 PUFAs	340 ppm	Ripening	–	30	TBARs, peroxides, volatiles, COPs[15]	Ciriano and others (2009)
23	Arbutus-berries (*Arbutus unedo L.*), common hawthorns (*Crataegus monogyna L.*), dog roses (*Rosa canina L.*) elm-leaf blackberries (*Rubus ulmifolius Schott.*)	Cooked burger patties (porcine)	3% of final product weight	PP trays with PVC films	2 °C	12	total carbonyls	Ganhão and others (2010)
24	Maillard reaction products (MRPs) from MDCR hydrolysates	Pork sausage (Cantonese type)	3% of meat	Vacuum	20 ± 3 °C	30	FFA, PV	Sun and others (2010)
25	Defatted canola (*Brassica napus*) meal	Cooked beef, pork and chicken	Equivalent to 100 mg GA/kg[16] meat	–	4 °C	6	TBARs	Brettonnet and others (2010)
26	Thuza (*Thuja occidentalis*) cones extract	Raw chicken ground meat	0.25% of meat	Aerobically/LDPE	4 ± 1 °C	8	TBARs	Yogesh and Ali (2014)
27	Curry (*Murraya koenigii L.*) berry extract	Chicken meat homogenate	0.25% of meat	Aerobically/LDPE	4 ± 1 °C	8	TBARs	Yogesh and others (2012)

[1] PE, polyethylene.
[2] Thiobarbituric acid-reactive substances.
[3] Free fatty acids.
[4] Low-density polyethylene.
[5] Peroxide value.
[6] Polyvinyl chloride.
[7] (45 GSM paper/20 l Al. foil/37.5 l LDPE).
[8] Hexanel content.
[9] Conjugated dienes.
[10] Ethylene-vinyl acetate copolymer multilayer structure.
[11] Phenolic contents.
[12] BA, biogenic amines.
[13] PS, polystyrene; PP, polypropylene.
[14] MDCM, mechanically deboned chicken meat; MDTM, mechanically deboned turkey meat.
[15] Cholesterol oxidation products.
[16] Gallic acid.
[a] Maximum concentration used.
[b] Storage days.

The other spice extracts could be separated into 2 main groups on the basis of their TBARS inhibition capability. The stronger antioxidant group with TBARS equal to or less than 0.85 mg/L or ≥40% inhibition (rosemary, nutmeg, clove, cassia bark, and round cardamom); and the weaker group with TBARS greater than 0.95 mg/L or <36% inhibition (aniseed, oregano, prickly ash, pepper, angelica, dahurian angelica root, and fennel). The TBARS production was significantly inhibited ($P < 0.05$) in pork patties treated with 0.05% clove, rosemary, or cassia bark extracts. The efficacies of these 3 spice extracts were comparable with that of BHA, which was also added at the 0.05% concentration. The TBARS values in treated pork patties were approximately 35% less than the control samples, after 7 d. The cooked pork patties containing clove, rosemary, and cassia bark extracts had also markedly low off-flavor scores and showed a more stable red color during storage.

Radha Krishnan and others (2014) studied the antioxidant effect of 4 different spice extracts (1%), [*Syzygium aromaticum* (SA), *Cinnamomum cassia* (CC), *Origanum vulgare* (OV), and *Brassica nigra* (BN)], in raw chicken meat stored at 4 °C during 15 d. The BHT (0.02%) was used as positive control. The samples treated with a combination of SA, CC, and OV showed significantly ($P < 0.05$) higher L^*, a^*, and b^* values, and the lowest TBARS values, among all the samples. These results showed that these spice extracts were very effective against lipid oxidation; and their combination increased the antioxidant potential most likely because of the synergistic effects of various antioxidative factors.

Cinnamon deodorized aqueous extract (CinDAE) was evaluated for its antioxidant potential in chicken meatballs as a function of storage time under chilled conditions (Chan and others 2012). It was concluded that treatment with 200 ppm CinDAE resulted in a longer induction period and more redness (a^*), whereas peroxide values (PVs) and TBARS values were decreased throughout storage (8 ± 1 °C), without negatively affecting sensory acceptability up to a comparable extent to that of ascorbic acid/BHA/BHT. The antioxidant effect of *Cinnamomum zeylanicum* essential oil (CZEO) in cooked sausage was evaluated by Moarefian and others (2013), and it was concluded that 20 and 40 ppm CZEO treatment resulted in lower peroxide and TBARS values than the control ($P < 0.05$), without affecting the sensory characteristics of the meat samples.

The effects of antioxidants (rosemary, carnosine, and taurine, together with ascorbic acid) under different lighting conditions (standard supermarket fluorescence, low-UV color-balanced lamp, and darkness) were studied in fresh beef patties packaged in modified atmosphere and displayed at 2 °C for 20 d (Sánchez-Escalante and others 2011). It was concluded that rosemary, and to a lesser extent, carnosine (both with ascorbic acid) were very effective in inhibiting metmyoglobin formation and lipid oxidation; thus stabilizing red meat color and retarding off-odor development. These effects were most noticeable in patties subjected to lighting during display, either with the standard fluorescent or with the low-UV color-balanced lamp. Treatment with rosemary and ascorbic acid in the absence of UV radiation gave rise to the lowest oxidation values. Conversely, the combination of taurine and ascorbic acid exerted a significant prooxidant effect.

Lara and others (2011) evaluated antioxidant activity of rosemary (*Rosmarinus officinalis* L.; Nutrox) and lemon balm (*Melissa officinalis* L.; Meliox) in cooked pork meat patties, under 70% N_2 + 30% CO_2 condition during 6 d of refrigerated (4 ± 1 °C) storage. The patties with natural extract showed higher redness (a^*) ($P < 0.001$) than the control and BHT samples. Antioxidant treatment also resulted in lower TBARS values and hexanal content throughout the storage period. Differences in the sensory attributes among batches were not detected by the panel of judges. However, the batches with natural antioxidants produced the highest concentration of free thiol groups at zero day and after 3 d.

The effect of addition of rosemary and oregano extracts (400 ppm) on the sensory qualities of irradiated (7 kGy) beefburger was investigated and compared with 200 ppm of BHT/BHA as a control during frozen (−20 °C) storage; and it was concluded that these natural antioxidants could prevent lipid oxidation without affecting the sensory scores of treated meat samples (Trindade and others 2009).

The antioxidative effect of a combinations of sage, oregano, and honey in cooked chicken meat at 4 °C for 96 h was determined by Sampaio and others (2012). The chicken samples (thigh and breast) were divided into 5 groups: control; BHT; oregano + sage; oregano + sage + 5% honey; and oregano + sage + 10% honey. The initial TBARS values for all the samples containing antioxidants were significantly lower than those found in the control group ($P < 0.05$). After 96 h, the samples with added herbs and honey had lower TBARS values than those of the control and BHT samples; thus, sage, oregano, and honey provided a better antioxidant effect than BHT. The combination of oregano, sage, and 5% honey was most effective for reducing lipid oxidation in the meat after 96 h. The treatments with oregano and sage; oregano, sage, and 5% honey; and oregano, sage, and 10% honey, in cooked chicken thigh after 96 h of refrigeration showed similar behavior. The authors suggested that these antioxidants retarded lipid oxidation immediately after cooking and during refrigerated storage. In another study, the effect of rosemary powder, rosemary extract, and α-tocopherol, and also their combinations, on the oxidative quality of Turkish sucuk during ripening and storage was investigated by GÖK and others (2011). The combination of 500 ppm rosemary extract and 500 ppm tocopherol resulted in the highest antioxidant activity, and the product color was also preserved better than in the other treatments.

The antioxidant effect of oregano and sage essential oils (3%, w/w) was determined in porcine and bovine ground meat stored at 4 °C, in the raw and cooked (85 °C for 30 min) state during a 12-d storage period (Fasseas and others 2008). The results showed that the essential oil treatment significantly reduced oxidation, whereas the heat treatment and storage time significantly reduced the oxidative stability of the meat. The role of antioxidants appeared to be much more important in the cooked state than the raw, and the meat proteins greatly affected the antioxidant activity.

In another study (Fratianni and others 2010), the antioxidant effect of thyme and balm essential oils was evaluated in fresh chicken breast meat stored at 4 °C for 3 wk. It was shown that thyme and, to a lesser extent, balm essential oil reduced DPPH radical formation in the meat (25% to 30% and 20%, respectively). The treatment with the essential oils also limited lipid peroxidation and the deterioration of sarcoplasmic proteins, helping to preserve the meat even after 2 wk of storage.

The antioxidant effect of oregano extract (0.5%, 1%, 2%, and 4%) was studied in fresh beef steaks under an active packaging system (Camo and others 2011). According to this study, a concentration of at least 1% oregano extract was needed to obtain a significant increase in beef display life from 14 to 23 d. However, a concentration of 4% oregano extract in the package gave rise to an unacceptable oregano odor, at least for the 1st day of display. Thus, the authors concluded that a 1% to 2% oregano extract concentration was most suitable for optimum active packaging.

The antioxidative effects of the peel, pulp, and seed from 2 avocado (*Persea americana* Miller) varieties ("*Hass*" and "*Fuerte*") were studied in pork meat patties (Rodríguez-Carpena and others 2011). It was reported that the peels and seeds had higher amounts of phenolics and a more intense *in vitro* antioxidant potential than the pulp. The peels and seeds were rich in catechins, procyanidins, and hydroxycinnamic acids, and the pulp was particularly rich in hydroxybenzoic acid, hydroxycinnamic acid, and procyanidins. The avocado extracts protected meat lipids and proteins against oxidation.

The effects of du-zhong (*Eucommia ulmoides* Oliv.) extracts (leaf, roasted cortex, and seed) on lipid oxidation, color, and metmyoglobin (MetMb) formation in raw pork patties were investigated and compared with that of BHT during refrigerated storage at 4 °C for 8 d (Xu and others 2010). The results indicated that the addition of leaf extract at 0.1% (w/w), roasted cortex extract at 0.1% (w/w), and BHT at 0.01% (w/w) decreased TBARS values by 35%, 20%, and 37%, respectively, on day 8. The du-zhong leaf extract at 0.1% (w/w) also exhibited a stabilizing effect on meat redness (a^*) and retarded the formation of MetMb.

The effect of rooibos tea extract (RBTE; 0%, 0.25%, 0.50%, and 1.00%) as a natural antioxidant on the lipid and protein stability of ostrich droewors (traditional South African dried sausage) after 15 d of drying was investigated by Hoffman and others (2014). The addition of 0.25% RBTE resulted in improved lipid stability and sensory attributes of the droewors.

The antioxidant potential of rooibos was evaluated by Cullere and others (2013). Three unfermented (green) rooibos forms (dried leaves, water extract, and freeze-dried extract) at the 2% level in ostrich meat patties were evaluated for 8 d of storage. The authors also evaluated the antioxidant effect of different concentrations (0%, 0.25%, 0.5%, and 1%) of the fermented rooibos extract in nitrite-free ostrich salami. The unfermented green rooibos inclusion considerably lowered the TBARS content of ostrich patties; and the fermented form (0.5% and 1%) was also effective in delaying lipid oxidation in ostrich salami up to 15 d of ripening.

The antioxidant effect of red grape pomace extracts obtained by different extraction systems (GPI: methanolic extraction + high-low instantaneous pressure, and GPII: methanolic extraction) were assessed at 0.06 g/100 g of final product concentration, in pork burgers packed under aerobic conditions (4 °C) at 0, 3, and 6 d (Garrido and others 2011). At day zero, TBARS values in control burgers were double that of the burgers with the GPI extract (1.07 compared with 0.54); and on day 6 the TBARS values for the burgers containing extract was 2 and 7 times lower than in the GPII and control burgers, respectively, which showed the intense antioxidant effect of the GPI extract in pork burgers.

The effect of grape seed and green tea extract was compared with sodium ascorbate on various quality parameters of cooked pork meatballs during 16 d aerobic retail refrigerated storage conditions (Price and others 2013). The green tea and grape seed extract-treated samples showed a lower level of TBARS and major volatile compounds than the samples with sodium ascorbate. The formation of cholesterol oxidation products was also inhibited to a greater extent in the extract-treated meat products. The color of pork meatballs was not affected by refrigerated storage; however, the addition of extracts resulted in brown shades. The addition of extract did not modify the sensory attributes, except for the color. Thus, it was concluded that the extracts were more effective than sodium ascorbate for the prevention of lipid oxidation without affecting the sensory attributes of the meat balls.

The effect of grape seed extract (GSE, 0.1%) in ground chicken thigh meat at 59%, 76%, 88%, and 99% relative humidity (RH), and with a 1% NaCl level, was examined by Brannan (2008) during refrigerated storage. The addition of GSE inhibited the formation of TBARS and altered the prooxidant effects of NaCl without affecting the moisture content and pH of the product during storage, when compared with the untreated control.

The effect of *Isabel* (IGE) and *Niagara* (NGE) grape seed and peel extracts (60 mg phenolic content/kg meat) on lipid oxidation and sensory properties of raw and cooked processed chicken meat stored at −18 °C for 9 mo was evaluated by Selani and others (2011). The IGE and NGE were effective in inhibiting the lipid oxidation of raw and cooked chicken meat, in comparison to synthetic antioxidants (0.01% BHT and 0.37% SE-mixture of sodium erythorbate, citric acid, and sugar). There was no significant difference for oxidation inhibition between the synthetic antioxidants (BHT and SE) and the natural extracts (IGE and NGE); this demonstrated the efficacy of the extracts as an antioxidant in chicken meat. However, the extracts caused darkening and lower intensity of red and yellow color in the meat products. The sensory evaluation revealed no significant alteration in odor and flavor score of the IGE-treated samples.

The effect of natural extract of green tea or commercial grape seed, in combination with synthetic tert-methyl-butylhydroquinone at different concentrations, on lipid oxidation and the redness of ground fresh goat meat, stored at 5 °C for 9 d was evaluated by Rababah and others (2011). The TBARS values ranged from 0.21 to 1.21 and 0.31 to 4.57 mg MDA/kg meat for the raw and cooked meat samples, respectively. Tert-methyl-butylhydroquinone and plant extracts significantly decreased lipid oxidation in the goat meat, with a higher level of addition being more effective in minimizing lipid oxidation. Grape seed extract significantly increased the redness, whereas green tea extract decreased it; no effect of tert-methyl-butylhydroquinone on the redness of goat meat was observed.

Bao and others (2009) evaluated the antioxidant activity of hydrophilic extract prepared from edible mushroom (*Flammulina velutipes*); and the stabilizing effect on fresh color of bigeye tuna (*Thunnus obesus*) meat was also studied in comparison with certain other antioxidants. On the basis of the color stability, it was concluded that treatment with mushroom extract at 1, 3, or 5 mL/100 g meat prolonged the duration of ice storage by more than 2, 4, and 6 d, respectively, in comparison with the control samples. The addition of 5 mL extract to 100 g minced bigeye tuna meat was more effective than ascorbic acid sodium salt (500 ppm) or α-tocopherol (500 ppm) with regard to prevention of lipid oxidation in the tuna meat.

Similarly, the antioxidative properties of a hydrophilic extract prepared from the fruiting body of edible mushroom (*Flammulina velutipes*) were evaluated in beef and fish meat (Bao and others 2008). It was found that the mushroom extract contained ergothioneine (ERT) at a level of 3.03 ± 0.07 mg/mL, which showed a higher DPPH radical-scavenging activity and suppressed lipid oxidation in the bigeye tuna meat more effectively than the authentic *L*-ERT at the same concentration. The addition of mushroom extract to the beef and fish meat resulted in less lipid oxidation; and the color values were unchanged for longer than 12 and 7 d during ice storage of beef and fish meat, respectively. Contrary to this, browning in the meat color was observed in the control samples after 6 and 2 d of storage, respectively. These authors suggested that ERT in the hydrophilic extract of *F. velutipes* played

an important role as a meat color stabilizer by preventing lipid oxidation.

The efficacy of conventional methanol/water and supercritical fluid extracts (SFE) of *Echinacea angustifolia* for the prevention of lipid and protein oxidation in cooked chicken meat was evaluated during cold storage (Gallo and others 2012). Results showed a protective action of plant extracts against lipid oxidation, but also with a greater selectivity, as a higher antioxidative efficiency of SFE than with the conventional extracts was observed. Data showed that the increment of TBARS values was much lower at the beginning than at the end of storage. This behavior confirmed that antioxidant activity decreased over time. Indeed, at day zero, the control had a lower TBARS value compared to the samples containing the extracts. At day 6, a completely opposite situation occurred; and the control showed a higher value compared with either of the treated samples. At day 10, the value of the control increased, whereas the value of samples with either of the extracts remained more or less equal to the values of the previous time analysis, which proved the antioxidative effectiveness of *Echinacea angustifolia* extracts in cooked chicken meat.

A natural citrus extract was evaluated as an antioxidant; and the activity was compared with α-tocopherol (Contini and others 2012). The extract was used as an ingredient for the production of antioxidant-active food packaging for cooked turkey meat, stored at 4 °C over 4 d. A coating density of 0.45 mg/cm^2 for the citrus extract and 0.28 mg/cm^2 for the α-tocopherol was applied. It was concluded that the citrus extract-coated trays effectively inhibited lipid oxidation in cooked turkey meat slices, which was represented by significantly lower TBARS and hexanal values. The α-tocopherol-coated trays exhibited no significant effect when compared to the control trays. The effectiveness of the citrus extract coating as compared with the α-tocopherol coating was attributed to its higher surface roughness (demonstrated by optical profilometry) and was also due to a higher level of antioxidant release (solubility) in water. These researchers also evaluated the antioxidant properties of citrus extract and α-tocopherol, by adding them in alcoholic solutions, which were then added directly to ground raw and cooked turkey meat at 1.35 mg/g and 0.84 mg/g meat, for citrus extract and α-tocopherol, respectively. At each time point, α-tocopherol and the citrus extract were shown to be equally effective as antioxidants, with no significant differences in lipid oxidation.

The oxidative stabilities of irradiated (2.5 kGy) ground beef rounds aged for 1, 2, or 3 wk after slaughtering were studied with treatment of 0.05% ascorbic acid + 0.01% α-tocopherol or 0.05% ascorbic acid + 0.01% α-tocopherol + 0.01% sesamol, placed on styrofoam trays and wrapped with oxygen-permeable plastic film (Ismail and others 2008). The meat samples were displayed at 4 °C under fluorescent light for 7 d. Irradiation, aging time, as well as storage increased lipid oxidation of ground beef. Sesamol increased the effectiveness of ascorbate and tocopherol combination in reducing lipid oxidation, especially when aging and storage time were increased. The redness of beef was decreased by irradiation; and ascorbic acid and α-tocopherol addition before irradiation was effective in maintaining the redness of ground beef during the storage period.

In experiments conducted by Min and others (2009), hexane-insoluble and hexane-soluble fractions (RBE-HI and RBE-HS) were separated from 100% methanolic purple rice bran extract; and the antioxidant activity was evaluated in restructured patties formulated with minced channel catfish (*Ictalurus punctatus*) belly flap meat and stored at 4 °C for 12 d. It was shown that, during storage, both fractions showed similar antioxidant activity in the raw and cooked patties. However, the lightness (L^*) and redness (a^*) of raw and cooked patties were decreased significantly by both fractions; whereas the yellowness (b^*) was significantly ($P < 0.05$) decreased by RBE-HI and increased by the RBE-HS fraction. Thus, it was concluded that purple rice bran extract might be applicable to meat products as a natural preservative, but color change in the product may limit its application.

The activities of *Hypericum perforatum* L. extract (Hp) to inhibit lipid oxidation in heated pork meat batters formulated with an oil combination of olive, linseed, and fish oils was evaluated by Sánchez-Muniz and others (2012). The antioxidant activities at 2 concentrations (Hp5: 0.0005% and Hp10: 0.001%) of Hp in the meat matrix during chilled storage was compared with the combination of BHA and BHT, and it was shown that the addition of BHA and BHT, and Hp prevented the oxidative process during the preparation and storage of meat batters; with the lowest alteration in the samples containing BHA and BHT. The polar material, thermal oxidized compounds, and TBARS values were increased in all the samples during storage, with the lowest trend-variation for BHA and BHT, followed by Hp10 and Hp5 samples.

The aqueous extract of mate, made from dried leaves of *Ilex paraguariensis*, St. Hilaire, was shown to be effective against oxidation of lipid and vitamin E, in pre-cooked chicken meat balls formulated with 0.5% NaCl and packed in atmospheric air, during 10 d of chilled storage (Racanicci and others 2008). The dried leaves were also compared with dried rosemary leaves in chicken meatballs; and mate (0.05% and 0.10%) was found to yield equal or better protection than rosemary against the formation of secondary lipid oxidation products, at the same concentration.

The experiments conducted by Duthie and others (2013) showed antioxidative potential of various vegetable powders (10 g/145 g meat) in cooked turkey meat patties. Six (spinach < yellow pea < onion < red pepper < green pea < tomato) of 11 (beetroot, broccoli, carrot, celery, green pea, onion, red pepper, spinach, swede, tomato, and yellow pea) vegetable powders significantly ($P < 0.05$) improved oxidative stability of patties by 20% to 30%.

Kim and others (2013b) assessed the antioxidant activity of 70% ethanolic butterbur and broccoli extracts (0.1% and 0.5%, w/w) in ground beef patties, in comparison to BHT, during 12 d of refrigerated storage. TBARS values were significantly lower in the samples containing plant extracts or BHT than the nontreated control. It was shown that the TBARS values of the control samples increased steadily 5.7-fold after 12 d, whereas the TBARS values of patties with 0.1% and 0.5% butterbur extract increased only 3.3-fold and 1.8-fold, respectively, after 12 d; which were significantly less than the control. The ethanolic extract of broccoli was moderately antioxidative at 0.1% and 0.5%, in the beef patties, with significantly lower TBARS values than the control, but it was less antioxidative than butterbur extract or BHT treatment. Moreover, 0.5% butterbur extract inhibited lipid oxidation as effectively as 0.5% BHT in beef patties. In addition, the beef patties formulated with the selected plant extracts showed significantly better color stability than those without the extracts.

The possibility of using the tamarillo [*Solanum betaceum* (Cav.) Sendtn (syn. *Cyphomandra betacea*)] epicarp, as a source of compounds with antioxidant activity in cooked beef meat (CBM) was explored by Castro-Vargas and others (2013). The SFE and Soxhlet extraction (SE) techniques were applied to obtain tamarillo extracts; and these were added at 200 mg/kg meat to CBM. The extract (SFE) obtained at 40 °C/30 MPa was shown to minimize

the TBARS concentration by 56% compared with the control (0.33 ± 0.10 compared with 0.75 ± 0.12 mg MDA/kg); and the extract (SFE) obtained at 50 °C/30 MPa reduced it by 51% (0.37 ± 0.12 compared with 0.75 ± 0.12 mg MDA/kg). However, the extracts obtained by SFE at lower pressure (10 and 20 MPa) and by SE (hexane) showed a prooxidant effect in CBM, as indicated by increased TBARS values over the control samples.

Kim and others (2013a) investigated the influence of chamnamul (*Pimpinella brachycarpa*) and fatsia (*Aralia elata*) extracts on lipid oxidation in raw beef patties. The extracts and BHT were individually added to patties, at 0.1% and 0.5% (w/w); and the patties were stored at 4 °C for 12 d. The addition of extracts and BHT resulted in a concentration-dependent decrease in the TBARS values, and it also improved the color stability of the meat product. The results showed that the TBARS values of 2 extract-added groups (0.1%) were increased from an initial 0.383 and 0.414 mg MDA/kg patties to 0.984 and 1.110 mg MDA/kg patties in the samples with fatsia and chamnamul extracts, respectively. At a concentration of 0.5%, the TBARS values increased from an initial 0.247 and 0.406 mg MDA/kg patties to 0.389 and 0.474 mg MDA/kg patties in the samples with fatsia and chamnamul extracts, respectively. The fatsia extract was more effective in retarding lipid oxidation than the chamnamul extract, which was as effective as the synthetic antioxidant when added at 0.5% (w/w).

The assessment of the antioxidant efficacy of black currant (*Ribes nigrum* L.) extract (BCE) in raw pork patties during 9 d of chilled storage was carried out by Jia and others (2012). The BCE was condensed and added to pork patties at 5, 10, or 20 g/kg for evaluation of antioxidant potential in comparison to BHA (0.2 g/kg). The BCE treatment significantly decreased the TBARS, carbonyl formation, as well as reduced the sulfhydryl loss of pork patties, in a dose-dependent manner ($P < 0.05$), which showed that the BCE significantly inhibited lipid and protein oxidation. The TBARS production was significantly inhibited ($P < 0.05$) by 74.9%, 90.6%, and 91.7% in the patties treated with 5, 10, or 20 g/kg of BCE, respectively, as compared with the control over 9 d of storage. The efficacy of BCE was comparable with that of BHA, which was added at 0.2 g/kg, and 10 and 20 mg/kg BCE treatments reduced TBARS values similar to that of 0.2 g/kg BHA. It was also demonstrated that the BCE-treated patties showed significantly higher redness ($P < 0.05$) than the control. These findings demonstrated strong potential of BCE as a natural antioxidant in meat and meat products.

The effect of addition of hydrodistilled winter savory (*Satureja montana* L.) essential oil (SEO) at 7.80, 15.60, and 31.25 μL/g on color and lipid oxidation in mortadella-type sausages was studied by Coutinho de Oliveira and others (2012). The sausages were formulated with different sodium nitrite ($NaNO_2$) levels (0, 100, and 200 mg/kg) and stored at 25 °C for 30 d. In SEO, 26 chemical compounds were identified by the authors; the most prominent of which were thymol (28.99 g/100 g), *p*-cymene (12.00 g/100 g), linalool (11.00 g/100 g), and carvacrol (10.71 g/100 g). The use of SEO (>15.60 μL/g) adversely affected the color of the product by reducing redness and increasing yellowness. A low level of TBARS was observed in mortadellas formulated with the lowest concentration of SEO and without nitrite addition.

The incorporation of protein hydrolysates in meat and meat products, for the protection against lipid oxidation, is a recent trend (Segura-Campos and others 2013). Thus, Nasri and others (2013) investigated antioxidant properties of goby (*Zosterisessor ophiocephalus*) protein hydrolysates (GPHs) in turkey meat sausage stored at 4 °C. These hydrolysates were obtained by crude alkaline protease extract treatment; and protease was obtained from the viscera of grey triggerfish (*Balistes capriscus*). The GPH-TF treatment resulted in more oxidative stability of turkey meat sausages. It was also noted that the meat system containing 0.01% of GPH had a similar TBARS level compared with that containing 0.02% vitamin C ($P < 0.05$). Further, the addition of 0.02% and 0.04% of GPH-TF was more effective ($P < 0.05$) than vitamin C, to reduce the peroxide autoxidation, in turkey meat sausage during storage. These results provided evidence that GPH-TF is a great natural antioxidant that could replace vitamin C.

Addition of casein peptides (20 mg/mL), obtained by the proteolytic enzymes alcalase and Flavourzyme, was shown (Rossini and others 2009) to effectively inhibit lipid oxidation in ground beef homogenates and mechanically deboned poultry meat (MDM). Casein peptides inhibited 80% of lipid oxidation, when added at 5 mg/mL, and reached complete inhibition of lipid oxidation at 20 mg/mL in ground beef homogenates. The addition of casein peptides (5 mg/mL) to MDM caused an inhibition of about 21% in lipid oxidation.

The antioxidant effect of hydrolyzed potato protein (HPP) (0% and 2.5%) was investigated in frankfurters formulated at 2 fat levels (15% and 30%), and stored for 7 d (Nieto and others 2009). Meat emulsions with added HPP were darker and also had lower redness and yellowness values than those made without HPP. The addition of HPP (2.5%) significantly ($P < 0.05$) decreased cooking losses and fracture force, and had a significant ($P < 0.05$) inhibitory effect on lipid oxidation in cooked frankfurters. It was shown that the production of TBARS in samples with 2.5% HPP after 7 d was 25% and 45% lower for meat emulsions containing 15% and 30% fat, respectively, compared with emulsions without HPP.

Some antioxidants are well known for their antioxidant potential and are available commercially in crude or active ingredient form (Table 3), such as rosemary and grape seed extract. Some other natural sources have also been investigated for their antioxidant potential in meat and meat products: soy protein hydrolysates prepared from microbial proteases for cooked ground beef (Zhang and others 2010); pomegranate peel extract for chicken meat products (Kanatt and others 2010); rice protein hydrolysates prepared by microbial proteases and ultrafiltration for cooked ground beef (Zhou and others 2013); grape dietary fiber for raw and cooked chicken breast hamburger (Sáyago-Ayerdi and others 2009); winery grape-residue extract for cooked chicken meat (Shirahigue and others 2011); grape seed extract, oleoresin rosemary, and water-soluble oregano extract for cooked beef and pork patties (Rojas and Brewer 2007); lavender (*Lavandula vera*) extract for minced chicken meat (Kovatcheva-Apostolova and others 2008); hydroxytyrosol in frankfurters (Cofrades and others 2011); mustard leaf (*Brassica juncea*) kimchi extracts for raw ground pork meat (Lee and others 2010). In most of these studies, it was demonstrated that these natural antioxidants were very effective to prevent lipid oxidation, when compared to some positive control (BHA/BHT), during different storage conditions.

Use of Natural Antioxidants for High-Pressure-Treated Meat and Meat Products

High-pressure processing is a technology by which meat and meat products are treated at or above 100 MPa, mainly to increase their microbiological safety. However, the use of high pressure usually above 300 MPa induces physicochemical changes which affect eating quality through flavor deterioration (rancidity), color changes, loss of nutritive value, and alterations of textural and

Table 3–Commercially available chemicals/extracts used as antioxidants for meat and meat products.

Serial number	Chemicals/extracts	Meat/meat products	MCU[a]	Packaging	Temperature	SD[b]	Oxidation indices	Positive control	Reference
1	Carob fiber pulp extracts (Liposterine and Exxenterol)	Cooked pork meat	3%	–	3 to 18 °C	20 180	TBARs[1], polar compounds	α-Tocopherol	Bastida and others (2009)
2	Hydroxytyrosol	Cooked pork meat batter	100 mg/kg	–	2 ± 2 °C	20	TBARs	BHA/BHT[2]	Cofrades and others (2011)
		Frankfurters	100 mg/kg	–	2 ± 1 °C	56	TBARs	BHA/BHT	
3	Hydrolyzed potato protein	Cooked frankfurters	2% of product	PS[3] trays, with OP[4] film	4 °C	7	TBARs	–	Nieto and others (2009)
4	STPP*, MM*, phytic acid	Raw ground beef	0.5%	PVC[5] film	4 °C	14	TBARs	–	Allen and Cornforth (2010)
	Rosmarinic acid, eugenol		0.05%	PVC film	4 °C	14	TBARs	–	
5	Ammonium hydroxide	Ground buffalo meat patties	2% (v/w)	LDPE[6]	4 °C	9	TBARs	–	Naveena and others (2011)
6	Colorifico	Raw and grilled chicken patties	0.4%	PE[7] films	−18 °C	120	TBARs	–	Castro and others (2011)
7	Adzuki bean extract	Cured and uncured Cooked pork sausages	0.2% to 0.3% of product	–	37 °C	5	TBARs	BHT	Jayawardana and others (2011)
8	Proteases	Dry-cured pork sausage	0.1%	–	–	–	TBARs, hexanals	–	Broncano and others (2011)
9	Grape seed extract	Raw and cooked pork patties	1000 mg/g	MAP[8]	4 °C	12 (raw)	TBARs	–	Carpenter and others (2007)
	Bearberry extract	Raw and cooked pork patties	1000 mg/g	MAP	4 °C	4 (cooked)			
10	Rosemary extract	Liver pâté	750 mg/kg	–	–		TBARs	–	Doolaege and others (2012)
11	Rosemary (*Rosmarinus officinalis L.*; Nutrox) Lemon balm (*Melissa officinalis* L.; Meliox)	Cooked pork patties	0.1%	MAP (PE/EVA)[9]	4 ± 1 °C	6	TBARs, hexanals free thiol groups	BHT	Lara and others (2011)
12	L-Ascorbic acid a-tocopherol sesamol	Irradiated/ nonirradiated ground beef patties	0.05%, 0.01%, 0.01%	–	4 °C	7	TBARs, volatiles	–	Ismail and others (2008)
13	Na_2EDTA	Pressurized minced pork	1%		4 to 20 °C	7	TBARs	–	Huang and others (2012)

[1] Thiobarbituric acid-reactive substances.
[2] Butylated hydroxy anisole/butylated hydroxy toluene.
[3] Polystyrene.
[4] Oxygen-permeable.
[5] Polyvinyl chloride.
[6] Low-density polyethylene.
[7] Polyethylene.
[8] Modified atmospheric packaging.
[9] Polyethylene-ethyl vinyl acetate copolymer multilayer structure.
[a] Maximum concentration used.
[b] Storage days.

functional properties through concomitant protein denaturation (Viljanen and others 2004; Fuentes and others 2010). In meat products, high pressure induces lipid oxidation and results in the formation of secondary lipid oxidation products. Thus, high pressure can be as harmful as heat treatment in terms of the oxidation level in cold-stored meat products. The composition, physical treatment conditions, mechanical processing, and type of products can influence the oxidation rate in the high-pressure-treated meat and meat products. The mechanisms by which HPP induces lipid oxidation are not fully understood. Generally, it has been suggested that HPP triggers lipid oxidation by 2 mechanisms: (a) increase release of iron from hemoproteins and (b) membrane disruption. The release of iron from myoglobin or ferritin (pro-oxidants) increases the rate of lipid oxidation. Membrane damage in the muscle and the rupture of adipocytes are other mechanisms by which the rate of lipid oxidation increases in different meat products. The reduction in the antioxidant enzyme activity after high-pressure treatment was also correlated with the higher oxidation rate in meat products. It has also been demonstrated by Bolumar and others (2012) that the formation of radicals could be a cause of lipid oxidation in pressure-treated meat products. Various researchers have studied the antioxidative potential of different natural antioxidants in high-pressure-treated meat and meat products. A waste product from industrial tomato paste production was found to provide effective protection against lipid oxidation in pressurized chicken meat (Alves and others 2012). According to these authors, addition of 0.30% tomato waste or of 0.10% final tomato paste to minced meat led to a lag phase of 6 d for the formation of secondary oxidation products in the pressure-treated (600 MPa) meat. The waste product was more effective in protecting the pressurized chicken meat against oxidation, which might be due to the presence of more flavonoid content in the waste product than the final paste product, because during washing the flavonoids are dissolved in the washing solution and leave with the waste fraction. The flavonoids washed out with the waste fraction might be more effective as an antioxidant than other phenolics or carotenoids present in the other paste processing fractions. In another study (Bolumar and others 2011), patties formulated with minced chicken breast and thigh portion, and packaged by standard vacuum-packaging (C) or in antioxidant-active packaging (AP), were subjected to high-pressure treatment (800 MPa, 10 min, 5 °C) and subsequently stored at 5 °C for 25 d. The antioxidant-active film had 0.45 mg rosemary extract/cm^2. The antioxidant-active packaging was able to delay the oxidation induced by high-pressure processing up to 25 d. However, in a recent study (Bolumar and others 2014), it was shown that the addition of rosemary extract (containing 4.5% of carnosic acid at 250 and 750 ppm), caffeic acid (500 μM), and ascorbic acid (500 μM) to beef meat, prior to high-pressure treatment (800 MPa and 20 °C for 10 min), did not provide protection against pressure-induced formation of radicals. This was explained by an increased accessibility of iron species which catalyzed radical generation during pressurization; and the presence of antioxidants aided in the regeneration of Fe^{3+} to the active Fe^{2+}.

Conclusions

The meat industry is demanding antioxidants from natural sources to replace synthetic antioxidants because of the negative health consequences or beliefs regarding some synthetic antioxidants. Fruits, vegetables, byproducts, and other plant materials provide good alternatives. Some of these antioxidants, apart from oxidation inhibition, may also affect other quality attributes positively or negatively, and ultimately affect consumer acceptability of the product. It has been shown that treatment with some natural sources can cause changes in the color of meat or meat products. Spices have shown to affect the flavor profile of treated meat and poultry products. Depending on the product, these flavors may be viewed as negatively or as positively by sensory panels. Some ingredients negatively affect the technological properties of meat and meat products, such as texture and emulsion properties. The safe edible use of these natural sources also depends on their health-related issues because some of these may also contain antinutritional or even toxicological factors. Thus, while establishing a new source of natural antioxidant for use in the meat and meat product at small, medium, or commercial level, following should be considered:

- The *in vitro* antioxidant activity should be based on various different analytical techniques. The activity should also be confirmed in targeted products during various processing conditions; thus, the effects of cooking, pressure, product ingredients, and so on, on antioxidant potential should be confirmed.
- The active ingredients/molecules of crude, concentrated or/and raw material should also be identified, and efficient conditions for extraction/separation of that particular molecule possessing potent antioxidant activity should be studied.
- Apart from oxidation inhibition, other product attributes should also be considered. Thus, the overall cumulative effect of identified antioxidants should be evaluated in different products before reaching to a conclusion. For example, if one source is a very potent antioxidant, it can also affect the color and sensory properties negatively and lower the acceptability of the final product; then a proper conclusion should be drawn to establish these negative implications. Some natural antioxidants are also sensitive to light, temperature, and pH which results in reduction of antioxidant potential. Thus, future studies should also be directed towards exploring the storage and processing environment effects on the antioxidative potential of natural antioxidants.
- Economics is the other main factor on which sustainability of any industry depends. Thus, economical extraction conditions should be well addressed relative to yield, time, infrastructure requirements, treatment materials, as well as the availability of natural sources. The correlation between economics of antioxidant use and economics of oxidation spoilage should also be considered before making any conclusion for the meat industry.
- Mere conclusions based on *in vitro*, *in vivo*, or *in producto* antioxidant activity is not suitable when new unconventional antioxidant sources are discovered. Thus, nutritional and toxicological studies (*in vitro*/*in vivo*) must be done to ascertain the safe edible use of these natural sources. This is the most important point because the meat industry is rejecting synthetic antioxidants on the basis of negative health-related issues; thus, while accepting new natural antioxidants, these must be analyzed for the same health-related consequences.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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