Alternatives for enrichment of eggs and chicken meat with omega-3 fatty acids

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González-Esquerra, R. and Leeson, S. 2001. **Alternatives for enrichment of eggs and chicken meat with omega-3 fatty acids**. Can. J. Anim. Sci. **81**: 295–305. Interest on the enrichment of eggs and poultry meat with omega-3 fatty acids (n-3 FA) has increased given their important role in human metabolism. The inclusion of n-3 FA into eggs and poultry meat is achieved by feeding ingredients such as flaxseed, fish oil, fish meal, marine algae and canola to birds. However, problems in various production parameters and sensory quality of eggs and meat may arise. The former possibly caused by antinutritional and physiological effects and the latter influenced by the interaction of volatile substances. Possible increases in formulation costs also deserve attention.

Strategies to ameliorate these undesirable effects include limiting the inclusion levels of n-3 FA sources, time of feeding, mixing different n-3 FA sources in commercial rations, and including high levels of vitamin E along with high-quality ingredients. A mild heat treatment may eliminate some of the drawbacks of feeding flaxseed to birds.

Key words: Omega-3, flaxseed, flax, menhaden oil, eggs, chicken meat

González-Esquerra, R. et Leeson, S. 2001. **Solutions de rechange pour l'enrichissement de la viande de volaille et des œufs avec les acides gras oméga-3**. Can. J. Anim. Sci. **81**: 295–305. L'enrichissement des œufs et de la volaille avec les acides gras oméga-3 (AG n-3) suscite de plus en plus d'intérêt à cause du rôle important des AG n-3 dans le métabolisme de l'être humain. Pour enrichir les œufs et la viande, on sert aux oiseaux des graines de lin, de l'huile et de la farine de poisson, des algues et du canola. Malheureusement, cette pratique peut poser des difficultés au niveau de certains paramètres de production ou de la qualité organoleptique des œufs. La première difficulté résulte peut-être d'effets physiologiques ou anti-nutritionnels, et la seconde, de l'interaction de composés volatils. Il convient aussi de s'attarder à la hausse éventuelle du coût des rations.

Plusieurs stratégies permettraient d'atténuer ces effets indésirables : réduire la quantité de sources de AG n-3, mieux choisir le moment où l'on nourrit les animaux, ajouter d'autres sources de AG n-3 aux aliments commerciaux et utiliser plus de vitamine E ainsi que des ingrédients de meilleure qualité. Un léger traitement thermique pourrait éliminer certains problèmes associés à l'utilisation des graines de lin.

Mots clés: Oméga-3, graines de lin, lin, huile de menhaden, œufs, viande de volaille

It is known that omega-3 fatty acids (n-3 FA) have potential in the prevention and treatment of cardiovascular diseases, some autoimmune disorders, diabetes, and some types of cancer aside from their important role in neuronal development. Research has shown that the current patterns of n-3 FA consumption in most of the Western countries are less than recommended values (for a review, see Simopoulus 2000). These findings have stimulated interest in improving the n-3 FA content of eggs and poultry meat.

In an attempt to increase n-3 FA content in poultry products, the utilisation of fish oil and flaxseed as feed ingredients has been a common practice. However, the decreased sensory quality of n-3 FA-enriched eggs and poultry meat caused by the presence of off-flavours, and their reduced lipid stability, cause some concern. Likewise, possible negative effects in production observed in birds fed the most suitable n-3 FA ingredients represent a drawback to the industry.

In this article, the major n-3 FA ingredients available to poultry, their potential as n-3 FA sources, and the specific problems associated to their utilisation in poultry feeds, will be discussed. The most important considerations to design n-3 FA poultry products will also be reviewed. Given the remarkable differences in the potential enrichment of eggs and meat these poultry products will be detailed separately.

EGG N-3 FA ENRICHMENT

Several factors affect egg composition and lipid profile including bird age, strain and breed (Edwards 1964;

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Abbreviations: **DHA**, docosahexaenoic acid; **DPA**, docosapentaenoic acid; **EPA**, eicosapentaenoic acid; **FM**, fish meal; **LCn-3**, long chain omega-3 fatty acids; **LNA**, α-linolenic acid; **MA**, marine algae; **ME**, metabolisable energy; **MO**, menhaden oil; **n-3 FA**, omega-3 fatty acid; **TBARS**, thiobarbituric reactive substances

Table 1. Potential sources of omega-3 fatty acids for inclusion in poultry diets

Source	18:3n-3	20:5n-3	22:5n-3	22:6n-3	Σn-3	Σn-6	Σn-3:Σn-6
				(% total fatty acids)			
Flaxseed oil[z]	53.3	–	–	–	53.3	12.7	4.2
Menhaden oil[z]	0.3	11.0	1.9	9.1	25.1	1.5	16.73
Marine algae[y]	–	–	3.8	7.4	11.2	–	–
Canola oil[z]	12.0	–	–	–	12.0	20.2	0.59

[z]National Research Council (1993).
[y]Herber and Van Elswyk (1996).

Washburn 1979; Nielsen 1998; Scheideler et al. 1998a). Scheideler et al. (1998b) reported that hens younger than 35 wk deposited 25 to 50% less n-3 FA in their eggs than did older birds. The same authors reported that Hisex White hens deposited ~30% more α-linolenic acid (LNA) in their eggs than did Hy-Line, DeKalb, or Babcock hens. Nevertheless, dietary manipulation still yields the most significant changes to yolk lipid profile (Sell et al. 1968; Leskanich and Noble 1997).

The arrangement of triglycerides and phospholipids formed in the liver for yolk synthesis can be affected by dietary modification (Walzem 1996). Graded levels of dietary saturated and monounsaturated fats have minor effects on the relative egg fatty acid profile (Baucells et al. 2000). In contrast, dietary polyunsaturated fats can cause major changes (Summers et al. 1966; Noble et al. 1990) thus allowing for manipulation of yolk lipids to better meet human nutritional requirements.

When eggs are to be enriched with LNA, flaxseed, flaxseed oil and to a lesser extent canola could be considered. When the aim of enriching eggs with n-3 FA is incorporating long chain n-3 FA [mainly eicosapentaenoic acid (EPA), docosapentaenoic acid (DPA), and docosahexaenoic acid (DHA) LCn-3] fish oil [most commonly menhaden oil (MO)], fish meal (FM), and marine algae (MA) are ingredients frequently used. Table 1 illustrates the fatty acid composition of these sources of n-3 FA for use in poultry diets.

Dietary concentrations of flaxseed directly affect yolk LNA deposition. However, the deposition of LCn-3, synthesised from LNA, by increasing dietary flaxseed does not follow the same trend suggesting a limited LNA-LCn-3 conversion (Caston and Leeson 1990; Cherian and Sim 1991; Aymond and Van Elswyk 1995; Scheideler and Froning 1996; Van Elswyk 1997a). Scheideler and Froning (1996) reported that with levels up to 15%, flaxseed has little effect on yolk LCn-3 deposition. Similar findings are reported in the literature with birds fed 10% (Yannakopolous et al. 1998) and 5% flaxseed diets (Aymond and Van Elswyk 1995; Van Elswyk 1997a).

Feeding whole flaxseed to birds could be advantageous in terms of oxidative stability because, in theory, lipid oxidation will be accelerated in ground flaxseed. Nevertheless, Aymond and Van Elswyk (1995) using no additional antioxidants in diets containing ground or whole flaxseed, stored under refrigeration, found no effect of flaxseed form on yolk thiobarbituric reactive substances (TBARS). Besides, LNA egg deposition is not affected by flaxseed form (whole vs. ground) at inclusion levels of >10% (Aymond and Van Elswyk 1995; Scheideler and Froning 1996). Table 2 summarises the effect of feeding graded levels of ground and whole flaxseed on egg n-3 FA content. In an attempt to standardise the comparisons among authors, the n-3 FA content of eggs was calculated considering 5 g of total fat per 50 g egg when not indicated by the original authors.

As previously mentioned, canola contains some LNA. Its potential as a source of LNA for hens was compared with that of flaxseed (Cherian and Sim 1991) by feeding hens diets containing 16% of either ingredient. As expected, LNA yolk enrichment was superior in birds fed flaxseed when compared with those fed canola (8.76 and 2.37% of LNA of yolk lipids, respectively). These results were confirmed in a further study using diets with 10% flaxseed or canola (5.77 and 1.37% of LNA in yolk fat, respectively; Cherian and Sim 1992). At an even lower dietary incorporation of canola, Panton et al. (1998) reported a rather moderate LNA yolk enrichment (0.69% vs. 0.43% of total yolk lipids from feeding 2.0% canola vs. 1.5% animal-vegetable fat, respectively).

Marine sources of n-3 FA offer the benefit of direct incorporation of LCn-3 into eggs which are metabolically more important than LNA for humans (Simopoulus 2000). Fish meals and oils are common ingredients within this classification, menhaden oil (MO) being particularly popular.

Increasing the amount of dietary fish oil results in sequential increases in LCn-3 deposition in eggs (Table 3). It is interesting to note that in spite of the higher concentrations of EPA (11%) relative to DHA (9.1%) in MO, the concentration of the latter found in yolks from hens fed MO is much greater than the former. For instance, in birds fed 3% MO, Huang et al. (1990) reported 29 vs. 192 mg yolk^{-1} of EPA and DHA, respectively. The same phenomenon occurs when FM is included in the birds' diet. Nash et al. (1996) reported that hens fed 12% menhaden meal (10.2% total fat) had EPA and DHA concentrations of 7 and 84 mg yolk^{-1}, respectively. The explanation to this finding possibly relates to the birds metabolism of n-3 FA where conversion of EPA from DHA and vice versa along with tissue specific preferential DHA deposition might occur as reported in mammals (Sprecher et al. 1995).

The extent of n-3 FA egg incorporation from FM reported in the literature is proportional to that expected from their residual oils (Table 4).

Another observation that warrants mention is the plateau in LCn-3 yolk accretion reported by some authors between 1.5 and 3% of MO dietary inclusion. Van Elswyk et al. (1995) and Van Elswyk (1997a) reported no appreciable dif-

Table 2. Yolk deposition of omega-3 fatty acids as influenced by dietary flaxseed

	Ground flaxseed															Whole flaxseed						
Reference	Scheideler and Froning (1996)[z]				Aymond and Van Elswyk (1995)[z]			Caston and Leeson (1990)[z]				Cherian and Sim (1991)[z]			Scheideler and Froning (1996)[z]				Aymond and Van Elswyk (1995)[z]		
Dietary flaxseed (%)	0	5	10	15	0	5	15	0	10	20	30	0	8	16	0	5	10	15	0	5	15
LNA	13	117	203	313	14	121	241	19	239	460	604	29	281	427	13	120	216	347	14	99	181
EPA	NR[y]	NR	NR	NR	28	6	23	0	3	6	3	0	6	8	NR	NR	NR	NR	28	3	8
DHA	27	64	88	86	32	75	103	2	5	12	11	48	69	75	27	87	87	88	32	75	81

[z]mg/egg considering atotal fat content of 5 g/50 g egg when not indicated by the authors.
[y]NR = not reported.

Table 3. Effects of feeding menhaden oil (MO) on omega-3 yolk incorporation[z]

	MO (%)		"Omega-3 oil" (%)[y]	
Adams et al. (1989)	3	6	3	6
LNA	Traces	Traces	27	35
EPA	16	16	31	32
DHA	78	47	153	118

	MO (%)			
Huang et al. (1990)	0	1	2	3
LNA	29	8	24	NR
EPA	2	13	20	29
DHA	38	136	211	192

	MO (%)			
Van Elswyk et al. (1995)	0	0.5	1.5	3
LNA	6	12	17	15
EPA	0	5	11	18
DHA	26	91	143	156

	MO (%)			
Van Elswyk (1997a)	0	1	2	3
Total n-3	48	144	198	193

	Regular and deodorized MO (%)					
González-Esquerra and Leeson (2000a)	0	2		4		6	
		Reg	Deod	Reg	Deod	Reg	Deod
LNA	26	23	26	30	38	37	58
EPA	0	16	13	30	31	45	61
DHA	26	87	85	114	123	144	196

[z]mg/egg considering 5 g of total fat per 50 g egg when not indicated by the original transcripts.
[y]As described by Adams et al. (1989).

Table 4. Effects of feeding fish meal on omega-3 yolk incorporation[z]

	Herring meal (%)[y]			
Nash et al. (1995)	0	4	8	12
LNA	NR[w]	NR	NR	NR
EPA	1	2	4	7
DHA	33	52	70	84

	Menhaden meal (%)[x]			
Nash et al. (1996)	0	4	8	12
LNA	NR	NR	NR	NR
EPA	Traces	3	4	8
DHA	29	54	67	79

[z]mg/egg considering 5 g of total fat per 50 g egg when not indicated by the original transcripts.
[y]14% fat.
[x]10.2 % fat.
[w]NR = not reported.

ferences in n-3 FA enrichment in eggs from hens fed diets ranging from 1.5 to 3% of MO. Moreover, Adams et al. (1989) even reported a numerically lower yolk DHA in hens fed 6% vs. 3% MO. Likewise, Huang et al. (1990) found lower DHA yolk concentrations in hens fed 2% vs. 3% MO. In contrast, González-Esquerra and Leeson (2000a) found a linear incorporation of LCn-3 in eggs from hens fed MO in the range of 0 to 6 %. The interference of other dietary components on n-3 FA metabolism and accretion can explain this discrepancy.

Yolk incorporation of n-3 FA is a gradual process. Yu and Sim (1987), feeding hens graded levels of pacific salmon oil, indicated that the maximum n-3 FA incorporation was reached at day 8. Lin et al. (1995) recorded the yolk n-3 FA content daily for 14 d from hens fed 1.5% MO. Within 14 d of feeding the test diets, yolk fatty acid profile was consistently modified. Herber and Van Elswyk (1996), scoring yolk fatty acid profiles weekly from hens fed 1.5% MO or MA at either 2.4 or 4.8% of the diet reported that yolk total n-3 FA stabilised 14 d after feeding the test diets, regardless of the n-3 FA source. For birds fed graded levels of MO, Van Elswyk (1997a) reported a gradual deposition of n-3 FA from week 0 to 3 reaching a plateau between weeks 3 and 4. Treatments with high MO tended to reach the plateau earlier than treatments with low levels. After removal of experimental diets, yolk n-3 FA content decreased at a rate of 20% during the first 2 wk, tending to plateau at week 3 and reaching control levels at week 4 in eggs from hens fed 0.5, 1 and 1.5% MO. These results illustrate the turnover of yolk lipids in the ovary.

Recently, MA has been studied as an alternative feedstuff for incorporating n-3 FA into eggs. Herber and Van Elswyk (1996) studied the potential of a dried high-DHA MA containing 11.2% of LCn-3 on a dry matter basis. After 4 wk of dietary supplementation with either 1.5% MO or 2.4% MA, yolks contained the same n-3 FA concentrations even though the former group received 189 mg more n-3 FA per day. Supplementing 4.8% of MA to hens only slightly

increased yolk total n-3 FA compared with hens fed 2.4%. The authors concluded that the MA is an efficient dietary alternative to current n-3 FA sources. The MA is also rich in carotenoids, which, as natural antioxidants, may enhance the oxidative stability of n-3 FA enriched eggs (Herber and Van Elswyk 1998).

Barclay et al. (1998) reported an n-3 FA enrichment of 150 mg egg^{-1} in hens fed a dried algae (*Schizochytrium* sp.) fermented product incorporated at a level designed to provide 165 mg of DHA hen^{-1} d^{-1}; however, the basal diet contained 2.5% flaxseed. Correcting for the possible effect of flaxseed in the yolk n-3 FA profile, the authors calculated an efficiency of DHA deposition of 55–56% from diet into eggs. Using the data reported by Herber and Van Elswyk (1996) the efficiency of DHA deposition from MA to eggs was calculated to be 42.6% in hens fed 2.4%. In hens fed 1.5% MO, the efficacy value was 50.5%. However, in the same experiment the efficiency of total n-3 FA conversion was 46 and 26.3%, respectively, favouring the hens fed 2.4% MA. Abril and Barclay (1998) reported a total n-3 FA content of 173 and 243 mg egg^{-1} in hens fed either 300 or 600 mg DHA d^{-1} hen^{-1} from MA. Van Elswyk et al. (1998) reported that feeding DHA from MA at levels up to 825 mg d^{-1} hen^{-1} has no adverse effects on bird performance or physiology. It is worth noting that under commercial conditions companies select birds of a specific age range (30–50 wk) to produce designer eggs, and that egg size is determinant on the whole n-3 FA egg content.

THE EFFECTS OF N-3 FA SOURCES ON PRODUCTION PARAMETERS IN HENS

There are inconsistent reports on the effects of flaxseed supplementation on layer production parameters. Scheideler and Froning (1996) reported decreases in body weight, egg weight, yolk size, and percentage eggshell in birds fed flaxseed for 8 wk. The latter was attributed to a laxative effect of flaxseed and an increased rate of passage of digesta. The experimental diets were calculated to be isonitrogenous and isoenergetic containing either ground or whole flaxseed included at 5, 10 and 15% and fed ad libitum for 8 wk. Yannakopoulos et al. (1998) reported reduced feed consumption and weight gain of birds fed flaxseed. Lower egg and hen weights were also reported by Caston et al. (1994) in hens fed flaxseed. The researchers attributed the former effect to a reduction in metabolisable energy (ME) of the flaxseed diet, resulting initially in loss of body weight and subsequently loss in egg size. Scheideler and Froning (1996) also reported an even lower yolk size in layers fed ground flaxseed vs. those fed whole seeds. In contrast, Jiang et al. (1991), Aymond and Van Elswyk (1995), and Pheko et al. (1998) reported no effect of dietary flaxseed on egg or yolk weights. Van Elswyk (1997b) suggested that the possible causes of the reduction in egg weight as a result of feeding flaxseed to hens could be: a) the lower serum lipids apparent in birds fed high amounts of n-3 FA, thus limiting the availability of lipids for yolk formation; b) the phytoestrogens contained in flaxseed; and/or c) the changes in circulating oestradiol as a consequence of either the latter substances or an effect of n-3 FA per se.

Scheideler and Froning (1996) found decreased feed consumption in some groups of hens fed flaxseed (5 and 15% ground or whole flaxseed). Aymond and Van Elswyk (1995) reported a similar observation in birds fed 15% flaxseed. In contrast, Caston et al. (1994) reported an increased feed consumption attributable to difference in dietary ME. From this experiment, the substantial decrease in ME associated with increasing amounts of flaxseed is an important observation. Thus, the experimental diet provided 2970 kcal kg^{-1}, while adding 20% flaxseed decreased the ME to 2440 kcal kg^{-1}, suggesting that the animals inefficiently digested flaxseed or the whole diet per se.

Reports have also been conflicting in regard to egg production. Scheideler and Froning (1996) found increased egg production ($P < 0.06$) in response to flaxseed with this effect most noticeable for brown vs. golden flaxseed varieties. Jiang et al. (1991) and Caston et al. (1994) reported no effect of flaxseed on egg production. Contrary to these reports, Aymond and Van Elswyk (1995) found lower egg production in response to dietary flaxseed inclusion. In these reports, differences in basal diets could partially explain conflicting results.

The association between dietary fish oil or FM and decreased yolk weight has recently been reported (Van Elswyk 1997a). This observation seems to be a consequence of the effect of n-3 FA on lipid metabolism and circulating oestradiol as mentioned previously. Herber and Van Elswyk (1996) observed a temporary decrease in yolk weight in hens fed 1.5 MO that consumed 345 mg n-3 FA d^{-1}. A similar observation was reported in hens fed 4.8% MA and consuming 365 mg n-3 FA d^{-1}. In a subsequent experiment, Van Elswyk et al. (1998) reported smaller egg yolks in birds fed as little as 165 mg DHA from MA. Other reports have shown comparable findings in birds fed ≥1.5% MO, or other n-3 FA sources (Van Elswyk et al. 1992; Whitehead et al. 1993; Marshall and Van Elswyk 1994; Van Elswyk et al. 1994; Ayerza and Coates 1999). Other workers, however, have failed to show any effect of such supplements on yolk weight (Yu and Sim 1987; Hargis et al. 1991; Nash et al. 1996; Yannakopoulos et al. 1998).

N-3 FA AND FATTY LIVER SYNDROME

Whether n-3 FA may have significance for fatty liver syndrome and/or fatty liver haemorrhagic syndrome in hens remains to be clarified. Histopatological evidence of a greater hepatocellular lipid infiltration in hens fed 3% MO vs. diets with no supplemented fat was reported by Hargis et al. (1991) suggesting a role of n-3 FA. Nevertheless, no difference in gross liver rank (assessed by liver integrity and friability) was found. In a further experiment, the same researchers first noted hepatic lipid infiltration after 4 mo of feeding hens diets with 3% MO (Van Elswyk et al. 1994). The infiltration consistently increased in severity after 5 and 6 mo, being statistically significant ($P < 0.001$) when compared with controls fed diets with 3% animal-vegetable fat. An interaction between n-3 FA and 17β-estradiol on the lipogenic activity of the liver was suggested, thus increasing the hen's susceptibility to hepatic lipidosis. In contrast, Schumann et al. (2000) used hens from an inbred line select-

ed for predisposition to fatty liver haemorrhagic syndrome fed LNA and LCn-3 enriched diets for 4 wk. There was a drop in serum triglycerides, lower hepatic dry matter and lipid content when compared with controls although haemorrhage scores were not affected. Reducing liver fat content was not effective in preventing haemorrhage. These workers also suggested that the hepatic oxidative status was not hampered by n-3 FA dietary supplementation although no histopatology was reported. Complete long-term trials using birds predisposed to fatty liver haemorrhagic syndrome would help to clarify apparent discrepancies between laboratories and the role, if any, of n-3 FA on these metabolic disorders.

OXIDATIVE STABILITY AND SENSORY QUALITY OF N-3 FA ENRICHED EGGS

Chain length and number of double bonds compromise n-3 FA oxidative stability. The inclusion of n-3 FA into diets increases the birds vitamin E requirements because once in eggs and tissues, n-3 FA increase their susceptibility to peroxidation (Aymond and Van Elswyk 1995). Dietary n-3 FA also decreases tocopherol egg accretion further compromising the eggs oxidative stability (Cherian and Sim 1997). The hazard to lipid oxidation is higher in eggs enriched in LCn-3 rather than LNA. Both LNA and LCn-3 eggs are shown to be stable over a period of 4 wk of storage (Marshall et al. 1994; Ahn et al. 1995); however, fresh n-3 FA eggs contain higher TBARS, used as an indicator of the extent of lipid oxidation (Marshall and Van Elswyk 1994; Cherian et al. 1996). Dietary vitamin E supplementation has been shown to alleviate this problem with eggs. Cherian et al. (1996) reported that eggs containing either LNA or LCn-3 had equal TBARS compared with eggs from hens fed saturated fats. With commercial n-3 FA egg production it is common practice to feed dietary vitamin E at levels up to 100 IU kg^{-1} (Leeson et al. 1998). In contrast, the theoretically improved lipid stability of feeding whole flaxseed vs. ground has not been proved (Aymond and Van Elswyk 1995).

The reduced sensory quality of eggs from hens fed fish oil or FM has long been recognised (Vondell 1932; Holdas and May 1966; Leeson and Summers 1978; Wakeling 1982). Koehler and Bearse (1975) noticed that the degree of impaired egg flavour varies according to type, level of inclusion and time of storage of FM fed to hens. Pacific Ocean hake meal caused the lowest flavour rating. At 10% dietary inclusion most of the FM diets resulted in objectionable egg flavours and, for some FM, a period of 4 wk of storage further worsen the egg sensory quality. The main off-flavour in eggs produced by feeding fish products to hens has been described as "fishy" by panelists. In general, unpalatable sensory attributes are due to an interaction of several compounds. The odours associated with volatile compounds in fish oil have been previously reviewed by Stansby (1990).

Lipids are not the only substances responsible for fishy flavours, and there might be a non-lipid fraction that, interacting with some lipid compounds, produces fishy flavours (Leskanich and Noble 1997). Volatiles seem to play an important role in the formation of odours and off-flavours in n-3 FA enriched products in general. Van Elswyk et al. (1995) found no specific volatiles contributing to odours in eggs from hens fed MO; however, volatile compounds of low molecular weight increased in contrast to those of high molecular weight. In this study 23 of the 42 volatiles tested in this experiment were influenced by dietary MO. The authors proposed that the changes in volatile concentrations could be responsible for the fishy flavours in eggs. As oxidation products could in part be responsible for fishy odours found in eggs, the use of stabilised n-3 FA sources in poultry diets in theory could ameliorate this problem (Van Ekswyk et al. 1995; Leskanich and Noble 1997). To test whether dietary volatiles may influence egg sensory characteristics, González-Esquerra and Leeson (2000a) conducted test panels on eggs from hens fed either 2% of deodorised vs. regular MO. Deodorization is a process in which most volatiles from oils are eliminated. These authors found that deodorization did not ameliorate the impaired sensory quality typically found in eggs from hens fed MO at those concentrations. Nevertheless, an experiment testing rancid vs. non-rancid high quality n-3 sources on egg sensory quality has not been performed.

The presence of fishy taints is not a problem exclusive to the utilisation of fish products in poultry diets. Dietary flaxseed has been reported to cause unpalatable flavours in eggs (Jiang et al. 1992; Caston et al. 1994). Recently, Leeson et al. (1998) reported that panelists were able to distinguish between eggs from hens fed 10% flaxseed or a zero flaxseed control diet, but not between 20 vs. 10% flaxseed. The addition of 100 IU of vitamin E kg^{-1} of diet further decreased the acceptability of eggs in the group fed 20% flaxseed. These authors concluded that high levels of vitamin E along with high levels of dietary flaxseed seem to interact and impair egg flavour.

There have been few sensory evaluations performed on n-3 FA eggs from birds fed MA. Herber and Van Elswyk (1998) reported no difference in egg flavour as a consequence of feeding hens either 2.4 or 4.8% MA vs. a control diet. The authors concluded that using MA in diets at levels of 4.8% would allow the incorporation of similar quantities of LCn-3 to using 3% MO, but without decreasing flavour quality. Barclay et al. (1998) found a higher lipid stability in eggs from birds fed MA compared with MO after 6 d storage at 38°C.

There is a considerable discrepancy among authors about the levels of fish oil or FM considered acceptable in terms of egg sensory quality. This is mainly due to differences in experimental procedures such as technique used for sensory evaluations, number of people recruited in panels, cooking procedures, type and quality of fish oil and FM used, presence or absence of dietary antioxidants, storage conditions of ingredients and that of the eggs tested, etc. From the consensus of these publications it is reasonable to consider levels up to 1 to 1.5% of fish oil and levels ranging from 2% to 10% FM to be acceptable depending upon geography. In countries like Chile or China, high levels of FM are commonly used in poultry diets; consequently, consumers in those areas are comfortable with the flavour and odour of high n-3 FA poultry products. The same problems have been observed in the case of flaxseed;

however, it is generally accepted that levels greater than 10% in hen diets could compromise egg sensory quality.

Genetics may also play a role in development of off-flavours in eggs. White Leghorn hens seem to produce fewer unsatisfactory taints than do Rhode Island Reds (Vondell 1932; Leeson and Summers 1978; Ahn et al. 1995). Wakeling (1982) reported more tainted eggs in Babcock hens than in Warren birds. Trimethylamine has been recognised as one of the substances associated with fishy flavours (Leeson and Summers 1978; Stansby 1990; Jiang et al. 1992). The genetic deficiency of trimethylamine oxidase in some brown-shelled eggs strains could explain the presence of offensive flavours in these strains (Leeson and Summers 1978). Thus, these birds should not be fed diets containing FM at levels above 2%.

As mentioned earlier, feeding fish oils to birds results in incorporation of LCn-3 into eggs, which are more metabolically active so potentially producing greater health benefits to consumers. Nevertheless these fish oils may compromise egg sensory quality. On the other hand, LNA is deposited in eggs by feeding flaxseed to birds, which is a less active n-3 FA for humans in spite of its conversion into LCn-3 (Simopoulus 2000), but is less objectionable to consumers. The ideal n-3 FA-enriched egg would be that which contains the highest possible concentrations of both, LCn-3 and LNA, without affecting its sensory quality. The former would be achieved by mixing LCn-3 and LNA sources. Baucells et al. (2000) fed layers graded concentrations of fish oil and flaxseed, obtaining eggs with variable amounts of both LCn-3 and LNA (Table 5). An experiment testing the effect of fish oils and flaxseed supplementation at commercial concentrations (i.e., 0 to 1.5% and 0 to 10%, respectively) on egg sensory has not been conducted.

Table 5. Eggs from hens fed graded levels of fish oil and flaxseed (adapted from Baucells et al. 2000)

Omega-3 in diets				Omega-3 in eggs (mg/50 g egg)	
Sources (%)		Diet content (g kg^{-1})			
Fish oil	Flaxseed oil	LCn-3	LNA	LCn-3	LNA
4	0	11.8	0.8	229	22
3	1	7.4	5.7	191	91
2	2	6.7	8.3	184	119
1	3	2.7	14.5	131	186
0	4	0.7	18.8	105	244

POULTRY MEAT N-3 FA ENRICHMENT

The fat in broiler white meat contains 33.5% of saturated, 30.5% unsaturated and 32% polyunsaturated fatty acids (Ratnayake et al. 1989). This profile is more favourable for human consumption compared with beef, which contains low levels of polyunsaturated fatty acids and high levels of saturated fats (Yau et al. 1991). Manipulating the ratio of these three fatty components could make chicken meat even more attractive to consumers. Different fractions within the fat of poultry are influenced by a number of factors. Sex of bird has some influence on changing the fatty acid profile of meat. Hulan et al. (1989) reported a ~10% higher n-3 FA carcass deposition in females compared with males in broilers fed redfish meal. Genotype, however, seems to have little influence on fatty acid profile (Leskanich and Noble 1997) although it can affect total body fat content in broilers. For instance, Hood and Pym (1982) reported that after eight generations, birds selected for improved feed conversion had less body fat than did those selected for increased feed consumption. Diet greatly influences body lipid profile, and so saturated, unsaturated, and polyunsaturated fatty acids tend to resemble the profile of the feed (Sanz et al. 1999). In this context, the adipose tissue is, in general, manipulated by diet more easily than are muscle lipids in the carcass (Yau et al. 1991).

The inclusion of n-3 FA into chicken meat is also possible through dietary manipulation and, as in the case of n-3 FA enriched eggs, flaxseed could be a key ingredient available to the poultry industry. Feeding graded levels of flaxseed oil or flaxseed to broilers augments LNA carcass deposition (Table 6). The slight increase in carcass EPA and DHA produced by feeding diets rich in LNA suggests an inefficient conversion of LNA into LCn-3 in broilers.

Canola has a limited potential for LNA enrichment compared with flaxseed. Ajuyah et al (1991) reported that carcass LNA enrichment was moderate after including 10% full-fat canola in contrast to flaxseed supplementation (Table 6). Thus, meat from birds fed a 10% flaxseed diet contained 260% more LNA compared to birds fed 10% canola.

In trying to increase chicken meat LCn-3, fish oils and FM are commonly considered. Among the fish oils used by the industry, MO is used most frequently. As with flaxseed, increasing the dietary levels of these ingredients proportionally increases LCn-3 carcass content when fed at levels of up to 5% (Tables 6 and 7). There is a linear LCn-3 incorporation using dietary MO up to 5% (Phetteplace and Watkins 1990). While DHA deposition predominates there are also proportional increments of EPA unlike the situation discussed previously in n-3 FA eggs (Mooney et al. 1998). Concentrations of LNA in carcass tend to remain unchanged after feeding birds marine n-3 FA sources (Chanmugam et al. 1992; López-Ferrer et al. 1999).

Little work has been done on the utilisation of MA as an n-3 FA source for broilers. Mooney et al. (1998) concluded that feeding 2.8% MA was equivalent to feeding 2.1% MO in terms of LCn-3 carcass enrichment. The theoretical improved meat lipid stability of birds fed MA was not observed in this experiment because carcass TBARS values were similar.

The metabolism of n-3 FA in tissue lipids involves a gradual turnover for both LNA and LCn-3. López-Ferrer et al. (1999) found a gradual LNA carcass deposition in birds fed flaxseed oil over 1, 2 or 5 wk. Similar findings were reported by Olomu and Baracos (1991). The same trend is observed in LCn-3 when marine n-3 FA sources are fed to broilers (Berrio and Hebert 1987). González-Esquerra and Leeson (2000b) showed that a substantial n-3 FA accretion in poultry meat is achieved by feeding birds flaxseed or MO for just 1 wk. Moreover, the combination of ingredients resulted in a wide variety of LNA and LCn-3 meat concen-

Table 6 Effect of feeding broilers various omega-3 sources on lipid meat profiles

	Total carcass lipids (%)[z]				
n-3 source	Control	Flaxseed		Canola seed	
Dietary inclusion (%)	0	10	20	10	20
LNA	1.5	10.1	19.2	3.6	6.2
LCn-3	0.8	1.6	2.7	1.0	1.0

	Thigh meat lipids (%)[y]						
n-3 source	Corn oil	Flaxseed oil			Menhaden oil		
Dietary inclusion (%)	1	1	2.5	5	1	2.5	5
LNA	1	4.4	11.4	21.9	0.8	1.2	1.9
LCn-3	0.3	0.7	1.3	1.2	2.3	4.7	8.4

[z]Ajuyah et al. (1991).
[y]Chanmugam et al. (1992).

Table 7. Effect of feeding broilers flaxseed and menhaden oil for different periods of time on lipid carcass accretion and sensory quality of selected portions (adapted from González-Esquerra and Leeson 2000b)

					Cooked skinless meat quality					
					Lipid composition (mg 100 g^{-1} cooked meat)					
Source of omega-3 in diets			Total carcass lipids (% of total fat)		Breast		Thigh		Sensory evaluation[z]	
Flaxseed (%)	Menhaden oil (%)	Feeding time (d)	LNA	LCn-3	LNA	LCn-3	LNA	LCn-3	Breast	Thigh
–	–	–	1.3	0.0	11	17	43	0	9.8	9.8
10	–	7	3.4	0.2	–	–	–	–	–	–
10	–	14	5.3	0.4	54	89	183	23	9.8	9.7
–	7.5	7	1.3	0.5	–	–	–	–	–	–
–	7.5	14	1.3	0.8	13	169	48	50	9.0	8.2
10	7.5	7	3.3	0.6	36	82	125	38	9.1	7.9
10	7.5	14	6.0	1.1	46	132	217	95	7.7	7.2

[z]Given by their acceptability in a range of 0 to 15 for dislike and like, respectively.

trations (Table 7). Under commercial conditions, limiting n-3 FA availability to just a few days prior to slaughter and/or combining n-3 FA sources could reduce feeding costs when producing n-3 FA-enriched poultry meat.

The phospholipid and triglyceride concentrations in meat differ significantly among various portions. Breast meat contains more lipids as phospholipids while triglycerides predominate in thigh meat. LCn-3 are more readily stored in phospholipids and LNA is mainly stored in tryglicerides. This may explain the preferential deposition of LCn-3 in breast meat reported by these authors, which contrasts with that of LNA found in dark meat (Table 7).

EFFECTS OF FEEDING N-3 FA SOURCES ON PRODUCTION PARAMETERS IN BROILERS

In general, no adverse effects on production performance of broilers are seen when birds are fed flaxseed oil (Olomu and Baracos 1991; López-Ferrer et al. 1999). In contrast, reduced performance has been reported in broilers fed either flaxseed or flaxseed meal (Kratzer 1947; Ajuyah et al. 1990; Ajuyah et al. 1991; Ajuyah et al. 1993a). González-Esquerra and Leeson (2000c) observed diarrhoea in birds fed flaxseed when performing ME studies. The authors tested different flaxseed dietary levels (up to 20%) with birds at different ages and found that the severity of the diarrhoea was dependent on flaxseed level of inclusion and bird's age. Some birds seemed to tolerate flaxseed better than others. Consequently, the ME of experimental diets varied widely among birds possibly due to direct influences of diarrhoea.

Flaxseed contains phytic acid (Palmer et al. 1980), which is known to: a) reduce the availability of minerals such as calcium, magnesium, zinc and iron; b) affect proteins by forming electrostatic linkages with lysine, arginine and histidine; and c) inhibit proteolitic enzymes (Caldwell 1992; Ravindran et al. 1995). In addition, flaxseed contains cyanogenic glycosides, mainly linamarin, linustatin and neolinustatin. These substances can form hydrogen cyanide which is potentially toxic (Chadha et al. 1995).

In traditional medicine, one tablespoon (10 g) of flaxseed soaked overnight is used as a laxative for humans (Rosling 1993). Flaxseed also contains linatine, which is a vitamin B_6 antagonist, and this impairs growth in chickens and its anti-nutritional effect can be compensated by supplementing pyridoxine (Klosterman 1974). Other components such as allergens and mucilage present in flaxseed (Spies 1974; Palmer et al. 1980) could also interfere with the utilisation of nutrients affecting production parameters.

Metabolisable energy of diets containing flaxseed increases remarkably in pelleted vs. mash diets (4578 and 3659 kcal kg^{-1}, respectively). The temperature and pressure

exerted during pelleting may inhibit some antinutritional factors offering a practical solution to producers when using diets containing flaxseed (González-Esquerra and Leeson 2000c). Feeding exogenous enzymes may also be attractive. However, at present, research in this area is lacking.

Marine n-3 FA sources, when well stabilised and used appropriately in commercial diets, do not usually influence broiler production. Fish meal specifically could reduce performance in broilers if its actual calcium and phosphorus content is miscalculated. Another cause for concern is the threat of salmonella contamination and problems associated with overheating during processing. If all of these conditions are avoided and/or monitored, FM should not affect production (Sugahara 1995; Leeson and Summers 1997).

The multiple beneficial effects on the cardiovascular system exerted by n-3 FA suggest that these fatty acids might decrease the incidence of cardiovascular diseases such as ascites. Walton et al. (1999) fed flaxseed oil at different concentrations to broilers housed in hypobaric chambers. The authors found reduced haematocrit, blood viscosity, and right ventricular hypertrophy and increased erythrocyte deformability in birds fed 5% flaxseed oil vs. those fed an animal and vegetable oil blend. Some of these effects were not found in birds fed 2.5% flaxseed oil. Nevertheless, the mortality due to ascites was numerically higher in birds fed flaxseed oil ($P > 0.05$).

OXIDATIVE STABILITY AND SENSORY QUALITY OF n-3 FA ENRICHED MEAT

The oxidative stability of poultry meat is influenced by its fatty acid composition. Meat rich in LNA is prone to lipid oxidation and usually contains more TBARS than does meat high in saturated or monounsaturated fats (Lin et al. 1989; Asghar et al. 1990). O'Keefe et al. (1995) reported higher TBARS in LCn-3 enriched pre-cooked meat after 2 d of refrigeration. The highest concentrations of lipid oxidation products were found in meat with higher LCn-3, and this effect increased over time. Thus, time and conditions of storage have a large effect on lipid stability (Ahn et al. 1995).

There are many volatile products derived from lipid oxidation that may exert a significant effect on flavour characteristics in meat (Whitfield 1992). Vitamin E supplementation increases carcass vitamin E content imparting better meat lipid stability, thus decreasing volatiles and possibly reducing objectionable flavours (Lin et al. 1989; Ajuyah et al. 1993ab; Wood and Enser 1997; Mooney et al. 1998).

Given the above, problems associated with sensory quality have been extensively reported in n-3 FA enriched meat. As described with eggs, it is somewhat difficult to compare results on sensory evaluation on meat (Poste 1990). However, a review of the literature suggests that off-flavours become noticeable when dietary fish oils range between 0.75 and 1.5% (Carrick and Hauge 1926; Carlson et al. 1957; Dansky 1962; Edwards and May 1965; Miller and Robisch 1969; González-Esquerra and Leeson 2000b). High dietary levels of FM may also produce off-flavours in broilers. Dean et al. (1969) reported detectable flavours in broilers fed 9% FM. Recommendations of other authors concur with this report (Scott et al. 1982; Leeson and Summers 1997). However, care must be taken when including FM with high oil content (Hardin et al. 1964; Fry et al. 1965). Contrary to broilers fed fish oils and/or FM-added diets, birds fed diets with flaxseed at levels up to 10% do not produce meat with objectionable flavours (González-Esquerra and Leeson 2000b).

The preferential deposition of LNA and LCn-3 discussed above for poultry meat, along with the wide differences in total fat among meat portions, could cause difficulties when designing n-3 FA-enriched poultry meat. González-Esquerra and Leeson (2000b) addressed this issue by testing the sensory quality of different cooked-meat portions from broilers fed various combinations of flaxseed and MO for 7 or 14 d. The sensory quality of breast and thigh meat from birds fed 10% flaxseed for 14 d was comparable with controls. In contrast, feeding birds 0.75% MO diets for 14 d resulted in lower thigh meat sensory quality than controls, while that of breast meat remained unchanged. Breast meat acceptability from birds fed diets with 10% flaxseed and 0.75% MO decreased when fed for 14 d, but did not change when offered to birds for just 7 d (Table 7). These findings imply that LNA is more palatable than LCn-3 once incorporated into poultry meat. Sources of n-3 FA and time of feeding affect sensory quality of various meat portions differently, so complicating their n-3 FA enrichment.

Interactions among ingredients should also be considered when formulating practical diets. As little as 5% dietary FM may produce off-flavours if combined with high levels of canola meal (Hawrysh et al. 1980). Salmon et al. (1984) suggested that broilers fed 5% FM with added DL-methionine (0.05%) and choline chloride (0.1%) could show objectionable taints in meat.

CONCLUSIONS

The egg rather than the poultry meat industry has progressed faster in terms of production and marketing of n-3 FA enriched products. The knowledge achieved so far on enriching eggs with n-3 FA has made possible the availability of designer eggs in most supermarkets in North America, which are currently supplying a rapidly growing market. Nevertheless, as illustrated in this review, there are many factors that affect n-3 FA deposition in eggs and these must be considered before marketing n-3 FA enriched eggs where standardisation is important for labelling purposes. Further investigations should focus on: a) mixing LNA and LCn-3 FA sources to optimise enrichment; b) studying new n-3 FA sources; c) searching for strategies to avoid side effects from common n-3 FA ingredients; and d) sensory quality and rancidity.

The poultry meat industry, in terms of marketing n-3 FA enriched products, still has a long way to go because, unlike eggs, the lipid fraction is unevenly distributed in different marketable meat portions, which further complicates their enrichment and marketing.

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