CHAPTER 11

The multifaceted value of camelina oil as a novel aquafeed ingredient

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Abstract

The global aquaculture industry has been seeking sustainable alternatives to fish oil, driven by its limited sustainable availability and escalating cost. Camelina oil (CO), derived from *Camelina sativa*, has garnered notable interest as a possible plant-based alternative due to its richness in alpha-linolenic acid and gamma-tocopherol. Additionally, CO provides significant nutritional benefits and stability against oxidation, making it an excellent choice for aquafeeds. This chapter explores the biochemical composition, digestibility, and physiological effects of CO in aquaculture diets for different species. Freshwater fish such as rainbow trout and Nile tilapia, benefit markedly from dietary CO supplementation due to their ability to desaturate and elongate alpha-linolenic acid (ALA) into long-chain ω-3 fatty acids like eicosapentaenoic acid (EPA, 20:5n-3) and docosahexaenoic acid (DHA, 22:6n-3). Marine species have lower activities of the necessary enzymes for this process, and the fatty acid profile benefits of CO are restricted to direct supply of ALA or total ω-3 levels in diets. In addition to its nutritional value, growing camelina brings environmental benefits, such as minimal water and fertilizer needs, suitability for less productive lands, and lower greenhouse gas emissions than close alternatives such as canola. Overall, CO is not a total replacement for fish oil, but forms part of the potential future basket of expandable, eco-friendly oils that allow some degree of decreased reliance on marine-sourced lipids in aquaculture nutrition.

Keywords

omega-3 fatty acids – plant-based lipids – sustainable aquafeeds – antioxidant stability – fish health

1 Introduction

Camelina (*Camelina sativa*) is an oil seed plant in the family Brassicaceae. Its agricultural origins date back as far as 4000 BC (Berti et al. 2016), however modern agriculture has favored its higher yielding mustard seed and canola/rapeseed relatives. Despite its lower yields, camelina has received renewed interest in recent years due to its adaptability to a range of agricultural environments, with its tolerance to cold and water stress particularly advantageous traits (Berti et al. 2016; Hosseini Sanehkoori et al. 2021). Cold-climate oil seed growth promotes production of polyunsaturated fatty acids and camelina grown in cold environments contains particularly high levels of the ω-3 a-linolenic acid (ALA) (Righini et al. 2019; Clemente et al. 2025). While this often makes oils prone to oxidation, camelina further contains high gamma-tocopherol (vitamin E) content (Clemente et al. 2025) which imparts antioxidant protection. Camelina therefore presents a unique value-proposition as a relatively stable source of plant-based ω-3 fatty acids.

1.1 Aquafeeds and oil supply

Oils in aquafeed contribute to the dietary supply of energy, essential fatty acids, and other non-triglyceride lipid nutrients. Fish oil traditionally comprised the primary source of lipids in aquafeeds, which in turn consume the majority of the world's fish oil supply, with 74% of global fish oil production estimated to be consumed in aquaculture in 2021 (IFFO estimates in FAO 2024). Fish oil production reached its peak in 1994, with a reasonably static annual supply since this time necessitating development of alternatives to facilitate the expansion of aquafeed production (FAO 2024). The energy supply from fish oil can be derived from many sources of lipids, and global aquafeed production has increasingly utilized a range of plant and animal-based lipid sources for this purpose. There has thus been a shift over the last 30 years away from marine oils to a predominance of terrestrial-derived oil sources.

The marine food chain has a unique fatty acid profile. Relatively little bioconversion of fatty acid classes occurs between trophic levels for non-ruminant animals, meaning that the fatty acid profile of consumers largely reflects their food. Animals are capable to lipogenesis of palmitate from other energy sources; however, the specificity of enzymes involved in elongation and desaturation of the carbon chain limits the resultant fatty acids. Specific limitations in fatty acid synthesis occur due to a lack of fatty acid desaturation at the third and sixth carbon from the methyl end, also known as the omega (ω) end, of the fatty acid chain. The lack of these ω-3 and ω-6 desaturase enzymes in animal systems means that the functions of these fatty acids must be satisfied by a nutritional supply. The physiological need for ω-3 and ω-6 fatty acids for normal growth and development makes their requirements nutritionally 'essential' or 'indispensable'. In the marine food chain, these fatty ac-

ids are derived from algae, where the ω-3 fatty acid group predominate. In contrast, lipids of the modern terrestrial agricultural supply chain contain a higher proportion of fatty acids in the ω-6 group.

The search for cost-effective and scalable sources of digestible lipids have driven aquafeed producers towards oils from terrestrial plants and byproducts from terrestrial animal processing. This shift away from fish oil has therefore changed the fatty acid profile of aquafeeds from ω-3 dominated towards more ω-6 dominated fatty acid profiles.

1.2 Omega 3 and omega 6 fatty acids

Fatty acids in ω-3 and ω-6 classes are polyunsaturated, long-chain fatty acids, and as such have a low melting point and are well digested by fish. They have similar roles in maintaining fluidity when incorporated into phospholipids of cell membranes and are involved in cell signaling processes (Innes and Calder 2018). The specific roles of these fatty acid classes in cell signaling can however be opposed. Fatty acids in the ω-6 class form precursors to proinflammatory leukotrienes and prostaglandins, initiating cellular response to injury and disease, while ω-3 fatty acids form precursors to the equivalent anti-inflammatory signaling mechanisms (Simopoulos 2002; Innes and Calder 2018). While inflammation is a normal part of damage and disease mitigation, excessive inflammation can cause significant tissue damage, and the de-escalation of this process is critical for healing after damage occurs. These pro- and anti-inflammatory signaling pathways utilize the same enzyme pathways, meaning that an excess of either ω-3 or ω-6 fatty acid classes is likely to unbalance inflammatory processes. Therefore, nutritionists have focused on the balance of ω-3 and ω-6 fatty acids to support effective immune function and recovery after injury.

The fatty acid profile of fish feed is firstly important to meet the essential fatty acid requirements of fish, secondly to control inflammatory signaling balance and ultimately for the health benefits to the human consumer.

1.3 Other lipid-soluble components of oils

1.3.1 Potential for the residual meal

While oilseeds are largely grown for their oil yield, extracted oil accounts for 30–50% of the seed dry matter, with the remainder sold as a secondary meal product (Bouallegue et al. 2020). Camelina seeds contain naturally low glucosinolate and erucic acid content (Clemente et al. 2025), which are antinutritional elements prevalent in unselected rapeseed and mustard strains. They further contain polyphenolic compounds that contribute to antioxidant processes within production animals (Kurasiak-Popowska and Stuper-Szablewska 2020).

2 Nutritional composition of camelina oil

2.1 Fatty acid composition and antioxidant profile

CO is particularly rich in α-linolenic acid (ALA), comprising 28–40% of its total fatty acids, a level much higher than in soybean, corn, or canola (Garcia-Mendoza et al. 2021; Hixson et al. 2014b). This makes camelina a unique plant oil source for aquafeeds, providing a favorable ω-3: ω-6 ratio that supports fish health and inflammation balance (Innes & Calder, 2018). In addition, CO contains moderate levels of linoleic acid (LA, 18:2n-6), oleic acid (18:1n-9), and gondoic acid (20:1n-9), which may contribute to membrane fluidity and energy metabolism. CO also contains high γ-tocopherol (700–900 mg/kg), an antioxidant that protects the oil from oxidation during storage and feed processing, helping preserve the nutritional quality of aquafeeds (Table 11.1).

CO also demonstrates higher oxidative stability than fish oil but is less stable than sunflower, corn, sesame, olive, and rapeseed oils under accelerated storage at 65 °C (Eidhin et al. 2003). This relative stability is mainly influenced by its high α-linolenic acid content, which increases susceptibility to oxidation compared with more saturated oils such as palm oil. Despite this, CO retains sufficient stability for aquafeed use, particularly when protected from light and stored appropriately. Its favorable biochemical composition further highlights its potential for sustainable and nutritionally appropriate inclusion in aquafeed formulations.

2.2 Metabolic relevance and application in aquafeeds

Although CO lacks eicosapentaenoic acid (EPA, 20:5n-3) and docosahexaenoic acid (DHA, 22:6n-3), it is a valuable source of ALA, the metabolic precursor to these long-chain omega-3 PUFAs. Freshwater species such as rainbow trout (*Oncorhynchus mykiss*) (Hixson et al. 2014a) and carp (*Cyprinus carpio*) possess enzymatic pathways (Δ6-desaturase, elongase, and Δ5-desaturase) that enable partial conversion of ALA into EPA and DHA (Figure 11.1) enabling them to utilize CO more effectively. In contrast, most marine fish exhibit limited capacity for this conversion resulting in reduced EPA and DHA levels in tissues when fish oil is replaced with CO (Glencross et al. 2024; Morais et al. 2012; Huyben et al. 2020). Thus, the nutritional role of CO depends strongly on species-specific biosynthetic capacity.

3 Camelina oil in aquafeeds: effects on fish growth, physiology, and health outcomes

3.1 Growth performance and nutritional utilization

While CO shows promise in effectively supplying lipid energy and essential ω-3 fatty acids in aquafeed formulation, its effects need to be placed in the context in

TABLE 11.1 Fatty acid and nutrient composition of camelina and other vegetable oils

Component	Camelina oil	Linseed oil	Soybean oil	Corn oil	Palm oil	Rapeseed oil	References
α-Linolenic Acid (18:3 n-3)	28–40%	45–55%	7–8%	<1%	<1%	8–10%	Günç Ergönül and Aksoylu Özbek, 2020
Linoleic Acid (18:2 n-6)	13–20%	15–18%	~50%	~60%	~10%	~20%	Günç Ergönül and Aksoylu Özbek, 2020
Oleic Acid (18:1 n-9)	15–19%	~20%	~24%	~28%	~40%	~60%	Günç Ergönül and Aksoylu Özbek, 2020
Gondoic Acid (20:1 n-9)	10–16%	–	–	–	–	1–2%	Günç Ergönül and Aksoylu Özbek, 2020
Saturated Fatty Acids (SFA)	7–9%	~9–10%	~14–16%	~13%	~50%	~7%	Günç Ergönül and Aksoylu Özbek, 2020
EPA (20:5 n-3)	0% (wild type)	–	–	–	–	–	Hixson et al., 2014b
DHA (22:6 n-3)	0% (wild type)	–	–	–	–	–	Hixson et al., 2014b
Total PUFA	~50-60%	~70%	~55%	~60%	~10%	30%	Garcia-Mendoza et al., 2021
Total MUFA	~25-30%	~20%	~23%	~28%	~40%	~60%	Garcia-Mendoza et al., 2021
Tocopherols (mg/kg)	700–1250	500–800	~800	~600	~500	~600	Günç Ergönül and Aksoylu Özbek, 2020

Note. Information adapted from: Günç Ergönül and Aksoylu Özbek (2020); Hixson et al. (2014b); Garcia-Mendoza et al. (2021). Values represent typical composition ranges for cold-pressed or refined oils reported in the cited literature. EPA and DHA values refer to wild-type Camelina oil.

which it is tested. Several studies have demonstrated that CO can effectively replace fish oil in aquafeeds without impairing growth or nutrient utilization, especially in freshwater species with active LC-PUFA biosynthetic pathways. For example, Atlantic salmon and rainbow trout achieved comparable weight gain and feed conversion ratios (FCR) when dietary fish oil was fully replaced with CO (Hixson et al. 2014b; Lu et al. 2020). However, this is only the case when any EPA and DHA specific requirements are met by the residual oil in the fish meal component of the diet. Salmonid fish have some ability to elongate and desaturate approximately 25% of their long chain PUFA from ALA (Hixson et al. 2014b; Hixson et al. 2014a), however this occurs most effectively when EPA and DHA content of the diet is low. Therefore,

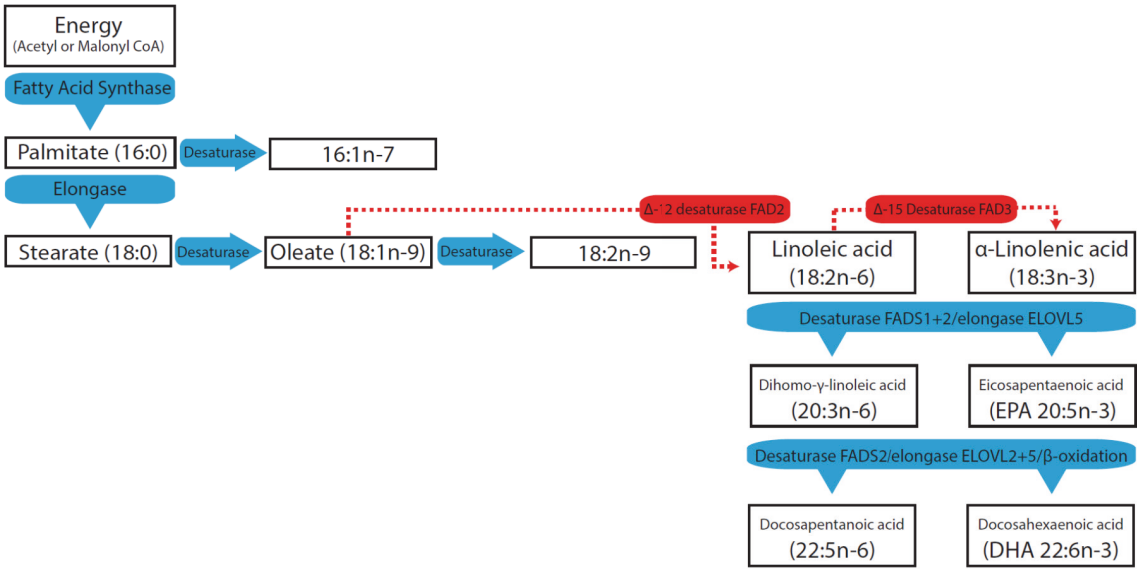

FIGURE 11.1 Fatty acid biosynthesis pathway in fish. Pathway is simplified for clarity. Blue symbols indicate pathways present in fish, while red color indicates pathways present in plants but absent in fish, necessitating dietary supply. Adapted from Bell and Tocher, 2009; Tocher, 2010

the degree to which ALA from CO can supplement EPA and DHA from fish oil in these feeds is highly dependent on the EPA and DHA targets in the edible portion of the fish being grown. Likewise, CO can enrich long chain PUFA in tilapia muscle when dietary levels are insufficient and present a potential non-fish oil pathway to increase health benefits to the human consumer without affecting production rates or efficiency (Toyes-Vargas et al. 2020).

In contrast, Atlantic cod catabolize the majority of the ALA from CO when it fully replaces fish oil, resulting in impaired growth and reduced tissue EPA and DHA levels (Hixson et al. 2014b). These findings exemplify the species-specific nature of responses, with freshwater fish generally more capable of utilizing ALA from CO compared to marine species (as previously discussed in detail in Section 2.2)

3.2 Physiological and health parameters

Physiological assessments in camelina-fed fish generally show minimal or no adverse effects. The liver indices, intestinal morphology, and hepatosomatic index (HSI) are generally unaffected at moderate inclusion levels of CO. However, adding more than 15% of CO to salmon diets has been linked to slight intestinal inflammation, suggesting this as a practical safe limit (Ye et al. 2016). Similar villi shortening have been observed in salmon fed other plant oils, likely reflecting reduced EPA and DHA availability for intestinal proliferation (Moldal et al. 2014).

The γ-tocopherol content of CO contributes to the antioxidant capacity of feeds and fish consumers, inhibiting peroxidation which prolongs shelf life of feed and fish products, as well as reducing oxidative stress in cells (Eidhin et al. 2003). While antioxidant effects are not unique to camelina, its relatively high γ-tocopherol concentration enhances these protective benefits compared to many other plant oils. Immune-related outcomes have also been reported, for example cytokine gene expression upregulation has been demonstrated in red seabream fed diets containing CO (Mzengereza et al. 2022). However, whether these immune responses are specific to CO remains to be clarified.

Overall, the nutritional value of CO has been validated across multiple freshwater and marine species. Findings from controlled feeding trials are summarized in Table 11.2 providing insights into species-specific growth, physiological, and health outcomes following CO and meal inclusion.

4 Industrial, economic, and sustainability applications of camelina oil

CO offers a distinctive array of nutritional, industrial, and environmental benefits. Camelina functions as a lipid source in aquafeeds and offers a viable and scalable

TABLE 11.2 Effects of camelina oil, alone and in combination with camelina meal on fish growth, physiology, and nutritional outcomes

Fish species	Environment	Oil/meal type	Inclusion level	Key outcomes	References
Rainbow trout (*Oncorhynchus mykiss*)	Fresh water	Camelina oil	100% lipid replacement	No difference in growth or tissue fatty acid composition	Lu et al. 2020
Rainbow trout (*Oncorhynchus mykiss*)	Fresh water	Camelina oil	100% lipid replacement	Stable growth, enhanced LC-PUFA biosynthesis	Hixson et al. 2014a
Nile tilapia (*Oreochromis niloticus*)	Fresh water	Camelina oil	100% lipid replacement	No impact on growth, survival, or tissue fatty acid profile	Toyes-Vargas et al. 2020
Nile tilapia (*Oreochromis niloticus*)	Fresh water	Camelina meal + oil	~25% meal + 5% oil	Stable performance, growth and muscle lipid composition	Toyes-Vargas et al. 2020
Atlantic salmon (*Salmo salar*)	Marine	Camelina oil	100% lipid replacement	Stable growth, muscle FA profile, enhanced LC-PUFA biosynthesis	Hixson et al. 2014b
Atlantic Cod (*Gadus morhua*)	Marine	Camelina oil	100% lipid replacement	Reduced growth, reduced EPA/DHA content	Hixson et al. 2014b
Gilthead seabream (*Sparus aurata*)	Marine	Camelina + chia oil	100% lipid replacement	Upregulation of immune genes, limited ALA to EPA/DHA conversion	Toyes-Vargas et al. 2020; Ofori-Mensah et al. 2020
Atlantic Salmon (*Salmo salar*)	Marine	Transgenic camelina Oil	60% oil + 20% meal	Improved tissue LC-PUFA retention, stable growth	Betancor et al. 2015

solution for sustainable agriculture and feed processing. As a hardy, short-cycle crop with low input demands, camelina can be cultivated on marginal lands with minimal water and fertilizer use, supporting climate-resilient farming (Berti et al. 2011). Its suitability for crop rotation and low competition with food crops further enhance its appeal in sustainable feed ingredient supply chains.

4.1 Environmental and economic advantages

The extraction of CO using cold pressing or solvents yields oil rich in α-linolenic acid (ALA) and γ-tocopherol, along with a protein-rich meal. This co-product can serve as animal feed or fertilizer, thus enhancing the crop's overall value. Life cycle assessment studies indicate that CO generates approximately 100–150 kg of CO_2 per tonne, far lower than fish oil, which produces 600–900 kg of CO_2 per tonne (Li and Mupondwa 2014; Mupondwa et al. 2016). Additional sustainability benefits include reduced water usage and smaller ecological footprint compared to marine derived fish oil.

While CO is lower yielding than the related canola or rapeseed crops, its ability to grow in colder and dryer climates may enable its cultivation in areas that are unsuitable for these higher yielding crops. Its viability is a combination of yield, production efficiency, and value proposition as an ingredient. With recent market prices estimated at USD 1,200 to 1,600 per ton, CO compares favorably to fish oil priced at USD 1,800 to 2,500 per ton (Jafari et al., 2022; USDA, 2020). Sustainably sourced fish oil is limited and global production unlikely to increase, likely enhancing the future value of alternative sources of ω-3 fatty acids.

Feeding trial evidence further supports its economic potential: Hixson et al. (2014b) demonstrated that substituting up to 60% of fish oil with CO in salmonid diets had no negative impact on economic feed conversion rations or gross profit margins. Similarly, Wei et al. (2019) reported that high-oil residue camelina meal could be included at levels up to 40 g/kg in trout and salmon diets without impairing growth or health outcomes. Together, these findings affirm that CO can reduce feed costs while maintaining production efficiency and product quality.

4.2 Innovation and future integration

Recent advancements in plant biotechnology have produced transgenic camelina lines that can synthesize EPA and DHA, providing a sustainable source of LC-PUFAs previously obtained solely from marine fish oil or marine algae. Feeding trials with European sea bass and Atlantic salmon demonstrated that these transgenic oils achieve performance and tissue enrichment results comparable to traditional fish oil (Betancor et al. 2021; Betancor et al. 2015).

Beyond aquafeeds, camelina contributes to a circular bioeconomy. Its oil and co-products are used in the production of biofuels, bioplastics, and specialty industrial oils, diversifying revenue streams and enhancing supply chain resilience.

Such versatility reinforces camelina's market value while supporting environmentally responsible aquaculture and eco-certified markets (Stamenković et al. 2023; Arshad et al. 2022).

The entire camelina production cycle, encompassing cultivation, oil extraction, and aquafeed integration, illustrates the crop's adaptability and minimal environmental impact (Figure 11.2). A comparative analysis of the sustainability attributes and economic indicators of CO in relation to fish oil is presented in Table 11.3.

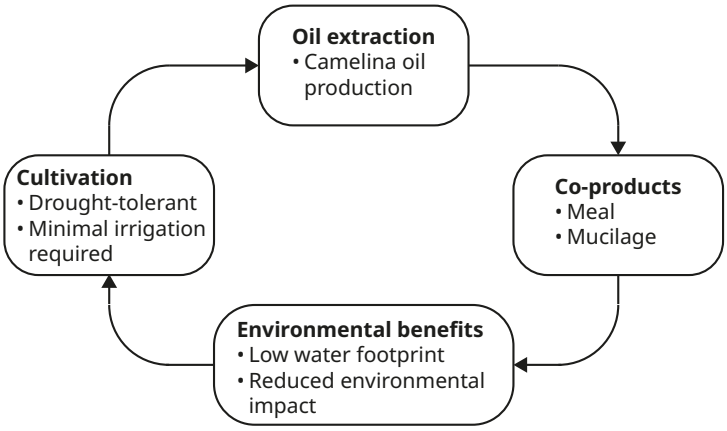

FIGURE 11.2 Diagram illustrating camelina's agronomic cycle, oil extraction, co-product streams (meal, mucilage), and aquafeed application. Adapted from Berti et al. 2011; Waraich et al. 2013; Mupondwa et al. 2016; Eidhin et al. 2003

TABLE 11.3 Sustainability and economic comparison of camelina oil and fish oil

Parameter	Camelina oil	Fish oil	References
LC-PUFA content (EPA+DHA)	0% native, 15–20% (transgenic camelina)	20–30% (natural)	Betancor et al. 2021
CO_2 emissions (kg/ton oil)	100–150	600–900	Mupondwa et al. 2016
Water use & ecological footprint	Low (minimal irrigation; marginal land suitability)	Moderate-High (linked to fisheries and processing impacts)	Li and Mupondwa 2014; Avadí and Fréon 2013
Estimated market price (USD/ton)	~ $1,200–1,600	~$1,800–2,500	Jafari et al. 2022
Co-product utility	High (meal, biodiesel, mucilage, fertilizer, bioplastics)	Moderate (fishmeal only)	Waraich et al. 2013;Arshad et al. 2022; Stamenković et al. 2023
Oxidative stability	High (γ-tocopherol preserves PUFA)	Moderate (prone to rancidity)	Hixson et al. 2014c

5 Effect on fish quality: nutritional composition, texture, flavour, and consumer acceptance

Replacing FO with CO in aquafeeds can affect multiple aspects of fish quality, including nutritional composition, oxidative stability, texture, flavor, and consumer acceptance. While CO provides a favorable omega-3-to-omega-6 ratio and is rich in α-linolenic acid (ALA), it lacks long-chain omega-3 polyunsaturated fatty acids (LC-PUFAs), EPA, and DHA, which are critical for human nutrition and desirable in aquaculture products. These limitations are particularly important when evaluating fish nutritional quality and consumer acceptance.

5.1 Nutritional composition of fillets

Replacement of FO with CO into fish diets significantly increases ALA concentrations in fillets, while concurrently decreasing EPA and DHA levels, particularly in species with limited capacity to synthesize LC-PUFA. Nile tilapia (Toyes-Vargas et al. 2020), rainbow trout (Lu et al. 2020), and Atlantic salmon (Hixson et al. 2014a) have all demonstrated this pattern although the magnitude of change varies with species, life stage, and feeding duration. The resulting enzymatic conversion of fatty acids via desaturases and elongases clearly differs between species and life stages within species. Salmonids exhibit moderate conversion of dietary ALA to EPA and DHA, whereas Atlantic cod and tilapia have much lower efficiency (Hixson et al. 2014b; Xue et al. 2015). Consequently, salmonid fillets typically retain higher LC-PUFA concentrations when fed CO-based diets. Selective breeding for genes such as elovl2 and elovl5 has been suggested as a mechanism to improve ALA conversion and preserve nutritional quality. These species-specific differences in lipid metabolism and LC-PUFA biosynthesis are fully detailed in Section 2.2. A summary of key fillet quality responses to camelina oil inclusion across species is presented in Table 11.4.

5.2 Fillet texture, oxidative stability

The relatively high PUFA content in CO could make fillets more susceptible to oxidation; however, camelina's naturally high γ-tocopherol along with phenolic compounds and flavonoids, helps prevent lipid peroxidation. This renders fillets from fish fed CO-enriched feeds more stable compared to those containing other PUFA-rich oils such as flaxseed oil (Sydor et al. 2022).

In terms of texture, most studies indicate no adverse effects when CO replaces up to about 40–50% of the added fish oil fraction (Betancor et al. 2015). At higher substitution levels, however, outcomes become more variable. Some studies such as (Betancor et al. 2016) reported no major changes in fillet texture even when more than half of the added fish oil was replaced, whereas others noted slight softening of fillets, likely linked to alterations in muscle lipid class composition and water-holding capacity (Jafari et al. 2022; Hixson et al. 2014b). In commercial aquafeeds, lipid

inclusion typically ranges from 10–20% of the diet (equivalent to ~ 25–30 % of dietary energy as lipids) (Salem et al. 2023). Within this lipid fraction, fish oil is only one of the several raw materials, and thus it is more precise to express CO substitution as a percentage of the added fish oil fraction, rather than as a percentage of total dietary lipid. At the research level, much higher substitution rates of this fish oil fraction have been tested. For example in Atlantic cod, CO successfully replaced 40% or even 80% of the fish oil component of the diet without compromising growth (Booman and Rise 2013).

Together, these findings suggest that CO can replace a substantial proportion of fish oil in aquafeeds without negatively affecting fillet texture or oxidative stability under practical feeding scenarios. At very high substitution levels, some variability has been observed, underscoring the importance of considering both the proportion of added fish oil replaced and the absolute amount of lipid included in the diet.

5.3 Flavor and consumer acceptance

Sensory evaluations suggest that substitution of FO with CO at levels up to 40%–50% of the added fish oil fraction does not significantly alter fillet flavor or consumer acceptance (Table 11.4; Hussin et al. 2019; Betancor et al. 2015). At higher substitution levels, however, mild off-flavors have been reported in certain species (Booman et al. 2014). Detailed sensory evaluations show this can include the development of a slight "plant oil" or "bitter" note in species like Atlantic salmon or cod when CO substitution exceeds the 50% threshold, highlighting the importance of balancing substitution rates with consumer panel outcomes and market expectations (Betancor et al. 2015).

Recent research indicates that fish oil replacement with CO can lead to subtle changes in fillet fatty acid composition and flavor, but these do not necessarily reduce consumer acceptance. In fact, sensory panel studies have shown that moderate inclusion of CO maintains acceptable taste and texture profiles. For example, Betancor et al. (2015) reported no significant differences in overall consumer preference or acceptability for steamed rainbow trout fillets fed diets containing 50% or 100% fish oil replacement with CO. Similarly, Hussin et al. (2019) found that Nile tilapia fillets from CO based diets exhibited only minor flavor and texture differences, with no negative impact on consumer preference or willingness to purchase. These findings provide empirical support for the sustainability narrative by confirming that sensory quality remains acceptable at moderate substitution levels.

Moreover, consumer perception of sustainability can further enhance acceptance. When panel participants were informed that the fish were raised on sustainable CO based diets, overall acceptance scores increased significantly (Hussin et al. 2019). This suggests that clear communication of environmental and nutritional benefits can enhance marketability, even if slight sensory variations occur. Consequently, retailers and processors are encouraged to integrate sustainability and health messaging to strengthen consumer confidence in CO fed fish products.

TABLE 11.4 Summary of key fillet quality changes in fish fed camelina oil

Parameter	Effect of camelina oil	Fish species	Inclusion level (fish oil substitution)	References
ALA Content ↑	Significant increase in fillets	Rainbow trout (*O. mykiss),* Nile tilapia *(O. niloticus),* Atlantic salmon *(S. salar)*	40–100%	Lu et al. 2020; Xue et al. 2015
EPA & DHA ↓	Marked reduction	Atlantic salmon *(S. salar)* Nile tilapia *(O. niloticus)*	40–100%	Betancor et al. 2015; Xue et al. 2015
Flavor changes	Mild off-flavor at high CO	Atlantic salmon *(S. salar)*	>50%	Betancor et al. 2015
Texture	Generally unaffected	Nile tilapia (*O. niloticus),* Rainbow trout (*O. mykiss)*	<50%	Betancor et al. 2015; Lu et al. 2020
Oxidative stability	Improved vs flax oil	Multiple species	Up to 50%	Sydor et al. 2022

Note: ↑ = increase; ↓ = decrease. ALA: Alpha-linolenic acid (18:3n-3); EPA: Eicosapentaenoic acid (20:5n-3); DHA: Docosahexaenoic acid (22:6n-3).

6 Digestibility and lipid metabolism in fish

CO is gaining prominence as a sustainable lipid source in aquafeeds due to its beneficial fatty acid profile and generally high digestibility across many species. Beyond growth outcomes and fillet quality (Section 3 and Section 5), understanding digestibility and lipid metabolism is essential to evaluate how fish utilize CO and how it can be integrated into sustainable diets.

6.1 Digestibility across fish species

Several studies confirm that CO is highly digestible in aquaculture species (Table 11.5). For example, rainbow trout fed CO-based diets showed lipid digestibility exceeding 90%, comparable to or slightly lower than traditional fish oil diets (Fraser et al. 2017; Lu et al. 2020). Similar digestibility values have been reported in Nile tilapia and common carp, with no significant impairment in lipid assimilation compared to fish oil diets (Chen et al. 2018).

Digestive and metabolic efficiency, however, varies by species due to differences in fatty acid desaturation and elongation pathways. Freshwater fish such as tilapia and carp possess robust enzymatic activity, particularly Δ 6 desaturase (fads2)

and elongase (elovl5) that supports conversion of ALA into EPA and DHA (Chen et al. 2018) while marine carnivores such as salmon, seabream, and cod have lower enzymatic capacity (Tocher et al. 2024; Venegas-Calerón and Napier 2023). In gilthead seabream, for example, digestibility estimates are more difficult to specify due to limitations in experimental design, but fatty acid balance and gene expression analyses indicate altered metabolism and reduced EPA/DHA retention (Ofori-Mensah et al. 2020). These differences, outlined in Section 2.2, explain why digestibility outcomes do not always translate into equivalent retention of long-chain PUFAs. As illustrated in Figure 11.1, fish possess the core biosynthetic pathway for fatty acid desaturation and elongation. However, species-specific differences in enzymatic activity are more clearly represented in Table 11.5, which contrasts freshwater species (higher fads2/elovl5 activity and omega-3 retention) with marine species (lower conversion efficiency).

6.2 Lipid metabolism, gene regulation

Beyond digestion, replacement of FO with CO influences lipid metabolic pathways, gene expression, and tissue lipid composition. In Atlantic salmon, dietary CO inclusion has been associated with hepatic upregulation of desaturase (fads2) and elongase (elovl5) gene expression (Betancor et al. 2016; Xue et al. 2015), reflecting an adaptive response to maintain LC-PUFA homeostasis. However, these adjustments do not fully offset the reduced EPA and DHA deposition in tissues associated with the reduced dietary supply of these fatty acids (Hixson et al. 2014a).

In addition, dietary CO has been shown to modify the fatty acid profile of tissue phospholipids in liver and muscle, rather than changing overall lipid class distribution. These shifts in phospholipid composition may influence membrane fluidity, oxidative balance, and energy metabolism, underscoring the need to align dietary formulations with species-specific metabolic capacity Betancor et al. (2021).

Taken together, these interspecies metabolic responses highlight a key point: while digestibility of CO is consistently high across species, the efficiency of ALA conversion and long-chain PUFA retention is highly variable. Table 11.5 provides a comparative overview, showing that freshwater species such as tilapia and carp retain more EPA and DHA due to higher desaturase and elongase activity, whereas marine species such as salmon and seabream exhibit lower conversion efficiency despite high digestibility.

6.3 Strategic formulation and nutritional implications

Feed formulation must take interspecies metabolic differences into account. In freshwater species with high desaturase and elongase activity (e.g., tilapia and carp), higher levels of CO are generally well utilized. In marine species, blending CO with DHA-rich oils or using transgenic sources may help maintain tissue EPA/DHA levels. These strategies complement the performance outcomes already discussed in Section 3 and the product quality outcomes covered in Section 5.

Advances in nutrigenomics and selective breeding offer further solutions. Selective breeding or genome editing of genes such as fads2, elovl2, and elovl5 may enhance LC-PUFA biosynthesis and improve the compatibility of sustainable oils like camelina in aquafeeds (Venegas-Calerón and Napier 2023). These approaches link nutritional biochemistry with future-oriented aquaculture sustainability.

7 Antinutritional considerations in camelina oil

While some antinutritional properties have been associated with whole camelina seed or the residual camelina meal after oil extraction, refined CO is essentially devoid of antinutritional compounds. The primary antinutritional factors typically associated with camelina seed such as glucosinolates, sinapine, phytic acid, trypsin inhibitor activity and condensed tannins are polar molecules which do not strongly associate with the non-polar CO (Pozzo et al. 2023). Antinutritional factors are therefore concentrated in the residual meal fraction after oil extraction (Zubr 2003; Eidhin et al. 2003; Pozzo et al. 2023; Zago et al. 2015).

TABLE 11.5 Digestibility and lipid metabolism response to camelina oil in different fish species

Fish species	Environment	Digestibility (%)	ALA to EPA conversion	EPA/DHA retention (tissue)	References
Rainbow Trout (*O. mykiss*)	Fresh Water	>90%	Moderate	Retention declines with CO diet	Fraser et al. 2017; Lu et al. 2020
Nile Tilapia (*O. niloticus*)	Fresh water	>90%	High	Better retention	Chen et al. 2018
Common Carp (*C. carpio*)	Fresh water	>90%	Moderate	Maintained at moderate CO	Tocher, 2010
Atlantic Salmon (*S. salar*)	Marine	>90%	Low	Limited, despite fads2↑	Hixson et al. 2014b; Xue et al. 2015
Gilthead Seabream (*S. aurata*)	Marine	Not clearly specified; difficult to determine due to study design	Low	Reduced retention (not composition); changes in phospholipid fatty acid profiles	Monroig et al. 2013 Ofori-Mensah et al. 2020

Note: Table values reflect both apparent lipid digestibility and subsequent tissue retention of LC-PUFAs where data are available. Note: ↑ = upregulation; CO = Camelina Oil; ALA = alpha-linolenic acid; EPA = Eicosapentaenoic acid; DHA = Docosahexaenoic acid.

Because CO is commonly evaluated alongside its co-product meal in aquafeed research, some studies report physiological effects that are attributable to meal inclusion rather than to the refined oil itself. While sinapine content is considered to be low in camelina meal, other antinutrients are present in variable concentrations according to genetics and growing conditions (Russo and Reggiani 2017; Pozzo et al. 2023; Jiang et al. 2016). This likely contributes to the large variation in responses reported in fish experiments with camelina meals, which have resulted in recommendations ranging from 4–20% of the feed (Mzengereza et al. 2022; Koskela et al. 2021; Wei et al. 2019; Ye et al. 2016). Excessive camelina meal inclusion results in growth impairment as well as diverse physiological impacts including intestinal alterations (Ye et al. 2016; Wei et al. 2019), impaired immune and growth regulation, digestive enzyme activity and altered antioxidant status (Mzengereza et al. 2021). This indicates diverse and variable antinutrients in camelina meal that require further species-specific elucidation, contrasting with the lack of negative impact associated with dietary CO inclusion (Table 11.2).

For the purposes of this chapter, which focuses specifically on CO, antinutritional constrains are considered negligible and are discussed only to highlight the distinction between oil and meal fractions.

8 Regulatory status and feed formulation challenges

The regulatory acceptance of CO for aquafeeds has progressed in recent years, driven by increased interest in sustainable feed alternatives and the growing body of research on camelina's nutritional and safety profiles. This section outlines the current status of regulatory approvals and highlights key challenges and opportunities in formulating camelina-based feeds for aquaculture.

8.1 Regulatory status and safety approvals

Regulatory agencies such as the European Food Safety Authority (EFSA) and the U.S. Food and Drug Administration (FDA) have issued guidance and approvals regarding the inclusion of CO in aquafeeds. EFSA has established safety thresholds for undesirable substances in animal feeds to ensure compliance with feed safety standards (EFSA, 2008). In parallel, the FDA has granted Generally Recognized As Safe (GRAS) status to CO for use in animal feeds, including aquaculture, under defined inclusion limits (FDA, 2016). These regulatory endorsements reflect institutional confidence in camelina's safety and open pathways for its broader adoption.

8.2 Formulation challenges and technological solutions

Despite regulatory approval, several nutritional and processing challenges must be addressed for optimal inclusion of CO in commercial aquafeeds. One primary

limitation is its fatty acid profile CO is rich in alpha-linolenic acid (ALA; 18:3n-3) but contains negligible amounts of long-chain omega-3 fatty acids such as EPA and DHA. Marine fish, which have limited enzymatic capacity to elongate ALA into EPA and DHA, may experience reduced tissue LC-PUFA content when fed CO based diets. To overcome this, feed manufacturers may employ 'finishing diets' that include marine oils or algal-based EPA/DHA supplements to restore fillet nutritional quality prior to harvest (Betancor et al. 2021).

Another concern is oxidative stability. While more stable than FO, the high PUFA content in CO poses a risk of lipid peroxidation, leading to rancidity and reduced feed palatability. Further supplementing tocopherols or adding alternative natural antioxidants such as rosemary extract can further improve oxidative stability in storage, transport and feed manufacture as reviewed for PUFA-rich fish oils by Shahidi and Zhong (2010). More conventional synthetic antioxidants (e.g., BHT, BHA) are also widely used in the feed industry, through their long-term viability may be limited by regulatory restriction and consumer preference for clean label ingredients. Given that camelina is already relatively expensive compared with other oils, reliance on costly additive strategies could constrain its competitiveness. Gentle processing methods such as cold-pressing and low-temperature extrusion further help maintain the oil's bioactive and nutritional qualities.

Overall, CO offers considerable promise as a sustainable, cost-effective alternative to marine-derived oils in aquaculture. Its success depends on continued regulatory alignment, strategic feed formulation, and technological innovation. Addressing these factors will be key to unlocking CO's full potential and advancing sustainable aquafeed production.

9 Future perspectives and research gaps

CO has shown considerable promise as a sustainable alternative to fish oil in aquaculture. However, to fully unlock its potential, future research must take a systems-level approach, addressing species-specific nutritional responses, feed formulation innovations, and environmental scalability. This section outlines key priorities and interdisciplinary directions that will shape the next frontier of CO application in aquaculture.

9.1 Nutritional physiology and species–specific considerations

A critical area for future research lies in understanding interspecies variability in LC-PUFA biosynthesis. Freshwater species such as rainbow trout and carp exhibit some capacity to convert alpha-linolenic acid (ALA, 18:3n-3) to EPA and DHA, whereas most marine species lack adequate enzymatic activity in key pathways

regulated by FADS and ELOVL gene families (Glencross et al. 2024; Monroig and Kabeya 2018). Genomic, transcriptomic, and enzymatic studies can guide selective breeding programs to enhance this capacity and optimize species-specific feed formulations.

Additionally, there is a need to investigate CO's effects during early developmental stages and broodstock nutrition. Parameters such as reproductive performance, embryonic development, larval health, and transgenerational epigenetic modifications require evaluation to determine life-stage-specific safety thresholds (Glencross et al. 2024; Izquierdo et al. 2001). Long-term and multigenerational studies are needed to ensure the safe integration of CO across the aquaculture production cycle.

9.2 Innovations in feed formulation and camelina crop engineering

Feed formulation strategies must evolve to overcome CO's limitations in LC-PUFA content. Blending CO with alternative lipid sources such as algal oil, insect lipids, or shrimp waste oil offers a promising avenue for balancing essential fatty acid profiles while reducing environmental impact (Azcuy et al. 2025; Glencross et al. 2024). Precision nutrition strategies that tailor lipid composition to species and developmental stages can further enhance feed efficiency and fish health.

Simultaneously, biotechnological advances in camelina crop improvement particularly transgenic and CRISPR-based modifications offer transformative potential. GM camelina lines engineered to produce EPA and DHA have already shown success (Betancor et al. 2016; Petrie et al. 2014). However, limitations with social license exist, as not all market accept GM ingredients in the aquaculture supply chain, with stricter resistance in regions such as Australia and Europe. Broader adoption will therefore depend not only on biosafety evaluations, and long-term feeding trials, but also on consumer acceptance, regulatory harmonization and clear sustainability narratives to support their commercial deployment.

9.3 Sustainability, scalability, and future research directions

Evaluating the broader environmental and economic sustainability of CO adoption requires robust life cycle assessments (LCA), techno-economic modeling, and regional feasibility analyses. Studies suggest camelina cultivation and oil extraction result in lower greenhouse gas emissions, land use, and water consumption compared to fish oil (IFFO 2025; Li and Mupondwa 2014).

Moreover, camelina's compatibility with regenerative agricultural systems and marginal land cultivation aligns with global goals for climate-adaptive food production. Future research should assess camelina's role in circular bioeconomy frameworks and investigate market integration, supply chain resilience, and policy incentives to support its large-scale adoption.

10 Conclusion

CO represents a highly promising feed ingredient with wide-reaching implications for sustainable aquaculture. It offers a unique combination of nutritional, economic, and environmental benefits, particularly due to its high ALA content and natural antioxidants such as γ-tocopherol, which support fish health, preserve feed quality, and reduce reliance on marine-derived lipids. CO can be utilized without affecting growth, feed efficiency, or tissue quality in numerous freshwater species capable of converting ALA into EPA and DHA. In marine species, where this conversion is limited, strategies such as blending CO with other lipid sources or employing transgenic camelina enriched with EPA and DHA may provide additional value in some markets.

From a sustainability perspective, camelina demonstrates several agronomic advantages. It can be cultivated on marginal land with minimal input and integrates well into crop rotation systems. Its production requires less water and results in a lower environmental footprint compared to fish oil. Nonetheless, careful processing and regulatory oversight remain important to ensure safe and consistent use in commercial aquafeeds.

Future research should focus on species specific responses in LC-PUFA biosynthesis, continued optimization of feed formulation strategies, and biotechnological crop improvements. Regulatory frameworks and consumer acceptance will also play key roles in CO's broader adoption. Overall, CO offers a strategic and sustainable pathway toward resilient, and nutritionally adequate aquaculture systems.

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