Research Article

Pork Quality Improvement Through Dietary Supplementation of Ingredients Enriched with Unsaturated Fatty Acid and Natural Antioxidants: New Research Trend

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Abstract | The review aims to take a comprehensive approach to summarizing the impact of dietary supplementation on pork quality. It specifically focuses on the effects of ingredients with high unsaturated fatty acid (UFAs) and natural antioxidants, as well as the various potential factors and mechanisms that influence the meat value change in pork. The fatty acids' profile, particularly UFAs, is a crucial determinant of meat's sensory quality. However, they are prone to instability due to lipid oxidation (LO) that occurs after slaughter. LO, caused by free radicals, is the most common process leading to unacceptable flavor in pork. It is now clear that LO is the primary process for reducing storage times, rather than the oxidation of proteins and vitamins, as UFAs easily react with oxidizing agents, leading to the destruction of lipid structure, change of meat texture and color, and alteration of pork taste from aroma to rancidity. The addition of ingredients with high UFAs into daily diets is, therefore, necessary to enhance the synthesis of these UFAs and improve pork quality value. Simultaneously, natural antioxidants effectively prevent LO by inhibiting autoxidation and preventing the appearance of free radicals, thereby enhancing pork flavor. This review comprehensively identifies, clarifies, and discusses the concentration of fatty acid profile in fat, how to improve the fatty acid profile, and how to tackle the prevention of autoxidation to enhance pork value quality. It also provides insight into the underlying mechanisms of meat quality changes under the potential supplementation of ingredients with high UFAs.

Keywords | Antioxidants, Meat quality, Lipid oxidation, Rancidity, Unsaturated fatty acids

Received | April 16, 2024; **Accepted** | June 15, 2024; **Published** | August 06, 2024
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Citation | Nguyen HT, Nguyen CK, Ngo DB, Dang ATN (2024). Pork quality improvement through dietary supplementation of ingredients enriched with unsaturated fatty acid and natural antioxidants: new research trend. Adv. Anim. Vet. Sci. 12(9): 1716-1730.
DOI | https://dx.doi.org/10.17582/journal.aavs/2024/12.9.1716.1730
ISSN (Online) | 2307-8316; **ISSN (Print)** | 2309-3331

INTRODUCTION

Pork is the most commonly consumed meat worldwide (UDSA, 2023) due to its necessary nutritional values (Petroski and Minich, 2020) and inclusion of no anti-nutrients (Zequan *et al*., 2021). In particular, pork consumption accounts for the largest proportion of the total meat with 36% every year, followed by the meat from poultry and cattle at 33% and 24%, respectively (UDSA, 2023). Currently, the meat quality of pigs is significantly affected by a wide range of potential elements such as raising protocols, daily feeding and diet, slaughtering procedures, or processing methods. Nutrients, tenderness, juiciness, and unique flavors in pork are important factors in determining meat quality. According to the Irish customer's standpoint, tenderness was the most important factor, followed by taste and juiciness (O'Mahony, 1991), while both Danmark and Belgian citizens have expected unique odors in pork (Bryhni *et al*., 2002; Verbeke and Viaene, 1999). Meat with high-fat compounds can decrease palatability due to unacceptable odors (Soldatova and Korzunov, 2022) during long-term storage (Buckley *et al*., 1989; Sohaib *et al*., 2017). The production and supply of fresh, nutritional, safe, and high-quality meat for human beings will be an urgently important strategy for the pork industry and other meat sources in the near future (Sofos, 2008).

On the other hand, it has been concerned the high consumption of saturated fatty acids (SFA) in pork seems to be unhealthy for humans since some negative impacts derived from SFA on the circulatory system have been recognized (Mozaffarian *et al*., 2009). It has been demonstrated the more these fatty acids are absorbed, the greater the risk of cardiovascular diseases (Zong *et al*., 2016). Recently, there has been interested in the addition of nutritional components into daily diets in order to increase the accumulation of unsaturated fatty acid (UFA) accompanied by decreasing that of SFA in muscle (Navarro *et al*., 2021). A series of reactions can be started occurring both inside and outside of pork by different pathways such as chemical, biological and physical (temperature, light) ones or bacterial contamination in post-slaughter (Lawrie RA, 1968). Bacterial contamination in post-slaughter meat processing is a significant concern addressed in various research papers. Previous studies have shown that microbial contamination of fresh meat occurs during different stages of processing, including slaughter, carcass dressing, and chilling (Aiyegoro, 2014). Besides, it has been indicated lipid oxidation has a positive effect on meat quality rather than other reactions happening in tissue. UFA has one or some double bonds in the chemical structure which is not as durable and more prone to oxidation, thus UFA is the precursor component for synthetic flavor compounds throughout the period of rigor mortis (Fan, 2021), but there seems to be an appearance of rancidity in the post-rigor stage by the excessive or uncontrolled oxidation (Nawar, 1969; Soldatova and Korzunov, 2022).

It has been showed the inclusion of linseed in the daily diet for pigs could have a feasible solution for improving nutritional components (Wang *et al*., 2021), such as the increase of Omega-3 PUFA in tissue (Dugan *et al*., 2015; Huang *et al*., 2020; Yi *et al*., 2023). The dietary supplementation of macadamia oil also had the positive effect on meat quality (Junior *et al*., 2022; Navarro *et al*., 2021). However, the potential main disadvantage of the high unsaturated fatty acid content in pork has been associated with the state of lipid oxidation (Domínguez *et al*., 2019). Furthermore, alpha-tocopherol is recognized as an effective antioxidant (Jensen *et al*., 2010), supporting to neutralize free radicals during post-mortem storage after slaughter (Li and Liu, 2012). It has been recommended a sufficient level of 100 mg alpha-tocopheryl acetate is needed for daily requirment of meat pigs to ensure meat quality and oxidative stability of pork (Jensen *et al*., 2010). The combinative supplemenation of linseed oil and alpha-tocopherol significantly modifies the ratio of n-6/n-3 fatty acids (Hoz *et al*., 2003). Several previous studies have reported that phytogenic compounds, such as phenolic compounds and essential oils (Puvača *et al*., 2013), can potentially improve the subtable oxidation in pork. Phenolic acid is noticed to have the ability to reject free radicals and protect membranes (lipoproteins) (Kiokias *et al*., 2020). In addition, phytogenic bioactive compounds can induce significant changes of the profile of fatty acids due to the deposition of IMF in pork loin (Yang and Zhang, 2015). The addition of herbal mixture into the daily diet at 2% on dry matter intake (DMI) improved the ratio of n-6 and n-3 PUFA in the pork (Paschma and Wawrzyński, 2007). However, the definitive conclusion of effect of the dietary addition of ingredients with high UFA and natural antioxidants in pig industry has not been obtained yet due to inconsistent previous results, as well as there is no comprehensively systematic overview of all existing findings on this issue. It should be required to comprehensively identify and discuss the possible aspects related to the changes in meat quality through the supplementation of ingredients with high UFA and natural antioxidants into daily diet for pigs. Furthermore, a better understanding of the underlying mechanisms of meat quality changes under the potential supplementation of ingredients with high UFA and natural antioxidants can provide further insights.

In the present systematic review, therefore, we comprehensively discuss all aspects and mechanisms of pork quality changes through dietary supplementation of ingredients enriched with unsaturated fatty acid and natural antioxidants.

The main chemical composition of pork

Protein in pork loin is generally recognized as a source of high biological value (Hoagland, 1945) and its content with stable levels (21-23.3%) in Longissimus dorsi (LD) muscles (Table 1). Furthermore, it contains a variety of essential amino acids (Wu *et al*., 2014) in sufficient quantity and proportion to meet nutritional requirements for humans (Ma *et al*., 2020) such as Lysine (8.1%) or Methionine (2.3%) (Greenhut *et al*., 1948). Evaluation of the

Table 1: Chemical compounds of *Longissimus dorsi* (LD) muscles.

Protein (g)	Fat (g)	Ash (g)	Ca (mg)	P (mg)	Fe (mg)	Reference
21.95	6.92	0.97	7.00	226	-	UDSA, 2022
23.30	3.20	1.12	6.00	370	-	NUTTAB, 2021
23.23	4.40	1.37	-	-	-	Anh *et al.*, 2019
22.10	3.01	1.20	5.00	210	-	Chen *et al.*, 2019
19.10	1.51	-	5.78	175.40	1.29	Tóth *et al.*, 2009
22.31	3.16	-	11.00	-	5.01	Ren guang-zhi *et al.*, 2008

Table 2: Fatty acid profiles of *Longissimus dorsi* muscle after slaughter in some countries.

Items	Vietnam[1]	Australia[2]	China[3]	Brazil[4]
Myristic acid (C14:0)	1.90	0.80	1.84	1.58
Palmitic acid (C16:0)	24.00	23.77	27.45	26.29
Palmitoleic acid (C16:1)	2.40	1.57	3.37	3.66
Stearic acid (C18:0)	12.95	21.62	13.23	11.35
Cis - Oleic acid (C18:1 n9)	0.4	35.71	47.77	42.56
Linoleic acid (C18: 2)	0.3	12.00	3.26	9.09
Linolenic acid (C18:3)	0.55	0.39	0.11	0.26
Saturated fatty acids (SFA)	41.00	46.78	42.86	40.92
Monounsaturated fatty acids (MUFA)	44.70	37.28	52.30	47.35
Polyunsaturated fatty acids (PUFA)	14.35	15.94	4.84	11.73
UFA/SFA	1.44	2.38	1.33	1.44

[1]Vietnam: Anh *et al.*,2019 ; [2]Australia: Navarro *et al.*, 2021; [3]China: Huang *et al.*, 2012; [4]Brazil: Alencar *et al.*, 2011.

impact of environmental conditions on meat quality can be demonstrated through the varying protein contents of pork in some countries (Skobrák and Bodnár, 2012). The nutritional compounds of pork could significantly be changed with the age and live weight of pigs (Zomeño *et al.*, 2023; Zullo *et al.*, 2003). The percentage of protein in pork loin considerably increased when the live weight of baconer increased from 80-90 to 120-130 kg at slaughter while there was an opposite trend with ash (Zomeño *et al.*, 2023; Zullo *et al.*, 2003). It has been revealed that the fat content in pork significantly changes in accordance with the crude protein in daily diets of pigs (Adamczak *et al.*, 2020). In particular, when crude proteins in the diet for pigs were at low (<15%), medium (15-25%), and high (>25%), fat content in pig meat changed at 20.1%, 17.9%, 14.7%, respectively (Adamczak *et al.*, 2020). Fat content only contributes a small proportion in pork loin (Table 1) and its value can fluctuate from 1 to 15% (Skobrák and Bodnár, 2012).

The main composition of pork lipids is glycerol esters formed by three carboxylic acids (Ros-Freixedes and Estany, 2014). Its structure has a long and unbranched chain of carbon linked to a molecule called glycerol (Small, 1984) and a small percentage of phospholipids (Cui and Decker, 2016) and sterols (Addis, 1986), thus the fatty acids in a triacylglycerol have determined the physical properties and the role of lipids (Karupaiah and Sundram, 2007) in pork. Fatty acids (Table 2) are divided into saturated fatty acids (SFA), monounsaturated fatty acids (MUFA), and polyunsaturated fatty acids (PUFA) (Yi *et al.*, 2023). Pork lipids have a better biological value from unsaturated fatty acids than from saturated fatty acids (Ros-Freixedes and Estany, 2014). Most of the latter were found in pork loin, such as palmitic acid (23.77-26.29%) and stearic acid (11.35-21.62 %) (Table 2). It has been indicated that the more these fatty acids are absorbed, the greater the risk of cardiovascular diseases (Zong *et al.*, 2016). Lipoprotein is a crucial substrate for the transport of triglycerides and cholesterol to cells in the circulatory system (Havel, 1987) formed by the combination of lipids and proteins (Havel, 1987; Kris-Etherton and Etherton, 1982). The central hydrophobic core, is non-polar lipids composed of cholesterol esters and triglycerides, surrounded by a hydrophilic membrane consisting of phospholipids with the main compounds from free cholesterol and apolipoprotein (Feingold, 2021). Lipoproteins are classified into seven distinct types based on size, lipid composition, and apolipoprotein, of which three items are of more interest, including very low density (VLDL), low (LDL) and high-density lipoprotein (HDL) (Wood *et al.*, 2011). The LDL is mainly responsible for the transportation of the cholesterol and it not only more easily enters the arterial wall but also binds more avidly to intra-arterial proteoglycans (Jaishankar *et al.*, 2022), which is associated with increasing the accumulation of cholesterol in the arterial walls (Liu *et al.*, 2020). Taken together from previous findings, these above reasons induce a tremendous effect on increasing the risk of atherosclerosis (Libby, 2021) and myocardial infarction (Byrne *et al.*, 2022; Schubert *et al.*, 2021) in consumer health problems. However, HDL plays an important role in reverse cholesterol transport to the liver (Voight *et al.*, 2012), resulting in decreasing blood cholesterol (Soares *et al.*, 2018; Voight *et al.*, 2012), probably due to the role of stearic acid (van Rooijen *et al.*, 2021). The process of endogenous monounsaturated fatty acid synthesis in tissues, is a chemical chain reaction from the necessary materials of palmitic acid and stearic acid (Figure 1) accompanied by myristic acid, to make short-chain saturated fatty acids easily absorbed in the digestive system of humans (Schmitt Jr *et al.*, 1977).

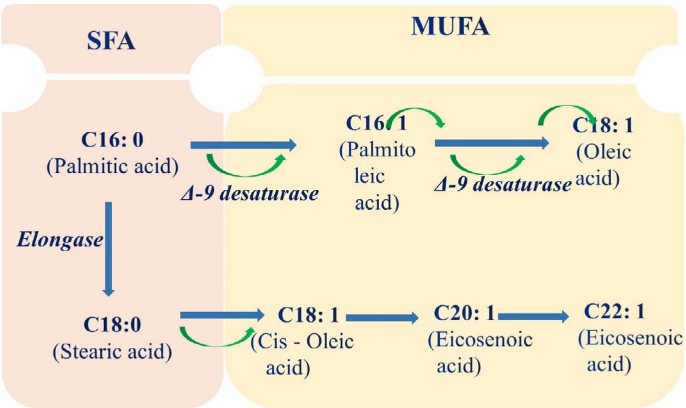

Figure 1: Synthesis of long-chain unsaturated fatty acids in mammals.

Recently, it has been recognized there are heaps of benefits for human health from the functions of some UFAs (Mozaffarian *et al.*, 2009), especially the omega-3 fatty acids with its structure always appeared the first double bond located in the third carbon (Bourre, 2004; Huang *et al.*, 2020). (Mozaffarian *et al.*, 2009) have shown that Omega-3 UFAs are conducive to preventing and protecting the circulatory system, as well as the beneficial effect of UFAs on anti-inflammatory activity and mechanism (Calder, 2015). It has been demonstrated there is a significant correlation between PUFAs and insulin sensitivity (Bhaswant *et al.*, 2015). Otherwise, UFAs have a primary effect on both desirable and undesirable aromas and flavors in pork (Cheng *et al.*, 2015) since the specific flavor of meat in each species is determined by liposoluble compounds in fat (Cui and Decker, 2016) and pork texture (hardness, springiness) (Anh *et al.*, 2022). Numerous previous investigations have demonstrated the amount of UFA is a vital factor for formation of the tenderness of meat and the structure of skeletal muscle (Xu *et al.*, 2021) as it is the main component of intramuscular fat (IMF). The infiltration and presence of UFA in pork muscle form the potential marbling in meat. The marbling score plays a key role in reflecting meat quality and the water-holding capacity of meat (Warner *et al.*, 1997). In addition, iron atoms in pork are significantly related to the interconversion of myoglobin redox forms (Wilson and Reeder, 2022), which is a catalyst for the change of meat color after slaughtering process.

The lipid oxidation in pork after slaughter

After the slaughtering process, the metabolism of cell death is interrupted (Lima *et al.*, 2013), and the reversible reactions using enzymatic would have converted the irreversible reactions due to the lack of both essential nutrients and oxygen (Schäfer *et al.*, 2002). Consequently, the spontaneous breakdown of tissue strongly occurs (Kanner, 1994) by several steps, including (1) to suspense cellular metabolism, (2) to destroy the bonds of compounds in the structure of tissue, and (3) to degrade complex substances into simpler subunits (Tuan and Hien, 2004). Based on post-mortem changes in meat, these steps can be arranged into 3 phases, including pre-rigor, rigor mortis and post-rigor (Lawrie and Ledward, 2014) (Figure 2).

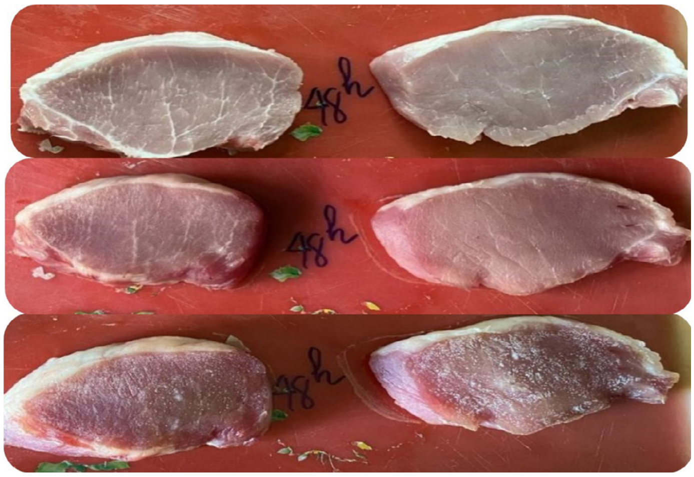

Figure 2: Post-mortem changes in pork.

The period of rigor mortis primarily occurs to degrade both glycogen and ATP (Van der Wal *et al.*, 1997) by muscle contraction from the combination of myosin and actin molecules, resulting in changing the muscles from this relaxed to rigor states (Ertbjerg and Puolanne, 2017). Glycogen is broken down to glucose in anaerobic conditions (Scheffler *et al.*, 2011), then glucose is continuously transformed into pyruvate by the biochemical pathways of glycolysis (Chauhan and England, 2018) and relies on the impact of lactate dehydrogenase enzyme on conversion process into lactic acid which resulted in muscle acidification (Zequan *et al.*, 2021). The acidification leads to advantageous and disadvantageous changes in both surface and inside of the meat (Lawrie RA, 1968) at the later stages. The transformation of actomyosin complex is an important biochemical process inside the meat. The actomyosin complex separates into actin and myosin which leads to increasing the water-holding capacity (Solomon *et al.*, 1998), the decomposition of protein accomplished in the rigor off stage (Bray, 1966) to create some distinct kinds of amino

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Table 3: List of volatile components derived from oleic, linoleic and linolenic acids.

Volatile components	Oleic acid	Linoleic acid	Linolenic acid
Alcohols	Hexanol Heptanol Octanol Nonenol	Butanol Pentanol	2 - Pentenol 1,3,6 - Nonatrienol
Aldehydes	Hexanal Octanal Decanal 2 - Decenal	Butanal Hexanal 2,4 - Decadienal Formaldehyde	2 - Pentenal 3 - Hexenal 2,4,7 - Decatrienal 3,6 - Nonadienal

acids namely hypoxanthine and glutamic (Tikk *et al*., 2006) concerned to the flavor meat. Therefore, the assessment of some potential parameters associated with tenderness, juicy levels, and odors in pork (Domínguez *et al*., 2019) are reliable and useful indicators to determine how the processes efficiently occurred inside the meat. It has been indicated that all undesirable changes have steadily happened in the final period of post-mortem changes in pork (Cheng *et al*., 2015). Lipid oxidation is the main process leading to reducing storage times (Mozuraityte *et al*., 2016) rather than the oxidation of proteins and vitamins, since UFAs are easily reacted with oxidizing agents, destroying lipid structure, causing texture and color changes and the pork taste could be changed from aroma to rancidity in meat (Pegg and Shahidi, 2012). Thus, controlling lipid oxidation plays a key role in ensuring stable meat quality and optimal efficiency for the meat industry (Nawar, 1969; Soladoye *et al*., 2015). Autoxidation, enzymatically oxidized lipids, and photo-oxidation are the three main lipid oxidation pathways in pork (Domínguez *et al*., 2019). The autoxidation would have destroyed both cells and lipoprotein, causing the harmful products (Rao *et al*., 2011). Oxidized mechanisms of these pathways are similar and a chain reaction originating from UFA with three sequential stages including initiation, propagation, and termination. It initiates with the formation of free alkyl radicals in the first stage (Cheng *et al*., 2015), then creates peroxy radicals and hydroperoxides and some main products of lipid oxidation in the propagation stage, and the last stage to build up sub-primary products such as aldehyde, alcohols, volatile and nonvolatile compounds (Wójciak and Dolatowski, 2012) (Figure 2). Concerning lipid autoxidation, r*eactive oxygen species (ROS)* which are undesirable by-products (its levels in overabundance or imbalance may lead to an increase in lipid peroxidation and DNA damage inside cell) of ATP production in mitochondria (Boyman *et al*., 2020), such as hydroxyl (OH^-), singlet oxygen (O_2^-) (Estévez, 2015), and acid hydroperoxide (H_2O_2), are always present in the tissue. Phagocytosis is necessary to generate some free radicals to prevent the invasion and inhibit the activity of virus (Rosen *et al*., 1995). It has been reported that ROS reacts with polyunsaturated fatty acid to produce lipid peroxides in cell membranes (Figure 3). Autoxidation of lipids would have continuously happened while enzymatic oxidation released in the tissue by breaking down the lysosome membrane (Lorenzo and Gómez, 2012) is activated when the pH value of meat hits a bottom of 5.3-5.5 (Lametsch and Bendixen, 2001). The quick or slow accumulation rates of lactic acid in the muscle determine the degradability of the nutritional compositions in pork (Warner *et al*., 1997). Lipid-oxidized enzymes are a catalyst for association with oxygen and hydrocarbon chains of UFAs originating from triacylglycerol and phospholipid (Jin *et al*., 2010) to produce several products such as free fatty acids (FFAs) (Huang et al., 2012). These FFAs continue to be oxidized in order to synthesize an array of products (Cheng *et al*., 2015), especially the formation of flavor compounds (Fu *et al*., 2022) which include volatile components derived from oleic, linoleic and linolenic acids (Domínguez *et al*., 2019; Schaich, 2013) (Table 3). It has been demonstrated that seven of the twelve structures of odorants in pork broth are identified as products of lipid oxidation, such as Hexanal, 1-Octen-3-ol, (E-E)-2,4-Decadienal (Fan, 2021) whose compounds are all related to Omega-6.

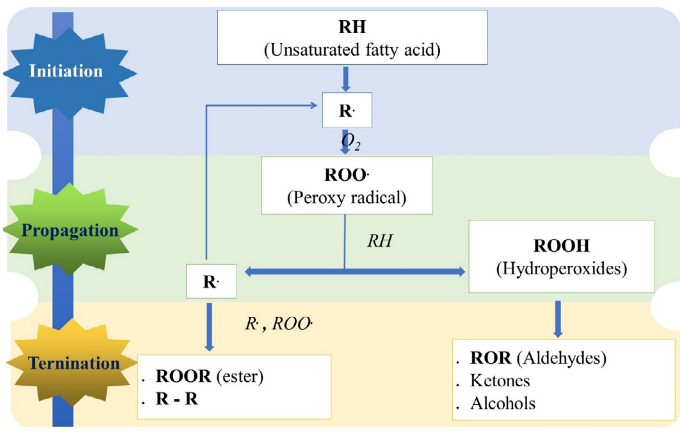

Figure 3: Autoxidation in meat after slaughter.

Improving the sensory and nutritional quality of pork

The UFA plays multiple crucial roles for humans since it is the primary compound to engage in the brain structure (Blank *et al*., 2002) and tissue membrane (Wood *et al*., 2011), as well as supports to increase the immune system (Blank *et al*., 2002) for reduction of the risk of chronic disease (Huang *et al*., 2020) and other functions (Domínguez *et al*., 2019). Therefore, improvement of UFA in pork, especially Omega-3 fatty acids, may be an optimal solution to decrease the harmful effect of SFA on the physical and mental health of humans (Huang *et al*., 2020). Furthermore, it is also necessary to assess the meat quality parameters based on fatty acid content in muscle, the percentage of each distinct type of fatty acid, and the ratio among them (Anh *et al*., 2022). Although there have been numerous studies about the ratio of fatty acids in pork, a definitive conclusion has not been obtained yet and is still in discussion due to some inconsistent results (Anh *et al*., 2022; Engel *et al*., 2001; Juárez *et al*., 2011; Navarro *et al*., 2021). The UFA/SFA ratio in pork raised in Vietnam's environment is about 1.44:1 (Anh *et al*., 2022); the PUFA/SFA ratio is 0.32-0.33:1 (Engel *et al*., 2001; Juárez *et al*., 2011)

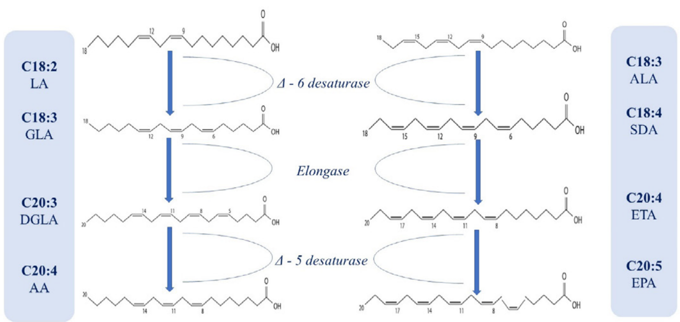

Figure 4: The convertion of LA and ALA into other unsaturated fatty acids.

while the ratio MUFA/PUFA of pigs fed the basal diet included wheat and canola oil during the period from 70kg to slaughter of 2.38:1 (Navarro *et al*., 2021). Moreover, a useful illustration of the ratio Omega-6/Omega-3 is 4.5:1 (Juarez *et al*., 2011) whereas there is only of 14.3:1 in the previous study (Romans *et al*., 1995).

On the other hand, the mechanism of fatty acid synthesis has been published (Ma *et al*., 2020) especially PUFA. There have been three different types of fatty acid desaturase *in vivo* found, including delta 5 (Δ-5), delta 6 (Δ-6), and delta 9 (Δ-9) (Nakamura and Nara, 2004). They play the vital role as catalytic enzymes for the reaction that removal of two hydrogen atoms from fatty acid to generate a double bond in the structure of products (Lee *et al*., 2016). The Δ-9 desaturase positively contributes to the biosynthesis of MUFA from SFA (Zhou *et al*., 2009) while the Δ-5 and Δ-6 desaturases are mainly responsible for long-chain polyunsaturated fatty acid biosynthesis since they are vital factors in converting LA and ALA into other unsaturated fatty acids (precursors of Omega-3 and Omega-6 group fatty acids) (Figure 4) (Mariamenatu and Abdu, 2021). Therefore, the supplementation of ingredients with high tion of long-chain PUFA in tissues (Huang *et al*., 2020). (Coates *et al*., 2009) have revealed that the Omega-3 index of pigs fed daily diets with supplementation of the long-chain Omega-3 PUFA at 41 mg/day is 4.4% and significantly lower than that of pigs under addition

Table 4: Previous investigations under pigs fed the daily diet containing linseed or linseed derivatives.

Environmental conditions					Treatments	References
n	Breeding Pigs	Based diet	Initial BW[5], kg	Finish BW, kg		
25	P[1] x German LD[2]	Barley +	40	105	0 % linseed oil	Nwernberg *et al*., 2005
		Wheat + Soybean meal			5% linseed oil	
144	-	Barley +	30	87	3 levels of 0, 50 and 100 g linseed/ kg	Mathews *et al*., 2007
		Wheat				
43	LW[3] x (LD x P)	Barley +	78.1	160	2.5% sunflower oil	Corino, 2008
		Wheat + Corn + Soybean meal			5% of whole extruded linseed	
24	LD x NDL[4]	Corn + Wheat middling + Soybean	35	115	2 treatments:	Luo *et al*., 2009
					Fat power	
					10% linseed	
72	Czech LW x (Czech LW x Czech LD)	Barley +	28.7	110	2 levels of 0 and 150 g linseed/ kg	Okrowhlá *et al*., 2013
		Wheat + Soybean meal				
48	LW	Barley + Soybean	79	150.5	5% of extruded linseed	Martini *et al*., 2020
					5% of extruded linseed + 200ppm of tocophenyl acetate	
					5% of extruded linseed + 3g vegetal extracts	

[1]P: Pietrain; [2]LD: Landrace; [3]LW: Lance White; [4]NDL: New Dan Line; [5]BW: Body weight.

at 185 mg/day (5.1%). Recently, it has been demonstrated a strong relationship between the diet with supplementation of ALA and the percentage of DHA in pork (Dugan *et al*., 2015). Thus, the DHA content considerably climbs by approximately 30% in pork after administration (Enser *et al*., 2000). Furthermore, the lower the ratio of n-6/n-3 PUFA in the diet is, the more significantly decrease the ratio of n-6/n-3 PUFA in pork (Yi *et al*., 2023) since this ratio has been associated with the presence of genes such as PPARγ (Chan *et al*., 2022), $FATP_1$ and $FATP_4$ (Jensen *et al*., 1997), It has also been reported that there is a significant increase of the MUFA and PUFA contents in pork after the oleic acid addition to the daily diets of pigs (Yi *et al*., 2023). One of the important sources of PUFA supplementation is from natural ingredients such as linseed (Table 4) since it contains a high level of omega-3 fatty acid. Linseed oil accounts for 40% of the compounds in linseed (Farag *et al*., 2021), and the main component is a polyunsaturated fatty acid (73% of the proportion of linseed oil). Therefore, it has widely been demonstrated that the inclusion of linseed in the diet of pigs is a feasible solution for improving nutritional quality in pork (Wang *et al*., 2021) such as the increase of Omega-3 PUFA in tissue (Dugan *et al*., 2015; Huang *et al*., 2020; Yi *et al*., 2023). Similarly, the beneficial effect of dietary supplementation of macadamia oil on meat quality has also been clarified (Junior *et al*., 2022; Navarro *et al*., 2021). The percentage of C18:1 fatty acid (Oleic acid) and the ratio of MUFA/PUFA in total fat in pigs fed the diet added macadamia oil tend to be higher than those of pigs under diets added corn oil (Navarro *et al*., 2021). The diet supplementation of macadamia oil also contributes to significantly improving the flavor, aroma and tenderness of pork (Navarro *et al*., 2021).

On the other hand, it has been recognized that the disadvantage of the high unsaturated fatty acid content in pork is associated with the state of lipid oxidation (Domínguez *et al*., 2019) which undesirable consequences have a negative effect on the sensory and nutritional quality of meat (Nawar, 1969). Therefore, dietary supplementation of antioxidants may be a feasible solution to reduce the lipid oxidation through the prevention of the formation of free radicals (Chen *et al*., 2023; Domínguez *et al*., 2019). The oxidative stability of meat is recorded when pigs have been fed a diet of antioxidants (Li and Liu, 2012) since the first priority of free radicals react with antioxidants (Lobo *et al*., 2010). Alpha-tocopherol is universally recognized as an effective antioxidant (Jensen *et al*., 1997) to neutralize free radicals during post-mortem storage after slaughter (Li and Liu, 2012). TBARS index in pork is significantly decreased as the dietary supplementation of Alpha-tocopherol to pigs (Lu *et al*., 2016) in six days of refrigeration (Phillips *et al*., 2001) by thiobarbituric acid reactive substances. In addition, 100mg/tons feed of alpha-tocopheryl acetate is recommended as a sufficient level to ensure meat quality and oxidative stability of pork (Jensen *et al*., 1997). The combination of linseed oil and alpha-tocopherol in feed not only significantly modifies the ratio of n-6/n-3 fatty acids but also reduces the lipid oxidation when pigs are fed under diets enriched with omega-3 fatty acids (Hoz *et al*., 2003). A similar positive result is reported by (Monahan *et al*., 1992) with the dietary supplementation of soybean oil and alpha-tocopherol at 200 mg/kg. Furthermore, the deposition of alpha-tocopherol in pig muscle is significantly improved in the diet added with alpha-tocopherol (around 2.8 times higher than those of other diets) (Monahan *et al*., 1992). Synthetic antioxidants such as butylated hydroxyanisole (BHA) and tert-butylhydroquinone (TBHQ) (Mika *et al*., 2023) can also prevent the lipid oxidation by inhibiting autoxidation and preventing the appearance of free radicals (Xu *et al*., 2021), leading to the formation of a more stable compound. However, consumers are still concerned about the negative impact of synthetic antioxidants on human health (Kornienko *et al*., 2019), so current research applications of natural antioxidants have still been interesting in the livestock industry (Chen *et al*., 2023; Manessis *et al*., 2020; Petcu *et al*., 2023).

Recently, there have been multiple studies to evaluate the potential of phytogenic compounds, including phenolic compounds and essential oils (Puvača *et al*., 2013), to improve the subtable oxidation in pork (Botsoglou *et al*., 2013; Giannenas *et al*., 2005). The minimal loss of nutritional components after slaughter in the period of storage can be achieved in two ways, including anti-oxidation (Kiokias *et al*., 2020) and anti-bacteria (Fasseas *et al*., 2008) to prohibit contamination and growth of spoilage microbes on the surface meat (Govaris *et al*., 2005) throughout pre-slaughter and post-slaughter. The dietary supplementation of phytogenics has witnessed an upward trend in the deposition of alpha-tocopherol in tissue (Botsoglou *et al*., 2013). Phenolic acid, which is one of the phenolic compounds (Anh *et al*., 2022), has been known to have the ability to reject free radicals and protect membranes (lipoproteins) (Kiokias *et al*., 2020). There are many classes of phenolic acids, such as caffeic acid (in bananas) (Siriamornpun and Kaewseejan, 2017), coffee (Deotale *et al*., 2019), ferulic acid (in cereal grains, linseed, and bananas) (Sgarbossa *et al*., 2015; Siriamornpun and Kaewseejan, 2017) and rosmarinic acid (in rosemary, sage, and musk) (Kiokias *et al*., 2020). Phytogenic bioactive compounds such as tannins, lignans, flavonoids, and allicin (Table 5) can cause the profile of fatty acids to significantly change due to the deposition of IMF in pork loin (Yang and Zhang, 2015) resulting in an increase in the marbling score. Pigs fed a dietary supplementation of 80mg cinnamaldehyde/kg (Luo *et al*., 2009; Yu *et al*., 2017) or with 2.5mg mixed-herbs/kg (Yu *et al*., 2017) significantly increase the marbling score. The addition of a herbal mixture (peppermint, chamomile, thyme, coriander, caraway, couch grass, savory, milk thistle

Table 5: Diet supplementation with phytogenics on meat quality indicators.

Pig	Number (pigs)	Live weight (Initial - Finish) (kg)	Durian	Natural sources	Treatments	Result	References
Retinto Iberian	90 barrows	90 - 150	70 - 80 days	Acorns *(enriched phenolic compounds)*	3 production systems: - Montanera (free-range system and feeding based on acorns and grass) - Recebo (free-range system and nutrition based in combination of acorns, grass and mixed feeds) - Intensive (confinement with mixed feeds)	**Increase:** The contents of phenolic compounds, alpha-tocopherol; MUFA and PUFA in pork **Decrease**: SFA	(Tejerina *et al.*, 2012)
P x LW[1]	27 barrows	7 - 131.34	35 - 180 days	Carob pulp (*including tannin*)	3 diets: - Control: Based diet - Carob 8%: Based diet + 8% Carob - Carob 15%: Based diet + 15% Carob	Feeding carob-containing diets: - **Increase**: MUFA, n-3 PUFA - **Decrease**: SFA, n-6/n-3 PUFA	(Inserra *et al.*, 2015)
D[2] x (L[3] x Y)	96 barrows and gilts	25.46-108.51	16 weeks	Artemisia capillaris *(leaves)* Acanthopanx senticosus *(leaves and roofs)*	3 diets: - CON: Based diet - NH: Based diet + 0.05% natural herbs - FH: Based diet + 0.05% fermented herbs	Compare NH, FH with CON: - **Increase:** PUFA, PUFA/SFA ratio - **Decrease**: SFA, TBARS index	(Lei *et al.*, 2018)
D x (L x Y[4])	450 barrows and gilts	7.21 - 103.2	28 - 154 days	Ginger (*Zingerone*), Garlic (*Alicin*), Tumeric (*Curcumin*)	3 diets: - C: Based diet - CHE 3: Based diet + 3g CHE/kg - CHE 5: Based diet + 5g CHE/kg	Feeding herbs-containing diets: - **Increase:** Sum of Omega -3 , Omega - 6, Omega - 9; MUFA; UFA/SFA - **Decrease:** SFA	(Anh *et al.*, 2022)

[1]LW: Lance White; [2]D: Duroc; [3]L: Landrace; [4]Y: Yorshire.

Table 6: Correlations between natural antioxidants and indicators associated with meat quality.

Correlations	Natural Antioxidants	Authors
Positive	Phenolic acid	(Botsoglou *et al.*, 2004; Fasseas *et al.*, 2008; Puvaca *et al.*, 2013; Yang and Zhang, 2015; Siriamornpun and Kaewseejan, 2017; Deotale *et al.*, 2019; Kiokias *et al.*, 2020; Serena *et al.*, 2020)
	Tocopherol	(Apple *et al.*, 2007)
	Cinnamaldehyde	(Frankič *et al.*, 2010; Kolodziej *et al.*, 2011; Yu *et al.*, 2017; Luo *et al.*, 2020)
	Organosulfur compounds	(Byun *et al.*, 2001; Janz *et al.*, 2007; Park and Chin, 2014; Samolinska *et al.*, 2020)
	Curcumin	(Joo *et al.*, 2002; Zhang *et al.*, 2020)
Negative	Curcumin	(Mancini *et al.*, 2016)

endosperm, and garlic bulb) into the daily diet at 2% on DMI improved the ratio of n-6 and n-3 PUFA in the pork, better human health (Paschma and Wawrzyński, 2007).

There have been a variety of amino acids in herbs, especially in garlic, found and published in previous studies that give positive benefits for humans (Liu *et al*., 2020), such as S-allyl cysteine, glutamic acid, arginine, aspartic acid, etc (Kodera *et al*., 2002; Liu *et al*., 2020). Methionine accounts for 0.55 g/100 g crude protein in garlic and is higher than that of cysteine (0.38 g/100 g protein), while the arginine concentration is the highest in ginger (Uchegbu and Iloeje, 2014). A free group of amino acids is one of the main materials of the Maillard reaction and Strecker degradation (Sun *et al*., 2022), whereas alpha aminoketone is a product formed by this reaction (Resconi *et al*., 2013), having an essential impact on meat flavor compounds (Shahidi *et al*., 2014). In recent decades, there have been a large number of numerous studies carried out to find out the correlations between natural antioxidants and indicators associated with pork quality among different natural kinds (Table 6), including phenolic acid (Botsoglou *et al*., 2004; Fasseas *et al*., 2008; Puvaca *et al*., 2013; Yang and Zhang, 2015; Siriamornpun and Kaewseejan, 2017; Deotale *et al*., 2019; Kiokias *et al*., 2020; Frankič *et al*., 2010), tocopherol, cinnamaldehyde (Frankič *et al*., 2010; Kolodziej *et al*., 2011; Yu *et al*., 2017; Luo *et al*., 2020), organosulfur compounds (Byun *et al*., 2001; Janz *et al*., 2007; Park and Chin, 2014; Samolinska *et al*., 2020) and curcumin (Mancini *et al*., 2016; Zhang *et al*., 2020). Up to now, although a causal relationship is still not established, there has been a consensus from a majority of the above studies that the positive correlations are found in between natural antioxidants and indicators associated with meat quality, except for one study in curcumin (Mancini *et al*., 2016).

In general, the amount of lipids in pork is significantly increased through the addition of ingredients with high UFAs into the daily diet, but the higher the unsaturated fatty acid is, the more strongly lipid oxidation occurs. Natural antioxidants are well known to be effective in preventing the lipid oxidation by inhibiting the autoxidation and the appearance of free radicals and enhancing pork flavour. Therefore, it seems that the combination of ingredients enriched with unsaturated fatty acids and natural antioxidants is a feasible solution to not only improve the chemical composition of pork but also optimize the storage time after slaughter. At present, however, actual interactions and mechanisms are poorly understood in the combination and require further investigation to fully ascertain.

CONCLUSIONS AND RECOMMENDATIONS

Pork is classified as a nutrient-rich food and does not contain antinutrients. Although it has been demonstrated to play an important role in numerous biological processes, consumers are concerned about the adverse effects of pork consumption on the health due to saturated fatty acids, while unsaturated fatty acids are widely recognized to have higher biological value. Recent research results have shown that using ingredients rich in UFAs, such as macadamia will improve this ingredient in pork. The limitations of this research are that high UFA in pork causes the oxidation process to occur faster, changing the color and flavor of pork. Therefore, our review under the comprehensive data from previuous publised findings suggest the trend of natural antioxidants are effective in preventing the lipid oxidation by inhibiting autoxidation and preventing the appearance of free radicals and enhancing pork flavour through joining in the structure of flavour compounds to form phytogenics extracted herbals. Furthermore, it is important and necessary to apply a feasible solution through the dietary combination of UFA-containing sources and natural antioxidants in the pig industry to improve the quantity and quality of the pork.

NOVELTY STATEMENT

Systematic review under comprehensive discussion within all aspects and mechanisms associated with currently new research trend for pork quality improvement through dietary supplementation of ingredients enriched with unsaturated fatty acid and natural antioxidants

AUTHOR'S CONTRIBUTIONS

Anh Thi Ngoc Dang and Hai Thanh Nguyen were responsible for the concept, manuscript preparation and edition. Cuong Kien Nguyen and Duy Ba Ngo contributed to brushing up on the quality of this review. All authors have read and approved the final version of the manuscript.

Conflict of interest

The authors declared no conflict of interest.

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