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Fatty acid composition in pork fat: De-novo synthesis, fatty acid sources and influencing factors – a review

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Abstract. Fats are among the basic nutrients the human organism needs as a source of energy, as well as to grow and regenerate cells, tissues, and organs. Particularly animal fats, with their higher proportion of saturated fatty acids and low content of n-3 fatty acids, are often seen by the public as relatively undesirable food components. Fatty acid (FA) composition of pork is affected by many factors: genotype, breeding, gender and feeding methods. Numerous research teams, therefore, have searched for means of effectively manipulating the chemical composition of animal fats. This paper reviews existing knowledge and means of effectively influencing the fatty acid composition in pig fat, which is a significant component of human food in European countries due to their high consumption of pork. The findings of various authors demonstrate that not only altering of fatty acids sources in animal diets but a range of other factors as well can significantly influence the composition of fatty acids in pig fat and consequently pork quality.

Key words: pig, fatty acid, nutrition, carcass, PUFA.

INTRODUCTION

Although pork remains today the meat most consumed in developed European countries, it increasingly is regarded among consumers as a relatively undesirable food due to the public's awareness of potential health problems related to consuming animal fats. The nutritional quality of pork is a significant factor affecting consumers' health, and this is particularly relevant to consumers worldwide for whom pork is the primary source of meat (Romans et al., 1995; Kouba et al., 2003; Wood et al., 2004; Jiang et al., 2017).

The content and composition of saturated and unsaturated fatty acids (FA) (i.e. the main components of fat) in human food are significant in terms of human health (Nuernberg et al., 2005). Compared to chicken and beef, pork has a lower content of unsaturated fatty acids in intramuscular fat. This implies a less favourable ratio of unsaturated and saturated fatty acids. The n-6/n-3 ratio of polyunsaturated fatty acids is unfavourable for pork and its fat (Woods & Fearon, 2009; Liu & Kim, 2018). Nutritionists often point out that conventional pork products provide too much n-6 while lacking n-3 polyunsaturated fatty acids (Wood et al., 2008; Kouba & Mourot, 2011).

Animals' muscle and fat tissues are the main sources of fat in human food, and therefore it is in the interest of food producers to modify the nutritional value of these tissues (Vehovský et al., 2015).

A high content of saturated fatty acids in food and an unfavourable ratio of n-6 and n-3 groups of polyunsaturated fatty acids may be the cause of a number of diseases, in particular cardiovascular diseases (Kouba & Mourot, 2011; Liu & Kim, 2018). Recommendations for healthy eating state that fats consumed in food should contain saturated fatty acids, monounsaturated fatty acids, and polyunsaturated fatty acids in the ratio of about < 1 : 1.4 : > 0.6. In terms of health, n-3 polyunsaturated fatty acids are the most important fatty acids. These are lacking in animal fats even as groups of n-6 polyunsaturated fatty acids are abundant. Fats contained in feedstuffs fed to pigs can have a significant effect on the resulting fatty acid profiles in pork fat. This means there exists an opportunity to manipulate the composition of fatty acids in pork fat by means of pigs nutrition, and thus to influence the quality of the resulting meat and fat (Čítek et al., 2015; Liu & Kim, 2018).

The aim of this review is to provide a comprehensive overview of the composition of fatty acids and their synthesis in pork meat. Furthermore, to provide overview of exogenous sources influencing the composition of fatty acids and consequently the quality of pork meat.

FAT AND FATTY ACIDS IN SWINE ADIPOSE TISSUE

Lipid composition of pork differs depending on the type of fat, muscle and muscle fibres, (see Table 1.) and it is affected by many factors. These factors include gender, genotype, breeding, and feeding methods. A current tendency in agricultural production is to feed animals so as to maximize production of lean meat and eliminate excessive fat development.

Table 1. Fatty acid composition (% of total fatty acids) in different pork tissue (Adapted from Sobol et al., 2016; Velíšek & Hajšlová, 2009)

Fatty acid	IMT	Backfat	Visceral tissue	Neck	Shoulder	Loin	Ham	Belly
Lauric acid	0.21	0.09						
Myristic acid	2.54	1.62	1.6	0.137	0.085	0.087	0.059	0.188
Palmitic acid	28.68	26.82	26.7	2.76	1.74	1.78	1.17	3.87
Palmitoleic acid	5.48	2.7	2.2	0.244	0.176	0.165	0.122	0.335
Stearic acid	8.67	15.94	10.2	1.85	1.08	1.15	0.721	2.53
Oleic acid	31.98	33.5	36.4	4.38	3.00	2.81	1.97	6.26
Linoleic acid	12.11	10.03	16.1	1.55	1.02	0.899	0.676	1.95
α-linolenic acid	4.09	5.79	1.2	0.518	0.305	0.312	0.193	0.697
Arachidic acid	2.92	0.13	0.3	0.052	0.044	0.038	0.034	0.068
Eicosenoic acid				0.109	0.070	0.073	0.046	0.163
Eicosadienoic acid	0.1	0.45						
Docosahexaenoic acid			1.8	0.019	0.018	0.011	0.009	0.025

Carcass composition of pigs of modern genotypes has been changed in recent decades to favour a higher proportion of lean meat and lower fat content while generally breeding pigs with increased attention to the quality of pork and fat tissue (Hallenstvedt et al., 2012).

Physical and chemical properties are greatly affected by the length of carbon chains, degree of saturation, and isomeric form of fatty acids (Rossi et al., 2010). The ratio of saturated and unsaturated fatty acids is reflected in the fat consistency, and fat quality is thus determined by the composition of fatty acids (Wood et al., 2004; Suzuki et al., 2006). Unsaturated FA provide the primary substrate for oxidative processes, and increasing of n-3 PUFA content, in particular, may reduce the oxidative stability of pork and consequently diminish its sensory properties (Kristinsson et al., 2001; Karolyi et al., 2012).

The pig's own diet is one of the significant factors influencing the structure of pork and lard. Even as nutrition may affect the fat composition amount of fat deposited in the body and also its fatty acid profile (D´Sousa et al., 2010), feeding strategies also can modify such sensory properties of both meat and fat as softness and tenderness. (Wood et al., 2008; D´Sousa et al., 2010; Skiba et al., 2012). Iodine value a measure of unsaturation fatty acid, is one method used by pork processors for assessing pork fat quality. Increases in fatty acid unsaturation or IV are associated with negative impacts on pork fat quality. This can lead to problems with belly slicing efficiency, fat smearing, and reduced shelf life because of oxidative rancidity (Wood et al., 2004 and 2008; Paulk et al., 2015).

Fatty acid composition in animal products is influenced both by biosynthesis of fatty acids in animal tissues and by lipids present in feedstuffs consumed by livestock. The effect of nutrition is more important in monogastrics than in ruminants because ruminants are capable of hydrogenating FA in the rumen (Wood et al., 2004; Kouba & Mourot, 2011). Thus, by modifying pigs' feed, daily intake of unsaturated FA's can be increased which will increase unsaturated FA content of pork products (Woods & Fearon, 2009). The differences in digestion between monogastric animals and ruminants is the reason that the recommended dietary PUFA/SFA ratio is 0.4 in swine and other monogastrics and is significantly higher compared to that for ruminants. On the contrary, the n-6/n-3 PUFA ratio is more favourable in ruminants. The nutritional recommendation of this indicator is $R \leq 4$ (n-6/n-3 PUFA ratio) (Warnants et al., 1999). These monitored ratios are considerably affected by external factors, and the choice of diet, in particular, can affect them significantly. A number of research teams have experimented with manipulating the FA composition in pig fat through feeding components (Enser et al., 2000; Wood et al., 2004; Corino et al., 2008; Haak et al., 2008; Bečková & Václavková, 2010; Raj et al., 2010). Corino et al. (2008) report a linear relationship between dietary PUFA intake and PUFA in intramuscular fat (IMF) and subcutaneous fat. Alonso et al. (2012) observed the lowest n-6/n-3 ratio in subcutaneous fat as an effect of soybean oil in the diet, while that ratio was highest in IMF within the same group and compared to groups supplemented with animal fats and the control group. This also suggests different incorporation of FA in swine tissue, and in particular of α-linolenic acid. D´Arrigo et al. (2002) state that changes in the profile of n-3 fatty acids manifest themselves more in neutral lipids of the reserve tissue than in the structural lipids of muscles (IMF).

According to Wood et al. (2008) as well as Bečková & Václavková (2010), pigs have a far higher level of the pivotal FA linoleic acid in IMF and subcutaneous fat than do cattle and sheep. The relationship between backfat thickness and FA composition is the focus of papers by Suzuki et al. (2006) as well as Wood & Enser (1997). Those authors report a positive correlation between backfat thickness and SFA content and they observed negative correlations between backfat thickness and palmitoleic acid (C16:1) and linolenic acid (C18:2) contents.

Duran-Montgé et al. (2010) studied the degree of essential FA utilization, monitoring the influence of fats fed to pigs on the levels of FA retained and the level of de novo FA synthesis in the pig carcasses. Fatty acids of the intramuscular fat and backfat mirrored those FA in the diet while visceral fat had a higher share of long-chain PUFA. The authors note that this suggests higher utilization of long-chain FA for the visceral fat.

Fatty acid in intramuscular fat

The specific taste, juiciness, and other sensory characteristics of pork are in large measure determined by intramuscular fat (IMF). In contrast to beef, IMF in pork (sometimes with the exception of meat from the Duroc breed (Suzuki et al., 2003; Dashmaa et al., 2011)) is not visually perceptible (Mourot & Hermier, 2001). As a result of intensive selection for a high proportion of lean meat in finished swine, this component in pork has been reduced significantly. Genetic selection has diminished the proportion of IMF in raw meat – which is the carrier of tenderness and juiciness – to less than 1% versus the 2–4% occurring in the past (Alonso et al., 2010). In general, the term intramuscular fat (IMF) refers to lipids and lipids related substances in lean muscle which can be extracted by organic solvents. Nevertheless, it is necessary to distinguish lipids of cell membranes, in particular phospholipids and neutral lipids composed of triacylglycerols localized in adipocytes along muscle fibres. The share of phospholipids as membrane components is relatively fixed so that the properties of cell membranes are maintained, and these exist in the range of 0.2–1% of the muscle weight (De Smet et al., 2004). Content of muscle triacylglycerols is closely associated with the total fat content and ranges between 0.2% and 5% and more of the muscle weight. Although the PUFA content of triacylglycerols can be influenced by dietary factors, particularly in monogastrics, it is diluted by de novo fatty acid synthesis consisting of SFA and MUFA, thus causing a decline in the PUFA/SFA ratio with increasing fat deposition (Alonso et al., 2012).

IMF composition in pork carcasses can vary considerably, and that composition is a trait with a medium to high level of heritability ($h^2 = 0.4–0.6$) (Bečková & Václavková, 2010). IMF content is greatly influenced by the sufficiency of energy content in pigs' diets (Alonso et al., 2012).

FACTORS AFFECTING FATTY ACIDS COMPOSITION IN PIG ADIPOSE TISSUE

Differences in FA composition depending on gender

In relation to carcass value, the effect of gender in slaughtered animals is reflected primarily in the amount of fat tissue. It also is known that FA composition of adipose tissues in pigs is associated with the expression of lipogenic enzymes that are considerably influenced by gender (Doran et al., 2006; Missotten et al., 2009). Thus, castration significantly affects FA composition of swine fat (Missotten et al., 2009). This was confirmed in a study by Nuernberg et al. (2005), which showed that gilts had significantly higher proportions of PUFA in IMF and backfat compared to surgically castrated barrows, regardless of the source of fat in the diet. This also was confirmed by results from a study conducted by Alonso et al. (2009), in which gilts of three hybrid combinations had higher proportions of PUFA in IMF compared to barrows. The influence of gender on FA composition was dealt with also by Halenstvedt et al. (2012), who recorded in their study a demonstrably higher content of PUFA in fattened young boars compared to fattened gilts while a significant higher level of MUFA was recorded in gilts. The authors observed no difference in SFA content in relation to gender.

Current trends in pig farming also include immunological castration (immunocastration) of fattened young boars. Pauly et al. (2009) conducted a study on immunocastration of fattened young boars in which they compared fattened young boars, barrows, and immunological castrates. Regarding FA composition, the authors recorded demonstrably the highest proportion of PUFA and lowest proportion of SFA in fattened boars compared to both surgically and immunologically castrated boars. A study conducted by Mörlein & Tholen (2015) dealt with the influence of the most important components of boar taint (androstenone, skatole, and indole) on FA composition in boar fat. In the boars with higher levels of boar taint components in backfat compared to boars characterized by lower levels of androstenone and skatole, the authors recorded in boar backfat a considerably higher content of SFA and a lower content of PUFA. According to those authors, the trend above all resulted from higher concentrations of linoleic acid and α-linolenic acid in boars with lower concentrations of androstenone and skatole in fat. Androstenone and skatole are correlation with fatty acid composition. The correlation between fatty acid composition and androstenone is higher than with skatole (Liu et al., 2017). MUFA were not significantly affected by concentrations of the aforementioned components. The literature generally thus indicates an apparent effect of gender and its expression of lipogenic enzymes on the composition of FA in pig fat. Some authors (e.g. Flachowsky et al., 2008) nevertheless state that FA proportions in pig fat are much more influenced by the dietary FA source than by gender.

Interbreed differences in fatty acid composition

Interbreed differences are reflected in the carcass value of slaughtered animals, including the proportions of fat and its composition. A number of authors have reported on the effect of breed on the concentration and composition of FA (Table 2.), proteins and fat in pig carcasses (Kouba & Mourot, 1999; Wood et al., 2004; Raj et al., 2010, Choi et al., 2016). Compared to the more crossbred pigs the authors recorded higher concentrations of PUFA in fat (above all C18:2) in the Pietrain breed, even though this breed typically is characterized by a higher content of protein and lower content of fat in the carcass. Monin et al. (2003) recorded more SFA and MUFA in the fat of the Large White breed and, on the contrary, less PUFA compared to the Pietrain breed. Alonso et al. (2009) studied the influence of hybrid combination on FA composition and meat quality, evaluating the effect of parental breeds Pietrain, Duroc, and Large White. Although the authors state that there were no significant differences in meat quality, the hybrid combination with Duroc as parental breed showed the highest proportion of IMF. Pietrain as parental breed manifested a significantly higher proportion of PUFA, as well as higher ratios of PUFA/SFA and of n-6/n-3 in MLLT and semimembranosus muscles. This reflects the fact that linoleic acid and PUFA generally occur at higher concentrations in the fat of leaner swine breeds than in the fat of breeds with higher carcass fat contents.

Raj et al. (2010) explain this phenomenon as the *de novo* synthesis of FA being lower in leaner breeds, which breeds have lower proportions of endogenous FA. In such breeds, there is lower dilution of exogenous linoleic acid by synthesized saturated FA. Also relevant to this subject is the conclusion from Alonso et al. (2009) that exogenous FA are utilized more in IMF.

Table 2. Difference of fatty acid contents (% of total fatty acids) of longissimus lumborum muscle from pig breeds (Adapted from Raj et al., 2010; Subramanian et al., 2016; Dashmaa et al., 2011)

Fatty acid	Duroc	Pietrain	Large white	Hampshire	Belgian landrace	Berkshire	LxLWxD
Myristic acid	2.23	1.21	1.81	1.27	1.28	2.27	1.76
Palmitic acid	29.49	21.34	26.96	22.41	20.32	34.8	29.61
Palmitoleic acid	4.5	1.91	4.33	1.9	1.26	5.13	3.14
Stearic acid	15.3	11.42	14.07	11.88	11.67	17.14	15.21
Oleic acid	40.19	35.26	38.18	37.31	38.01	29.85	38.06
Linoleic acid	6.65	21.87	12.87	18.53	19.22	8.2	12.69
α-linolenic acid	0.57	1.05	0.59	0.92	1.21	0.76	0.1

LxLWxD (Landrace x Large White x Duroc).

DE NOVO SYNTHESIS AND EXOGENOUS SOURCES OF FATTY ACIDS IN PIG NUTRITION

Traditionally fats are included in pig diets in such forms as cereals rich in oil, oilseeds, and fish oil as high-energy feed ingredients. Nutritionally, they are concentrated sources of energy, providing essential fatty acids that are the building blocks for hormone-like compounds and are carriers for the liposoluble vitamins A, D, E, and K. Compared to other feed nutrients, the use-efficiency as metabolized energy of lipids is very high and with a minimal heat increment (Woods and Fearon, 2009; Rossi et al., 2010, Krogh et al., 2017).

Fatty acid synthase is a key enzyme catalyzing the de novo synthesis of long-chain FA from acetyl-CoA and malonyl-CoA. Fatty acids (FAs) are essential constituents of lipids involved in membrane biogenesis and are critical substrates in energy metabolism (Mendez & Lupu, 2007; Guo et al., 2017). An absence or excess of some FA – in particular long-chain FA – influences the pig´s organism in relation to de novo synthesis of FA mediated by elongase and desaturase enzymes (Kouba et al., 2003). Several authors have reported that activity of desaturases, and in particular Δ-9 desaturase, increases with the proportion of dietary SFA, while a dieat rich in oleic acid reduces the activity of this desaturase (Klingenberg et al., 1995; Kouba et al., 2003; Pascual et al., 2007). Pascual et al. (2007) mention a lower inhibition of Δ-9 desaturase in the Duroc breed compared to the Large White and Landrace breeds.

Hallenstvedt et al. (2012) are among those who have studied the effect of FA in swine nutrition. They describe retention of FA in subcutaneous fat in proportions similar to those in the diets fed but increased *de novo* FA synthesis when low fat diets were provided. The latter case resulted in mainly saturated and monounsaturated FA (C16:0, C18:0 and C18:1) being synthesized and the total proportion of PUFA in final product being thus reduced. According to Duran-Montgé et al. (2010) as well as Alonso et al. (2012), dietary fat limits *de novo* synthesis and feeding low-fat diets thus causes higher concentrations of SFA and MUFA to occur in pig fat. Kouba & Mourot (1999) state that n-6 PUFA inhibit activity of stearoyl-coenzymeA desaturase, the key enzyme in the process for desaturating stearic acid to MUFA. Therefore, higher concentrations of exogenous linoleic acid in feed contribute to an increase in PUFA with concurrent decrease in the MUFA portion (Kouba & Mourot, 1999; Alonso et al., 2012). This theory is confirmed by results presented by Riley et al. (2000) and by Enser et al. (2000), who observed higher proportions of MUFA – in particular oleic acid – in pig fat when a higher proportion of saturated fats was included in the diet.

Warnants et al. (1999) compared retention in fat of PUFA, MUFA, and SFA from a diet enriched with soybeans. In that study, PUFA were observed to be incorporated most effectively in pig fat while MUFA and SFA in the diet had a smaller effect on the pig fat composition.

In a study as to the effect of various FA sources in the diet and their influence on the *de novo* synthesis of FA in pigs, Duran-Montgé et al. (2010) observed that when a diet not enriched with fats and oils was fed palmitic acid, stearic acid, and oleic acid were *de novo* synthesized in the ratio of 1.6 : 1.0 : 3.0. When feeds supplemented with oil were provided, the *de novo* synthesis was influenced by the type of oil supplemented and its FA composition.

SOURCES OF FATTY ACIDS

Several studies have been conducted to modify the FA composition of pork fat tissues by nutritional means, including by supplementing specific oils, oilseeds, or forages in the animals' diets (see Table 3).

Table 3. Updated summary of data known for different feed supplement which affected fatty acids composition in pig tissue

Reference	Feed supplement	Effect of FA composition
Bee et al., 2002	Soybean oil/ Tallow	Soybean oil or tallow increased proportion of PUFA that has been compensated by reduced (SFA) and (MUFA) proportions.
Apple et al., 2009	Soybean oil	Soybean oil increased proportion of PUFA.
Alonso et al., 2012	Soybean oil/ Tallow / Palm oil	Soybean oil decreased proportion of MUFA and increased PUFA without negative effect of meat quality.
Warnats et al., 1999	Soybeans	Soybeans in the final 6 weeks before slaughter increased PUFA/SFA ratio in backfat.
Park et al., 2009	Soybean oil	Soybean oil increased PUFA without effect on growth performance and carcass traits.

Table 3 (continued)

Missotten et al., 2009	Linseed oil/ Fish oil	Maternal diet with fish oil or linseed oil increased the level of n-3 PUFA in muscle of piglets.
Enser et al., 2000	Linseed oil	Linseed oil increased levels of EPA and DHA in adipose tissue.
Sheard et al., 2000	Linseed oil	Linseed oil increased α-linolenic acid levels, with increases in total n-3 PUFA content and reduced n-6 PUFA.
Kouba et al., 2003	Linseed	Linseed increased the content of n-3 PUFA in plasma, muscle, and adipose tissue.
Bečková & Václavková, 2010	Linseed oil	Linseed oil reduced the n-6/n-3PUFA ratio and SFA/PUFA ratio.
D´Sousa et al., 2010	Linseed oil / Canola oil /Soybean oil/ PUFA commercial oil	Linseed oil improved lean tissue accretion (lean meat and loin area in the carcass) and meat quality.
D´Arrigo et al., 2002	Linseed oil	Linseed oil improved n-6/n-3 ratio due to increase in α-linolenic.
Romans et al., 1995	Linseed	Linseed improved FA composition after 7 days feeding.
Jing et al., 2017	Linseed oil/ Soybean oil	Linseed oil improved meat tenderness compared to soybean oil.
Huang et al., 2008	Linseed	Linseed increased the content of n-PUFA in muscle and adipose tissue, stimulated IMF accumulation, and promoted the hypertrophy of the *longissimus dorsi muscle*, *quadriceps femoris muscle mass*, and *semitendinosus muscle.*
Luo et al., 2009	Linseed oil	Linseed oil could be effected IMF content, FA profile and gene expression in tissue.
Okrouhlá et al., 2013	Linseed	Linseed increased PUFA content and PUFA/SFA ratio, especially through increasing the n-3 PUFA content, and decreased the MUFA content, the MUFA/PUFA, MUFA/SFA, and n-6/n-3 PUFA ratios and the thrombogenic index.
Čítek et al., 2015	Linseed/ Maize	Maize and lineseed reduced the PUFA/SFA ratio and improved atherogenic and thrombogenic indexes without negative effect on technological characteristics of meat and backfat.
Vehovský et al., 2015	Linseed / Maize	Linseed significant increased PUFA content compared to additional maize.
Sobol et al., 2016	Mixture (Linseed, Rapeseed, Fish oil)	Mixture of linseed, rapeseed and fish oils improved the FA content in pork.
Della Casa et al., 2010	Maize	Maize showed wide differences in linoleic acid due both to total lipid content and to fatty acid profile.
Opapeju et al., 2006	Maize (2 variety of corn)	Maize increased linoleic acid and decreased stearic acid in pig fat greater concentration of PUFA.

Table 3 (continued)

Rossi et al., 2002	Maize/ Tallow/ Rapeseed oil	Tallow increased SFA in backfat, rapeseed oil increased the proportion of linolenic acid.
Han et al., 2005	Maize/ Wheat	No differences were show between wheat and maize groups in FA composition in backfat and backfat colour.
Hoz et al., 2003	Sunflower oil	Sunflower oil increased proportion of PUFA, proportion of n-6 PUFA, and the decreased proportion of n-3 PUFA.
Boselli et al., 2008	Sunflower oil	Sunflower oil increased triacylglycerols containing oleic acid in the raw meat, and a decreased of both linoleic and SFA.
Mitchaothai et al., 2007	Sunflower oil/ Tallow	Fat type had no significant effect on carcass traits, sunflower oil increased content of linoleic acid and PUFA.
Realini et al., 2010	Sunflower oil/ Linseed oil/Tallow/ fat bland / oil bland	Sunflower oil and linseed oil showed high percentages of n−6 and n−3 FA, PUFA/SFA ratios were increased by feeding all supplements.
Corino et al., 2002	Rapeseed oil / Sunflower oil/ Maize	Rapeseed oil increased linoleic acid content of total lipid.

Park et al. (2012) evaluated the effect of various oils in the diet and concluded that the type of fat in the feed mix, including soybean oil, did not have a demonstrable effect on the chemical composition and quality of meat or on the fattening capacity parameters. Fat in the diet did, however, influence FA composition in the pig fat. Including soybean oil in the diet for pigs significantly increases the proportion of PUFA (Bee et al., 2002; Apple et al., 2009; Alonso et al., 2012). Incorporation of FA in fat tissue and their subsequent elimination upon withdrawal of the dietary fat source was the subject of a study by Warnants et al. (1999). They found that healthier fat with favourable PUFA/SFA and n-6/n-3 PUFA is produced by pigs fed with soybeans during fattening. The experiment evaluated the time needed for feeding with a source of PUFA in order to achieve the desired incorporation in pig fat. The authors concluded that the content of important PUFA (linoleic, α-linolenic, eicosadienoic, and arachidonic acids) and total PUFA in the loin and backfat increased when feeding a diet enriched with PUFA during pig fattening. Experimental groups fed a PUFA source during the final 6–8 weeks prior to slaughter showed the same FA composition in IMF and backfat as did an experimental group fed the PUFA source all through the fattening period (16 weeks). The authors observed the greatest increase of PUFA in backfat during the first two weeks following incorporation of the source into the diet. A similar trend was observed in the experiment upon excluding soybeans from the feeding diet. An experiment by Warnants et al. (1999) demonstrated that the PUFA/SFA ratio in backfat can be increased from 0.34 to 0.55 by addition of soybeans in the final 6 weeks before slaughter. Park et al. (2009) evaluated the effects of soybean oil supplementation in pigs' diets. Pigs on the soybean oil diet had poorer average daily gain compared to a control group receiving supplemental tallow, but only up to live weight of 80 kg. Thereafter, the group with addition of soybean oil compensated for the earlier slower growth in the final phase of fattening. There were no overall differences in growth between the two groups. Extending the period of feeding soybean oil caused the proportions of α-linolenic and docosahexaenoic acids to increase.

Supplementing the diet with soybean oil boosted n-3 PUFA without negatively influencing either growth or carcass value of the fattened pigs. Alonso et al. (2012) conducted a study examining the effect of oil in the diet of young boars. Groups of animals were fed a control diet with no added fat or diets supplemented with tallow (1%, 3%), palm oil (1%), or soybean oil (1%). The 1% supplementation with soybean oil throughout fattening was sufficient to cause a significant increase in the contents of linoleic and α-linolenic acids, as well as of total PUFA (including the n-3 family). A higher concentration of n-6 PUFA was the cause of a slightly higher n-6/n-3ratio in the group of young boars fed with soybean oil.

According to some studies, higher doses of unsaturated FA can lead to excessive fattening of animals while having a negative impact on quality of pig fat (by influencing its consistency). In a study by Duran-Montgé et al. (2010), feeding tallow, which characteristically has a low content of PUFA, resulted in decreasing the total proportion of fat in the swine carcass. Nuernberg et al. (2005) examined the effect of feeding components with higher proportion of PUFA. When they added 5% linseed oil and 5% olive oil to the pig ration, they observed no effect on carcass value and meat quality.

The most important sources of PUFA include linseed, due to its favourable FA composition, and the linseed oil produced from it. If this oil plant is fed, particularly the content of linoleic acid and α-linolenic acid increases. Conversely, the content of SFA decreases and favourable decreases the ratio of n-6/n-3 PUFA. This has been confirmed in studies by Enser et al. (2000), Sheard et al. (2000), Kouba et al. (2003), Huang et al. (2008), Bečková & Václavková (2010), and D´Sousa et al. (2010), Sobol et al. (2016). The maximum increase content of n-3 PUFA was observed by D´Arrigo et al. (2002), as well as Romans et al. (1995) during first weeks of a linseed diet. D´Arrigo et al. (2002) stated that changes in the profile of n-3 FA due to pig nutrition manifest themselves more in neutral lipids of the reserve tissue than in the structural lipids of muscle (IMF). Jiang et al. (2017) concluded that the inclusion of linseed oil as a substitute for soybean oil in pig diets, in combination with organic selenium, altered the FA profile such that there was a lower omega 6:omega 3 ratio in the organic selenium + linseed oil treatment. Although the dietary treatments showed no notable influence on the oxidative stability of pork, the organic selenium supplementation combined with linseed oil did substantially reduce drip loss (by 58–74%) and increased tenderness.

Huang et al. (2008) observed linear growth in the IMF content with increasing period of feeding linseed before slaughter. The same paper reported increase in α-linolenic acid and total n-3 PUFA, both in IMF and backfat. With increasing period of feeding, the authors noted decreasing content of SFA and the n-6/n-3 ratio.

In an experiment testing various dietary FA sources in the forms of 2% soybean oil, rapeseed oil, linseed oil, or a commercial PUFA oil, D´Sousa et al. (2010) observed no changes in pigs' growth rates. They did, however, note demonstrable increase in the proportion of meat in the carcass and loin area with the diet containing 2% linseed oil. FA composition in intramuscular fat (MLLT) reflected the composition of oil added to the feed mix. Linseed oil in the feed mix for the final stage of fattening increased gain in muscle (lean meat and loin area in carcass body).

The effect of a higher ratio of unsaturated fatty acids was examined by Woods et al. (2003), who studied the effect of a diet containing 6% ground linseed. The study's results demonstrate the effect of linseed meal causing a higher proportion of n-3 PUFA in blood plasma, in IMF, and in backfat unless the level of docosahexaenoic acid (an important n-3 PUFA) is increased. The authors reported an effect of duration of feeding linseed meal on n-3 PUFA in pig tissue. Higher PUFA levels were observed in pig tissues within the group of pigs slaughtered 60 days after the start of supplementing the diet with linseed meal compared to the groups slaughtered 20 and 100 days after the start of linseed meal supplementation. Luo et al. (2009) observed under the influence of a diet including linseed a positive correlation between the IMF content and the content of linoleic acid, α-linolenic acid, EPA, docosahexaenoic acid, total PUFA, and n-3 PUFA. In a study by Okrouhlá et al. (2013), supplementation with 15% of extracted linseed meal had a positive effect on increasing PUFA. It improved the n-6/n-3 PUFA ratio without any negative effects on the physical and chemical properties of the pork. Thus, linseed has been shown to have favourable effects on FA composition in pig fat. Due to its high content of PUFA, however, which may negatively influence the stability and consistency of fat in pork products, it is appropriate to investigate further what would be the optimal amount of this ingredient to include in feed mixes for fattening pigs.

Maize is today widely grown and utilized as a livestock feed. Although there is a great variability in the content of linoleic acid in modern maize hybrids, the average content of this acid can reach as high as 59.7% of the total FAs in maize grain. That means maize grain is among the most pronounced sources of PUFA (Della Casa et al., 2010). Products from pigs fed a diet based on maize grain can be regarded by some markets as being of low quality, however, compared to the products from pigs fed with commercial mixtures based on barley or wheat. This may be due to a difference of meat and fat colour inasmuch as maize contains a higher content of carotenoids and these are readily incorporated into swine tissues. The higher unsaturated fatty acids content in maize grain may cause pigs to synthesize fats of soft consistency that are susceptible to rapid oxidation and that can be regarded negatively. Opapeju et al. (2006) concluded that a diet containing maize grain as the main energy component was the cause for a 20% increase in linoleic acid and demonstrable decrease in stearic acid in pig fat. Those authors mention, too, that a maize diet does not have a negative effect on the firmness of either backfat or lard.

The studies by Della Cassa et al. (2010), Opapeju et al. (2006), and Rossi et al. (2002) demonstrated decrease in total SFA and MUFA and concurrent increase in total PUFA in pigs fed with a diet including maize compared to the control group. The total content of n-3 PUFA was reduced, thus resulting in a demonstrable increase in the ratio of n-6/n-3 PUFA. A worsening of this ratio is attributed in particular to a significant increase in linoleic acid (Della Casa et al., 2010). Han et al. (2005) and Morales et al. (2003) report overall less favourable carcass value parameters in pigs fed with an addition of maize to the diet. Doing so increased the proportion of fat in pig carcasses, and particularly in backfat.

Various genotypes of modern maize hybrids show differences both in the content of fat and its FA composition. By selecting the appropriate maize hybrids, however, the content of these feed ingredients can be controlled at a particular level. Differences as small 0.3% in linoleic acid content between maize hybrids can result in considerable differences in the FA composition in swine fat (Della Casa et al., 2010).

Sunflower also stands among those crop plants containing a higher PUFA content. Compared to other oil plants with high PUFA content, however, sunflower oil is characterized by a high content of n-6 PUFA, particularly due to a high proportion of linoleic acid and low content of α-linolenic acid within the total FA content. In an experiment conducted by Hoz et al. (2003), sunflower oil supplement in the pig diet was associated with the significant highest proportion of PUFA, the highest proportion of n-6 PUFA, and the lowest proportion of n-3 PUFA in *psoas major* muscle. Boselli et al. (2008) observed an effect of feeding Italian heavy pigs with high-oleic sunflower. This was associated with significant increase in oleic acid at the expense of linoleic acid and saturated fatty acids, particularly triacylglycerols. Fatty acids in phospholipids were less affected by animal nutrition. Conversely, a study conducted by Mitchaothai et al. (2007) showed that diets with added sunflower oil increased content of saturated and polyunsaturated fatty acids at the expense of monounsaturated fatty acids. Addition of sunflower oil was reflected most significantly in an increased content of linoleic acid in various tissues while having no other effect on the meat properties and quality. In a feeding study involving gilts, Realini et al. (2010) observed the influence of sunflower oil in the diet to be a higher proportion of fat and a lower proportion of lean muscles in carcasses from gilts.

Rapeseed oil is among the oils with the highest proportion of MUFA. In particular, it contains the highest amount of oleic acid relative to other commonly used oils. Its proportion of PUFA is not inconsiderable (Table 4). A study by Corino et al. (2002) also dealt with the issue of different fats in feed rations. The authors observed the effects of feeding animal fat, sunflower oil, and rapeseed oil in the amount of 3% or 2.5%, in later stages of fattening. In the group supplemented with rapeseed oil, the authors observed the highest content of α-linolenic acid in fat. No significant differences between the groups were observed in terms of body weight, pH, fat, and juiciness 45 min *post mortem*, and subsequently no differences in the contents of fat and protein of *longissimus lumborum* muscle. Oxidative stability of IMF was not affected negatively by rapeseed oil after 60 mins of forced oxidation. In animals fed with a supplement of unsaturated oils (rapeseed oil, corn oil), poorer oxidative stability was seen only after 300 min of forced oxidation. The results presented in the paper by Corino et al. (2002) indicate that long-term pig nutrition with the stated amount of rapeseed oil in a feeding diet have no or only minimal negative effect on quality and sensory properties of pig meat. Via inclusion of 5% or 3% of rapeseed oil in a feed mix, Raj et al. (2010) and Rossi et al. (2002) achieved increase in α-linolenic content and decrease in linoleic acid content. This also resulted in decreasing the ratio of n-6/n-3 PUFA in the feed.

Table 4. Fatty acid composition of oils containing α-linolenic acid (% of total fatty acids; ranges of values repo
Velíšek & Hajšlová (2009)

Fatty acid	Rapeseed oil	Soybean oil	Linseed oil	Sunflower oil	Palm oil	C
Lauric acid	0	0.0–0.1	–	0.0–0.1	1	0.
Myristic acid	0.0–0.2	0.0–0.2	–	0.0–0.2	5	0.
Palmitic acid	3.6–6.0	8.0–13.3	4.0–7.0	5.0–8.0	32–59	1(
Palmitoleic acid	0.1–0.6	0.0–0.2	–	< 0.5	1	0.
Stearic acid	1.1–2.5	2.4–5.4	2.0–5.0	2.5–7.0	1–8	1.
Oleic acid	52.0–66.9	17.7–25.1	12.0–34.0	13.0–40.0	26–52	24
Linoleic acid	16.1–24.8	49.8–57.1	7.0–27.0	40.0–74.0	5–14	39
α–linolenic acid	6.4–14.1	5.9–9.5	35.0–65.0	< 0.3	2	0.
Arachidic acid	0.2–0.8	0.1–0.6	–	< 0.5	1	0.
Eicosenoic acid	0.1–3.4	0.0–0.3	–	< 0.5	0.1	0.
Eicosadienoic acid	0.0–0.1	–	–	–	–	–
Docosanoic acid	0.1–0.5	0.3–0.7	–	0.5–1.0	–	–
Docosenoic acid	0.0–2.0	0.0–0.3	–	0.0–1.8	–	0.
Docosadienoic acid	0.0–0.1	–	–	–	–	–
Docosapentaenoic acid	–	–	–	–	–	–
Docosahexaenoic acis	–	–	–	–	–	–
Lignoceric acid	0.0–0.2	0.1–0.4	–	0.2–0.3	–	0.
Tetracosenoic acid	0.1–0.4	0	–	–	–	–
Behenic acid	–	–	–	–	–	0.

CONCLUSIONS

Many studies have confirmed that adding vegetable oils and/or fatty acids to pig diets can have a positive effect on the n-6/n-3 PUFA ratio and overall nutritional value of pork. A subject of current research is to evaluate the influence of feed mixes enriched with PUFA, and particularly n-3 PUFA. For manipulating PUFA and particularly its n-3 group in pig fat, oilseeds or their oils directly (linseed, rapeseed, soybean, etc.) are most often mentioned as the appropriate sources of fatty acids. Fish oil, too, has a favourable effect on FA composition in fat of animal products, but it also bears the risk of tainting the products with fish odour. Further studies are needed, however, to determine the most suitable oil additive and the correct dosing for each pig age category.

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