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Dossier

Linseed: a valuable feedstuff for ruminants

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Abstract – Linseeds are used in ruminant feeding for a long time, but this feedstuff knows now increasing interest. Linseeds are rich in alpha-linolenic acid, a fatty acid from the omega-3 series. Despite an extensive biohydrogenation of dietary alpha-linolenic acid in the rumen, its concentration in milk and beef meat increases with linseed incorporation in diets; this increase is accompanied by that of other fatty acids produced during biohydrogenation, especially conjugated linoleic acids and *trans* 18:1 fatty acids. The increase in cow fertility due to omega-3 fatty acids has not been demonstrated. Furthermore, linseed incorporation in ruminant diets is one of the most efficient ways to decrease enteric methane emissions. In addition to a global mitigating effect of all lipid sources on methane, linseeds have a specific effect due to changes in rumen microbial ecosystem. The practical use of linseeds in ruminant feeding at a large scale requires the absence of negative effect at any step of the ruminant production system. An excessive supply of lipids from linseeds can have deleterious effects on digestive efficiency, milk fat and protein content, beef susceptibility to oxidation, milk and beef fatty acid composition, but when linseed incorporation in the diet does not exceed ca. 3% of additional fat, only positive effects are remaining. A challenge is the increase in linseed cropping to meet increased needs for animal feeding.

Keywords: Linseed / milk / beef / omega-3 fatty acids / methane

Résumé – La graine de lin : un aliment de choix pour les ruminants. La graine de lin est utilisée depuis longtemps dans l'alimentation des ruminants, mais son emploi suscite un regain d'intérêt. Le lin est en effet riche en acide alpha-linolénique, un acide gras de la série des oméga 3. En dépit d'une biohydrogénation poussée dans le rumen, sa concentration dans le lait et la viande bovine est accrue lorsque la ration est enrichie en graines de lin ; cet accroissement va de pair avec celui d'autres acides gras intermédiaires de la biohydrogénation comme les acides gras monoinsaturés *trans* et les acides linoléiques conjugués. L'amélioration de la fertilité des vaches liée à cet apport d'oméga 3 n'a pas été démontrée. Par ailleurs, l'incorporation de lin dans la ration des ruminants est un des moyens efficaces pour réduire l'émission de méthane entérique. Outre un effet de toutes les sources de lipides pour réduire le méthane, le lin a un effet spécifique lié à son action sur le microbiote ruminal. L'utilisation de la graine de lin à grande échelle dans l'alimentation des bovins nécessite qu'il n'ait pas d'effet négatif à quelque niveau du système de production. Un apport excessif de lipides du lin peut diminuer la digestibilité de la ration, les taux butyreux et protéique du lait, modifier sensiblement la composition en acides gras du lait et de la viande, et augmenter la susceptibilité à l'oxydation des produits. Toutefois, lorsque l'incorporation de lipides du lin ne dépasse pas 3 % environ de la ration, seuls les effets positifs subsistent. Le défi est maintenant d'accroître les surfaces cultivées en lin pour répondre à une demande croissante pour alimenter les bovins.

Mots clés : Graine de lin / lait / viande bovine / acides gras oméga-3 / méthane

1 Introduction

Although linseed is not commonly used nowadays in ruminant feeding, this is an ancient feedstuff which has been used from the nineteenth century, as crude seed or cake (Grandeau, 1876). In the first part of the twentieth century, linseed expeller cake has been used especially for beef fattening, and was used not really for nutritional benefits but for giving a shiny coat, and also a tasty meat (Dumont *et al.*, 1997). The development of the use of fat sources in ruminant feeding in the 1990s as a mean to increase energy density of the diet concerned first palm oil, animal fat derivatives, and commonly used seeds such as cottonseed, soybean and rapeseed. A significant use of linseed is very recent and due to its richness in alpha-linolenic acid (18:3 n-3, or *cis*-9, *cis*-12, *cis*-15 18:3), potentially allowing an increase in omega-3 fatty acids (FA) in milk and meat. However, the extent of increase in omega-3 FA in these products is limited because of the wide biohydrogenation of polyunsaturated FA in the rumen, prior to absorption.

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A few years ago, an additional interest for linseed has been put forward: linseed FA have been shown to significantly decrease enteric methane production by ruminants (Martin *et al.*, 2010). Methane mitigation is a major issue for decreasing greenhouse gases emissions from livestock. The Bleu-Blanc-Coeur initiative, born in France and aiming to develop omega-3 FA in human foods through promoting feeding animals with omega-3, considers this double interest of linseeds. Linseeds are now used essentially as an extruded mixture of 50–70% linseeds and 30–50% other feeds such as bran, in order to obtain a product which is easy to handle and to incorporate in concentrates. This paper presents an overview of the interest of the incorporation of linseed in diets for providing omega-3 FA to ruminants, then of the use of linseed for methane mitigation. In the last part, the perspectives of increase in linseed use for animal feeding are discussed.

2 Linseed, a provider of omega-3 for ruminants

Linseeds varieties fed to animals contain a high level of oil (40%) with 55% of 18:3 n-3 (Glasser *et al.*, 2008a, Petit, 2010). Adding linseeds to ruminant diets is susceptible to increase the concentration of polyunsaturated FA in dairy products and beef. Ruminant products contain a variety of FA. Some of them may be of potential benefits to human health, including polyunsaturated FA of the omega-3 FA series. The main omega-3 FA in milk fat is 18:3 n-3. In beef, omega-3 FA are composed of both 18:3 n-3 and 20- and 22-carbon FA. The omega-3 FA, and more particularly 20- and 22-carbon FA, can reduce the risk of cardiovascular diseases (Mills *et al.*, 2011). Details on omega-3 FA effects on human health are reported in a paper by Mourot (this issue).

A specificity of digestive processes in ruminants is an extensive biohydrogenation of dietary FA in the rumen, prior to absorption which occurs in the small intestine. As a consequence, the amount of omega-3 FA reaching the small intestine is much lower than the dietary intake of omega-3 FA, resulting in a quantitatively low transfer of these FA in milk and meat, compared to monogastric animals (Doreau *et al.*, 2011). Forage FA are in the form of galactolipids, and to a lesser extent, of phospholipids, glycerides and free FA. In concentrates, FA are in the form of phospholipids and cholesterol esters in membranes, and of glycerides as storage lipids; oilseeds are thus rich in triglycerides. In addition, additives providing fats and oils are sometimes given as triglycerides or as calcium salts. In the rumen, which is the first digestive compartment where feed fermentation and metabolism occur, lipids are first hydrolysed by microbial enzymes. Free FA are then hydrogenated and isomerised by other microbial enzymes, to a large extent in the case of polyunsaturated FA, incompletely in the case of monounsaturated FA. These processes are detailed in Doreau *et al.* (2012). Disappearance of 18:3 n-3 is close to 90%. Few 18:2 FA reach the intestine, but, besides significant amounts of stearic acid (18:0), a very large panel of *cis*- and *trans*-18:1 FA is found (Glasser *et al.*, 2008c). The major one is vaccenic acid (*trans*-11 18:1), but 12 other *trans* isomers and 5 *cis* isomers, mainly oleic acid (*cis*-9 18:1) reach the intestine and are thus absorbed and available for transfer into milk and meat. Different attempts have been made to decrease biohydrogenation through protection of lipids. The only one which has been proved to be efficient is the encapsulation of lipids in a coat of proteins treated with formaldehyde (Doreau *et al.*, 2011; Fievez *et al.*, 2007). However this technique is not used, in particular owing to its cost, to the use of formaldehyde, and to possible adverse effects of excessive amounts of polyunsaturated fats on animal health and product quality.

Concerning the FA metabolism, 18:3 n-3 represents on average 1.9% of 18-carbon FA reaching the duodenum because of its extensive biohydrogenation in the rumen. Nevertheless, the transfer rate from duodenum to milk is lower for 18:3 n-3 than that for other 18-carbon FA (Glasser *et al.*, 2008b). In mammary gland and in muscle, an important *de novo* synthesis occurs from plasma acetate and butyrate, leading to a variety of short- and medium chain FA in milk fat. Moreover, the activity of a Δ9-desaturase leads to the formation of *cis*-9, *trans*-11 18:2 (rumenic acid) from vaccenic acid. In addition, a specific metabolic pathway occurs in the muscle, but not in the mammary gland: the elongation and desaturation of 18:3 n-3, leading to the formation of eicosapentaenoic acid (EPA, 20:5 n-3) and docosapentaenoic acid (DPA, 22:5 n-3) in muscle. However, the last step of desaturation towards docosahexaenoic acid (DHA, 22:6 n-3) is of very low extent in vertebrates (Doreau *et al.*, 2011).

The general responses of milk FA composition to linseeds feeding concern saturated FA, *trans*-18:1, conjugated and non-conjugated isomers of 18:2 and 18:3 n-3. The extent of change in milk FA concentration is generally proportional to the level of inclusion of linseeds in the diet (Ferlay *et al.*, 2013; Glasser *et al.*, 2008a). The effects of increasing amounts of extruded linseeds in the diet have been studied by different authors (Brunschwig *et al.*, 2010; Ferlay *et al.*, 2013; Hurtaud *et al.*, 2010). The major changes concern increases in *trans*-18:1 and total conjugated linoleic acid (CLA) concentrations in milk. Feeding linseeds increases the milk concentrations of different isomers of CLA: *cis*-9, *trans*-11 18:2, *trans*-11, *cis*-13 18:2, *trans*-12, *trans*-14 18:2, and *trans*-12, *cis*-14 18:2) (Chilliard *et al.*, 2007, Lerch *et al.*, 2012c). These FA concentrations increased linearly with increasing amounts of linseeds whereas 18:3 n-3 concentration increased slightly (Ferlay *et al.*, 2013), confirming that this FA was highly biohydrogenated in the rumen. The relationship between 18:3 n-3 intake and 18:3 n-3 as a proportion of milk FA is linear (Fig. 1). The transfer of 18:3 n-3 from diet to milk is close to 4.5%. Only Kennelly *et al.* (1996) reported a higher transfer when cows fed a protected linseed oil, with a milk concentration of 18:3 n-3 higher than 20% of total FA. Moreover, the milk saturated FA decreased linearly with increasing amounts of linseed. For the same level of *cis*-9, *trans*-11 18:2 in the milk fat, linseed supplementation increased the milk concentration of *trans* FA other than *trans*-11 18:1 and *cis*-9, *trans*-11 18:2 more than grazed grass (Ferlay *et al.*, 2008, 2013). Significant increases were observed for *cis*-9, *trans*-13 and *trans*-11, *cis*-15 18:2 with linseed or linseed oils because these FA are main intermediates of ruminal biohydrogenation of 18:3n-3 (Chilliard *et al.*, 2009; Ferlay *et al.*, 2013; Glasser *et al.*, 2008c; Lerch *et al.*, 2012b). Lerch *et al.* (2012c) studied the

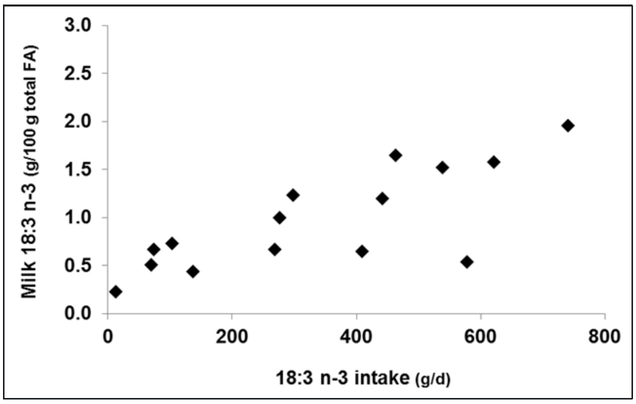

Fig. 1. Effect of increasing amounts of 18:3 n-3 intake from linseeds on milk 18:3 n-3 proportion (from Chilliard *et al.*, 2009; Ferlay *et al.*, 2013; Hurtaud *et al.*, 2010). Equation of linear regression is: $Y = 0.0018X + 0.38$ ($R^2 = 0.59$), where Y is milk 18:3 n-3 proportion (g/100 g of total FA) and X is 18:3 n-3 intake (g/d).

effects of long-term supplementation (2.5 to 3% of oil in DM) with extruded linseed over 2 consecutive lactations, successively on a grass silage-based diet and at pasture. Compared to control diet, linseeds resulted in the enrichment of different isomers of CLA and conjugated linolenic acids, particularly *cis*-9, *trans*-11, *trans*-13 18:3, identified for the first time in bovine milk fat.

Supplying linseeds for beef production has the same global consequences on FA meat composition as on milk, but with some particularities. The increase in 18:3 n-3, EPA and DPA has been demonstrated in all trials where linseeds were used (*e.g.* Corazzin *et al.*, 2012; Scollan *et al.*, 2005). Due to ruminal biohydrogenation, the proportion of 18:3 n-3 in percentage of total FA remains low. For example in *Longissimus thoracis*, it increases from 0.5 to 0.9–1.6% (Normand *et al.*, 2005, 5 trials), from 0.4 to 1.9% (Mach *et al.*, 2006), from 0.4 to 0.8% (Barton *et al.*, 2007), from 0.6 to 2.0% (Herdmann *et al.*, 2010), from 1.2 to 1.6% (Corazzin *et al.*, 2012), from 0.4 to 0.6% (Habeanu *et al.*, 2014), from 0.9 to 1.4% (Mialon *et al.*, 2015). Differences in the extent of the increase depend more on the amount of added fat and their processing than on the duration of distribution before slaughter. It can also be noted that pasture feeding, which is another source of 18:3 n-3, increases 18:3 n-3 in meat, although generally to a lower extent (Scollan *et al.*, 2005). The increase in muscle 18:3 n-3 concentration is significantly higher with extruded linseeds than with rolled linseeds (Normand *et al.*, 2005), and higher in ground or rolled linseeds than with whole linseeds (Maddock *et al.*, 2006). The increase in 18:3 n-3 was higher in *Longissimus thoracis* than in *Rectus abdominis* and *Semitendinosus* in a trial by Mialon *et al.* (2015), but this difference was not observed in trials by Normand *et al.* (2005) and by Habeanu *et al.* (2014). Despite elongation process, very long-chain FA are present in muscle in low proportions whatever the diet: less than 0.7 and 0.4% of total FA for DPA and EPA, respectively, and this proportion is either unchanged or moderately increased by linseed supply (Barton *et al.* 2007; Corazzin *et al.*, 2012; Habeanu *et al.*, 2014; Herdmann *et al.*, 2010; Mialon *et al.*, 2015). These three latter authors also observed an increase in CLA, but the two former authors did not. In any case, the CLA concentration in beef is too low for a possible effect on human health. Beef *trans*-18:1 FA comprise a significant amount of isomers other than *trans*-11, but few studies are available about the effect of linseeds on this pattern. With diets based on 30% straw and 70% concentrates, extruded linseed did not change the proportion of *trans*-11 (33%) but *trans*-12, -13, -14 and -15 increased at the expense of *trans*-9 and -10 (Habeanu *et al.*, 2014).

There has been a steady decline of fertility in major dairy cow breeds associated with the improvement of genetic merit for milk production (Barbat *et al.*, 2010; Butler, 2003). Part of this decline is due also to extended period of negative energy balance and intense mobilisation of body reserves during early lactation. The relationships among energy balance, body condition score and reproductive function are well documented (*e.g.* infrequent LH pulses, delayed ovarian activity, abnormal estrous cycles, poor follicular response to gonadotropins, reduction of oocyte quality and embryo survival (Butler, 2003, Chagas *et al.*, 2007). Recent interest on lipid feeding to cows has focused on reproduction because of their high energy density and a supply of specific FA. Lipid supplementation could influence reproduction by altering the size of the dominant follicle, shortening the interval between calving and the first postpartum ovulation, increasing progesterone concentration during the luteal phase of the oestrous cycle, modulating uterine prostaglandin synthesis, and improving oocyte and embryo quality and maintenance of pregnancy (Santos *et al.*, 2008). The omega-6 and omega-3 polyunsaturated FA seem to have the major effects on reproductive responses. Nevertheless, results from feeding linseeds on reproductive variables are inconsistent. Some authors reported an improved increased follicular and corpus luteum growth (Santos *et al.*, 2008), oocyte (Moallem *et al.*, 2013; Zachut *et al.*, 2010) and embryo quality (Thangavelu *et al.*, 2007), decreased pregnancy loss (Ambrose *et al.*, 2006), reduced plasma prostaglandin (Petit *et al.*, 2002), and increased serum progesterone concentration (Jahani-Moghadam *et al.*, 2015), reduced interval from calving to ovulation (Colazo *et al.*, 2009). In contrast, others noted no changes in milk progesterone concentration or corpus luteum activity (Ponter *et al.*, 2006), or oocyte quality (Bilby *et al.*, 2006, Fouladi-Nashta *et al.*, 2009). The inconsistencies among these studies could be due to differences in the amounts of lipid supplements, duration of supplementation, and season. The global effect on cow fertility has not been evidenced: no effect of linseed feeding has been reported on conception rate (Ambrose *et al.*, 2006; Bork *et al.*, 2010; Petit and Twagiramungu, 2006; Petit *et al.*, 2008), or pregnancy rate (Jahani-Moghadam *et al.*, 2015). Further studies with a larger number of animals are necessary to be conducted in order to confirm these results.

3 Linseed, a way to mitigate methane emissions by ruminants

Among greenhouse gases, which are responsible of global warming, methane is the major contributor for livestock activities: more than 40% of greenhouse gases, when they are expressed as carbon dioxide-equivalents. The major part of methane is produced in the digestive tract of ruminants, especially in the rumen, which is the main site of digestion. In the rumen, dietary carbohydrates are fermented by bacteria and protozoa in volatile fatty acids, which are the main energy source for ruminants. During fermentation, hydrogen is produced, then is converted in methane by the action of another type of microbes, archaea methanogens. The abatement of methane emissions is a challenge for scientists.

Dietary lipids are considered now by the scientific community as the best way for enteric methane mitigation (reviews by Hristov *et al.*, 2013; Martin *et al.*, 2010). Although their effect on methane emission is not systematic, lipids present advantages compared to other dietary options: chemicals and additives such as nitrates raise the issue of acceptability by consumers, tannins often reduce animal performances, high-cereal diets question about the use of large amounts of cereals in ruminant feeding. When lipids are given in substitution to carbohydrates, methane is reduced because it is produced from carbohydrates, but not from lipids. In addition, some lipid sources decrease rumen protozoa which are important producers of hydrogen, which is the precursor of methane. The strongest decrease in rumen protozoa is obtained with linseeds on one hand, and coconut and palm kernel oil on the other hand. These latter lipid sources have the drawback to be rich in medium-chain saturated FA (12:0 and 14:0), which are considered as deleterious for human health. As a consequence, linseeds could be the best choice for methane mitigation. Review of experimental data shows that on average linseeds reduce more methane emission than saturated sources (calcium salts of palm oil, tallow), and unsaturated sources containing oleic acid (rapeseed) or linoleic acid (sunflower, cottonseed) (Martin *et al.*, 2010). However, between-experiments variability of response is high, so that some authors do not distinguish fat sources for their effect on methane emission (Grainger and Beauchemin, 2011). It has been shown that the effect of linseeds remains at least for one year after starting their distribution to cows (Martin *et al.*, 2011). This long-term effect is especially interesting because products which decrease methane often have a short-term effect, due to the adaptation of rumen microbes to dietary changes. Increasing the proportion of linseeds in the diet until 5% additional fat results in a strong decrease in methane (Fig. 2). In practical conditions, a lower addition of linseeds is recommended, to avoid any risk of disturbances of fibre digestibility, which often occurs for high linseed supply, and any risk of excessive increase in some *trans* FA in products which may have a negative effect of human health. Although most results evidence the effect of linseed for methane mitigation, for an unknown reason, linseeds did not decrease methane emission in some experiments (Van Zijderveld *et al.*, 2011).

For any option aiming to decrease methane emission by animals, it is mandatory to check that the decrease is not compensated for by an increase in the other greenhouse gases, carbon dioxide and nitrous oxide. For linseeds, there is a compensation for a minor part, due to the higher carbon footprint for linseed than for cereals that they replace. The effect of introducing linseeds in the diet has been calculated by life cycle assessment for the whole farming system, for beef cattle (Nguyen *et al.*, 2012) and for dairy cattle

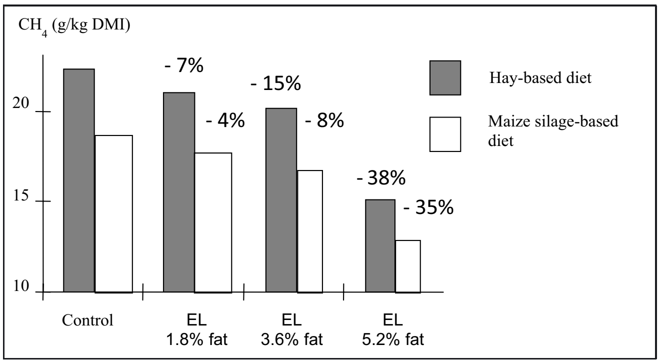

Fig. 2. Effect of increasing amounts of extruded linseeds (EL) on methane emission in two different diets (from Martin *et al.*, 2009).

(Nguyen *et al.*, 2013). In these studies, linseed supply was of limited extent and given to high-producing animals (2% additional fat to lactating cows in winter for dairy, 3% of additional fat to the bull fattening herd for beef), corresponding to present practices in France for farmers who use linseeds. In both types of farms, the use of linseeds slightly decreases greenhouse gases emissions, and slightly increases other environmental impacts as energy use, due to extrusion process, and land use, because crop yield per hectare is lower for linseeds than for cereals that linseeds replace. If strong public policies for decreasing greenhouse gases are implemented, all ruminants receiving concentrates could be fed lipids all year long, in order to provide 3.5% additional fat. In this case, lipid supply can reduce total greenhouse gases emissions from cattle by 6%. However, this option is expensive at present due to the higher cost of oleagineous seeds compared to cereals (Doreau *et al.*, 2014).

4 Increasing the use of linseed: potential and limits

Use of linseed in ruminant feeding could be developed if linseed crops are developed. In several countries, the use of linseed in crop rotations is limited by a lower yield per ha than cereals, and by the relative price of cereals and linseeds. Among crops which are frequently used in rotations in Europe, rapeseed is competitive, and grain legumes allow the decrease in N fertilisation in the multiannual system. This is not the case of linseed, for which average yield stagnates at 20 q/ha. For France, national linseed production covers one half of present needs for animal nutrition. The potential of increase in surfaces is high, but a significant rise requires a strong coordination of actors of the food chain (Charrier *et al.*, 2013). Ways of improvement which may lead in the short-term to tripling French surfaces (30 000 ha instead of 10 000 ha now) have been proposed by Labalette *et al.* (2011), and include a larger choice of varieties, better rotation choices and higher prices relative to cereals. This latter can be achieved by feed industry, but the price of milk and meat enriched in omega-3 should also be higher. This is possible by a selective milk collection, which is already organised in some dairy factories, by the development of dairy and beef brands for niche markets, and by the promotion and lobbying such as the Bleu-Blanc-Cœur initiative, which is positively received by consumers. Incentives related to public policies can be thought, owing to the environmental interest on linseed use for the abatement of methane emission by ruminants.

The positive effect of linseeds on omega-3 FA in milk and beef, and the methane abatement, are two arguments for using linseeds at a large scale. However, this practice will increase only if animal performances (milk yield and composition for dairy cows, liveweight gain and carcass characteristics) are unchanged or improved. Lipid incorporation in diets may decrease fibre digestibility, due to possible disturbances in rumen microbial ecosystem and fermentation. However, most scientists agree that this risk is negligible when FA content of diets does not exceed 5% of dry matter; this corresponds to 3.5% added FA from linseeds in diet DM. Higher proportion sometimes decreases digestibility (Petit, 2010).

A range of experiments has been carried out in dairy cows, using linseeds in different forms and amounts. During most short-term studies, feeding up to 15% linseed in diet dry matter (DM) did not change DM intake (Ferlay *et al.*, 2013; Petit, 2010). In early lactation, discrepancies among experiments on the effect of whole or processed linseed supplementation on milk yield could result from differences in diet composition and length of experiment (Petit, 2010). The whole linseed supplementation did not modify milk yield and milk fat content and yield in mid- or late lactation (Petit, 2010). Nevertheless, linseed micronisation or extrusion results in variable effects on milk fat concentration, with a possible decrease. One explanation could be the possible increasing rate of oil release from extruded seeds into the rumen compared to whole seeds, which could result in an increased production of *trans* FA in rumen and then a decrease in milk fat content (Chilliard *et al.*, 2009). A decrease in milk fat yield with linseed oil feeding is often reported (Glasser *et al.*, 2008a). Generally, feeding diets with whole or crushed or micronized linseed had no effect on the milk protein content in mid lactation (Petit, 2010) whereas a decrease in protein content (0.5 g/kg) was observed with extruded linseed (Brunschwig *et al.*, 2010). Concerning the long-term linseed supplementation, during the first year of experimentation, linseed diet had no effect on the milk and fat yields compared to the control diet. Linseed supplement decreased the milk protein content, without changing protein yield. Thus, long-term effects of supplementation with linseeds were similar to those observed during short-term (1 to 3 months) studies (Lerch *et al.*, 2012a). With a moderate linseed incorporation in the diet (less than 3% additional fat), milk yield is unchanged and the risk of decrease in milk fat or protein yield is low.

Linseed supply to diets has also been studied in fattening cattle. Table 1 summarizes 20 comparisons between control and supplemented diets. On average, animal liveweight gain is higher by 9% with linseed-supplemented diets than with control diet, differences ranging between +25% and –15%. Within experiment, differences are often non-significant. Difference between experiments is due to the level of linseed supply, the experimental design (addition of linseeds or substitution to carbohydrates and protein) and the characteristics of substitution, leading to differences in diet energy value between control and supplemented diet. Five comparisons between rolled and extruded linseeds have been performed by Normand *et al.* (2005): differences are very low (Tab. 2). Whole linseeds have been used by Maddock *et al.* (2006) and Corazzin *et al.* (2012). Results suggest that linseed hull does not limit a normal digestion of the seed. It can be concluded that the incorporation of linseeds for finishing cattle has no effect or a slightly positive effect on performances. Although it has been shown that lipid supply in fattening diets generally increases carcass fat proportion (Clinquart *et al.*, 1995), available data for linseed supply do not fully support this statement: linseeds may increase (Dufrasne *et al.*, 1991) or not (Maddock *et al.*, 2006; Normand *et al.*, 2005; Razminowicz *et al.*, 2008) carcass fatness. The reality of a difference between linseed and other lipid sources needs further research.

It is sometimes argued that linseeds contain cyanogenic compounds which could be toxic for animals. They are present as glycosides, and are likely to vary more with cultivar than with location or year (Oomah *et al.*, 1992). Seed treatments can decrease cyanides. Pelleting decreases total cyanides, especially at high and prolonged temperatures (Feng *et al.*, 2003). Extrusion divided cyanhydric acid by 4, whereas rolling divided them by 2 (one comparison, Normand *et al.*, 2006); a very pronounced decrease in cyanhydric acid was observed with another extrusion technology: 10 mg/kg for extruded linseeds *vs.* 165 to 240 mg/kg for rolled linseeds (6 comparisons, Normand *et al.*, 2005). However, cyanhydric acid content in plasma is not increased by rolled or extruded linseed inclusion in the diet, suggesting a possible detoxification in the rumen (Normand *et al.*, 2006). Nevertheless, cyanogenic compounds are transferred to a low extent in milk, but according to Petit (2010), milk concentrations are too much low to result in a toxic effect for humans, if taking account the daily doses which are considered as safe by health authorities.

Due to their high amount of polyunsaturated FA, linseeds may be subject to oxidation. During a 120-day conservation, peroxide value and vitamin E content are stable for rolled linseeds, whereas the former increases and the latter decreases for extruded linseeds (Normand *et al.*, 2005). It is recommended to use new batches of extruded linseeds every 2 months if there is no incorporation of antioxidant, in order to prevent a possible decrease in intake by animals. A concern related to the use of polyunsaturated FA is the susceptibility of lipids to oxidation (Durand *et al.*, 2005). Milk and beef lipid oxidation may occur, when linseeds are incorporated in diets, but often there is no increased susceptibility to oxidation, for example when rolled or extruded linseeds are fed to fattening cattle in moderate amounts (750 g/day) (Normand *et al.*, 2005). However, lipid oxidation may occur when animals have been submitted to oxidative stress during their lifetime, after inflammatory or infectious events, or in the pre-slaughter period, after an emotional or physical stress (Durand *et al.*, 2013). For this reason, an additional supply of vitamin E or of vegetal antioxidants in the diet may reduce milk susceptibility to oxidation (Focant *et al.*, 1998) and in beef meat after carcass ageing and meat display on shelfs (Gobert *et al.*, 2010).

Published literature does not mention flavour problems of milk from cows fed linseeds. When linseeds are given as formaldehyde-treated seeds, protecting them from rumen degradation and resulting in high 18:3 n-3 absorption, a fish taste in meat, an increase in rancidity and in a decrease in

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Table 1. Effect of linseed supply on beef liveweight gain.

Reference	Type of cattle	Control diet	Linseed supply[1]	Liveweight gain Linseed/control ×100
Clinquart *et al*. (1991)	Young bull	41% dried beet pulp, 59% concentrate	Flaked linseed, 10% (+2.1% fat)	99
Dufrasne *et al*. (1991)	Young bull	45% dried beet pulp, 55% concentrate	Flaked linseed, 10% (+2.0% fat)	113
Raes *et al*. (2004)	Young bull	85% concentrates, 15% maize silage	Crushed linseed, 7% of concentrates	116
			Extruded linseed, 7% of concentrates	109
Normand *et al*. (2005)	Young bull	90% concentrates 10% straw	Extruded linseed, 750 g/d	85
			Rolled linseed, 750 g/d	96
Normand *et al*. (2005)	Young bull	90% concentrates 10% straw	Extruded linseed, 750 g/d	111
			Rolled linseed, 750 g/d	121
Normand *et al*. (2005)	Young bull	55% maize silage + hay, 45% concentrates	Extruded linseed, 750 g/d	111
			Rolled linseed, 750 g/d	109
Normand *et al*. (2005)	Heifer, 2 yr	58% maize silage + hay, 42% concentrates	Extruded linseed, 750 g/d	107
			Rolled linseed, 750 g/d	87
Normand *et al*. (2005)	Culled cow	75% maize silage + straw, 25% concentrates	Extruded linseed, 750 g/d	119
			Rolled linseed, 750 g/d	125
Maddock *et al*. (2006)	Heifer, 1 yr	30% maize silage, 14% lucerne hay, 56% concentrates	Whole linseed, 8%	107
			Rolled linseed, 8%	115
			Ground linseed, 8%	117
Barton *et al*. (2007)	Heifer, 1 yr	unclear	Extruded linseed, 7.6% (+ 2.3% fat)	98
Razminowicz *et al*. (2008)	Steer, 18 mo	75% grass, 25% concentrates	Extruded linseed, 12% of concentrates (+ 1.1% fat)	108
Corazzin *et al*. (2012)	Young bull	18% maize silage, 25% hay, 6% straw, 51% concentrates	Whole linseed, 8% (+2.4% fat)	100

[1]In experiments by Raes *et al.* (2004) and Normand *et al.* (2005) feed intake was not determined so that additional fat supply is not known. In the experiment by Maddock *et al*. (2006) fat content of diets was not specified.

overall liking are observed (Scollan *et al*., 2005). Rancidity is due to oxidation, and fishy taste is likely due to components related to 20- and 22-carbon FA produced by FA elongation. This negative judging is not observed when linseeds are unprotected (Normand *et al*., 2005; Wood *et al*., 2003), *i.e*. when biohydrogenation normally occurs. It can be concluded that at normal levels of incorporation, linseeds do not affect milk or beef taste.

5 Conclusion

The major interest of linseeds in ruminant nutrition is the increase in omega-3 FA in milk and beef with a moderate supply in cattle diet. Although this increase in quantitatively slight, due to rumen biohydrogenation, it contributes to enhance milk and beef nutritional quality, and the image of these products for the consumer. This positive role of linseeds in ruminant nutrition is reinforced by their role for enteric methane mitigation. However, an excessive incorporation in diets may increase some *trans* FA in products or decrease milk fat and protein contents, and feed efficiency of the diet. It could be recommended to limit linseed incorporation to ca. 3% additional fat in the diet. However, a large increase in the use of linseeds for feeding ruminant is limited by the possibilities of increase in linseed cropping.

Highlight

Linseed use in ruminant nutrition can be developed in the future owing to interest in improving fatty acid composition of milk and meat, and also in decreasing methane emissions. Incorporation in diets up to 3% is possible without negative side effects on animal performance. An increase in linseed use requires an increase in areas devoted to linseed crops.

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