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Omega-3 fatty acids: dietary components for the promotion of human and animal health

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Omega-3 fatty acids, commonly found in fish and other natural sources, are essential polyunsaturated fats with significant health benefits. This study provides an overall quantitative literature analysis on omega-3 fatty acids. Bibliometric data were collected through the search string TOPIC = ("omega-3 fatty acid*" OR "omega-3 polyunsaturated fatty acid*" OR "ω-3 fatty acid*" OR "ω-3 polyunsaturated fatty acid*" OR "n-3 fatty acid*" OR "n-3 polyunsaturated fatty acid*" OR "omega-3 oil*"). It yielded 35,575 publications indexed in the online Web of Science Core Collection database. Using VOSviewer software, term maps were generated to visualize frequently mentioned terms together with their citation data. The literature had a steady growth since the 2000s and predominantly consists of original articles, with a ratio of 5.4:1 compared to reviews. The most productive author was Professor Philip C. Calder from University of Southampton, whereas the most productive country was the United States. Fish is a common source of omega-3 fatty acids mentioned by the literature, along with olive oil, corn oil, soybean oil, flaxseed, microalgae, linseed oil, vegetable oil, and seafood. Recurring medical conditions mentioned by the literature included inflammation, cardiovascular disease, cancer, obesity, depression, and diabetes. This bibliometric review highlights the dominant contributors, major research themes, and emerging applications of omega-3 fatty acids in human and animal health.

KEY WORDS: omega-3 fatty acids / docosahexaenoic acid / eicosapentaenoic acid / alpha-linolenic acid / bibliometrics / Web of Science / VOS viewer

Introduction

Omega-3 fatty acids are exogenous nutrients that must be obtained from external sources, primarily through diet or supplementation. They are essential for maintaining health in both humans and animals, playing important roles in the structure and function of cell membranes as well as the production of bioactive lipids. Their unique molecular structure enhances cell membrane fluidity, supporting optimal cellular function and overall well-being. [Stillwell and Wassall 2003, Saini and Keum 2018]. Main dietary sources of these essential fatty acids include fish, red meat like ostrich meat, seafood, flaxseed, and plant oils [Horbańczuk *et al*. 1998, 2007, 2008, Simopoulos 1999, Cooper and Horbańczuk 2004, Jiang *et al.* 2011]. Omega-3 fatty acids are known for promoting heart health, reducing inflammation, and potentially lowering the risk of chronic diseases like cardiovascular disease, cancer, and diabetes [Mozaffarian and Wu 2011]. They are also linked to mental health benefits, such as reducing depression symptoms [Martins 2009]. The three primary types of omega-3s vary in chain length and unsaturation, influencing their specific physiological roles [Gomez-Pinilla 2008].

Types of omega-3 fatty acid – characteristic

Omega-3 fatty acids are a class of polyunsaturated fatty acids (PUFAs) and the most important fatty acids are alpha-linolenic acid (ALA), eicosapentaenoic acid (EPA), and docosahexaenoic acid (DHA) [Calder 2016].

Alpha-Linolenic Acid (ALA*)* is an essential omega-3 fatty acid and one of the most abundant sources of polyunsaturated fatty acids in the plant kingdom. It is particularly notable for its chemical diversity and serves as a precursor to plant oxylipins, which are produced through aerobic oxidation [Gerwick *et al.* 1991]. ALA is an 18-carbon fatty acid with three double bonds, making it a polyunsaturated fatty acid. The "alpha" in its name refers to the position of the first double bond, which is located at the third carbon atom from the methyl end of the fatty acid chain. This positioning classifies ALA as an omega-3 fatty acid. The three double bonds in ALA are located at the 9th, 12th, and 15th carbon atoms, giving it a high degree of unsaturation. This structural feature contributes to ALA's fluidity in cell membranes and its role in modulating membrane-associated functions [Calder 2018]. Primarily known for its anti-inflammatory and cardiovascular benefits, ALA also supports brain development, cellular signaling, and immune response. Being hydrophobic, ALA integrates into cell membranes, affecting their fluidity, permeability, and the function of membrane-bound proteins. Additionally, ALA can be metabolized through a series of desaturation and elongation steps to produce longer-chain omega-3 fatty acids, such as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), which are vital for numerous physiological processes [Burdge and Calder 2005]. ALA is primarily found in plant-based sources, including flaxseeds, chia seeds, walnuts, and canola oil [Lane *et al.* 2014]. The importance of ALA in human nutrition has been recognized for decades, particularly due to its role in reducing the risk of chronic diseases such as cardiovascular disease, type 2 diabetes, and certain cancers [Simopoulos 2002]. However, the metabolic conversion of ALA to EPA and DHA is limited in humans, leading to questions about the sufficiency of ALA as a sole source of omega-3 fatty acids [Plourde and Cunnane 2007, Szpicer *et al.* 2019].

Eicosapentaenoic Acid (EPA) – is a 20-carbon omega-3 fatty acid with five double bonds, which are located at the 5th, 8th, 11th, 14th, and 17th carbon atoms, making EPA a highly unsaturated fatty acid with significant fluidity in cell membranes [Calder 2017]. EPA is classified as an omega-3 fatty acid due to the position of its first double bond, which is located at the third carbon from the methyl end of the molecule. EPA is metabolized in the body to produce eicosanoids, which are signaling molecules that influence various physiological processes, including inflammation, immunity, and blood clotting [Calder 2017]. The eicosanoids derived from EPA, such as prostaglandins and thromboxanes, generally have anti-inflammatory and vasodilatory effects, contrasting with the pro-inflammatory eicosanoids derived from omega-6 fatty acids like arachidonic acid [Simopoulos 2002]. Along with docosahexaenoic acid (DHA), EPA is a critical component of omega-3 fatty acid supplementation strategies, particularly in Western diets that are often deficient in these nutrients [Kris-Etherton *et al*. 2002]. The significance of EPA in human health extends beyond its structural role in cell membranes. It serves as a precursor to bioactive lipid mediators such as resolvins and protectins, which play essential roles in resolving inflammation [Serhan *et al.* 2008]. EPA is primarily found in marine sources such as fish, krill, and algae.

Docosahexaenoic Acid (DHA) – is a 22-carbon omega-3 fatty acid with six double bonds, located at the 4th, 7th, 10th, 13th, 16th, and 19th carbon atoms, which contributes to DHA's high degree of unsaturation and flexibility [Innis 2007]. This structural flexibility is critical for the function of cell membranes in the brain and retina, where DHA accounts for up to 40% of the total fatty acids [Lauritzen *et al.* 2016]. As a major structural component of the brain and retina, DHA is critical for cognitive function and visual acuity. DHA is essential for maintaining neuronal structure and function, supporting cognitive health, and protecting against neurodegenerative diseases [Bazinet and Layé 2014]. While DHA can be synthesized in small amounts from its precursor, alpha-linolenic acid (ALA), this conversion is inefficient, making dietary intake crucial to meet the body's needs [Brenna *et al.* 2009].

DHA is primarily obtained from marine sources such as fish, shellfish, and algae. Due to its importance in early development and throughout life, DHA is a focus of research in nutrition and public health. DHA also plays a role in the production of neuroprotective and anti-inflammatory molecules, such as neuroprotectin D1 (NPD1), which helps protect neurons from oxidative stress and apoptosis [Bazinet and Layé 2014].

Dietary sources of omega-3 fatty acids

Omega-3 fatty acids are found in various dietary sources. Alpha-linolenic acid (ALA) – the primary sources of that fatty acid are plant-based, with flaxseed oil being one of the richest sources, containing approximately 50-60% ALA by weight. Other significant sources include chia seeds, walnuts, hemp seeds, and canola oil [Lane *et al.* 2014]. Leafy green vegetables and soybeans also contribute to dietary ALA intake, although in smaller amounts. Given the plant-based nature of ALA, it is a key component of vegetarian and vegan diets, where direct sources of EPA and DHA (found in fish and seafood) are limited. Fortification of foods with ALA, such as margarine and certain bread products, has also been explored as a strategy to enhance omega-3 intake in the general population [Lane *et al.* 2014].

Eicosapentaenoic Acid (EPA) – the primary dietary sources of this fatty acid are marine-based, with oily fish such as salmon, mackerel, sardines, and herring being particularly rich in this fatty acid. Fish oil supplements are also a concentrated source of EPA and are commonly used to enhance omega-3 intake in populations with low fish consumption [Kris-Etherton *et al.* 2002]. Additionally, krill oil and certain types of algae provide EPA, offering alternatives for individuals who prefer non-fish-based sources. The content of EPA in these sources varies depending on factors such as species, diet, and environment. For example, wild-caught fish typically contain higher levels of EPA compared to farmed fish, which may have diets lower in omega-3s [Givens and Gibbs 2008]. For vegetarians and vegans, algal oil supplements are an important source of EPA, as they provide a direct form of this fatty acid without the need for marine animal consumption.

Docosahexaenoic Acid (DHA) – similarly to EPA, is predominantly found in marine sources, with fatty fish such as salmon, mackerel, sardines, and herring. Other sources include fish oil supplements, krill oil, and algae-based supplements [Brenna *et al.* 2009]. Algal oil is particularly important for vegetarians and vegans, as it provides a non-fish-derived source of DHA. The content of DHA in fish and seafood varies depending on species, habitat, and diet. Wild-caught fish generally contain higher levels of DHA compared to farmed fish, as their diet in the wild includes DHA-rich microalgae and smaller fish [Givens and Gibbs 2008].

In addition to natural sources, many foods are fortified with omega-3 fatty acids, typically EPA and DHA derived from fish oil or algal oil, particularly in populations with low fish consumption [Koletzko *et al.* 2008]. These foods include for example omega-3 enriched eggs, fortified dairy products such as milk, yogurt, and cheese, fortified bread and cereals or infant formulas.

Health benefits of omega-3 fatty acids

One of the most well-established benefits of ALA is its positive effect on cardiovascular health (CVD), including heart attacks and strokes [Calder 2018]. ALA's cardioprotective effects are attributed to its ability to reduce inflammation, lower blood pressure, improve endothelial function, and modulate lipid profiles by reducing total cholesterol, low-density lipoprotein (LDL) cholesterol, and triglycerides [Simopoulos 2002]. Additionally, ALA may offer neuroprotective benefits in older adults by reducing the risk of cognitive decline and neurodegenerative diseases such as Alzheimer's disease [Simopoulos 2002]. Emerging research indicates that ALA may play a role in reducing the risk of type 2 diabetes and metabolic syndrome. ALA has been shown to improve insulin sensitivity, reduce inflammation, and modulate adipose tissue function, thereby contributing to better glucose regulation and metabolic health [Plourde and Cunnane 2007]. Several studies have explored the potential role of ALA in cancer prevention, including breast, prostate, and colorectal cancer [Simopoulos 2002].

EPA has been extensively studied also for its cardiovascular benefits. Higher intake of EPA has been associated with reduced risk of coronary heart disease (CHD) and other cardiovascular events. EPA exerts its cardioprotective effects through multiple mechanisms, including reducing triglyceride levels, lowering blood pressure, improving endothelial function, and preventing blood clot formation [Mozaffarian and Wu 2011]. Additionally, EPA has been shown to stabilize atherosclerotic plaques, reducing the risk of plaque rupture and subsequent cardiovascular events [Yokoyama *et al.* 2007]. EPA's role in reducing inflammation is well-documented, with its anti-inflammatory effects being mediated through the production of eicosanoids and specialized pro-resolving mediators (SPMs) such as resolvins [Serhan *et al.* 2008]. These lipid mediators are crucial in preventing chronic inflammatory diseases such as rheumatoid arthritis, inflammatory bowel disease, and asthma [Calder 2017] and neurodegenerative diseases such as Alzheimer's disease and Parkinson's disease by reducing neuroinflammation and oxidative stress [Freeman *et al.* 2006]. EPA can also help reduce the severity and progression of autoimmune conditions, including multiple sclerosis and lupus [Simopoulos 2002]. EPA also contributes to neurological function, particularly in the context of mood regulation and neuroinflammation [Freeman *et al.* 2006]. EPA has been shown to improve symptoms of depression [Sublette *et al.* 2011]. Moreover, EPA's anti-inflammatory effects has beneficial effects on metabolic health, particularly in the management of hypertriglyceridemia and insulin resistance [Calder 2017]. By reducing triglyceride levels and improving lipid profiles, EPA can help mitigate the risk of metabolic syndrome and type 2 diabetes [Mozaffarian and Wu 2011].

In turn, DHA is critical for brain development, particularly during the prenatal and early postnatal periods, where it supports the growth of neuronal cells, the formation of synapses, and the development of cognitive functions [Innis 2007]. Adequate DHA intake during pregnancy is associated with improved neurodevelopmental outcomes in infants, including better cognitive function, visual acuity, and motor skills [Koletzko *et al.* 2008].

In adults, DHA continues to play a vital role in maintaining cognitive function and protecting against age-related cognitive decline, as well as a reduced risk of neurodegenerative diseases such as Alzheimer's disease [Yurko-Mauro *et al.* 2010]. DHA has well-documented cardiovascular benefits, including the reduction of triglyceride levels, improvement in blood vessel function, and reduction of blood pressure [Mozaffarian and Wu 2011] and also improves lipid profiles, and stabilize atherosclerotic plaques [Maki *et al.* 2009].

Moreover, DHA plays a key role in reducing heart rate variability and arrhythmias, which are risk factors for sudden cardiac death [Mozaffarian and Wu 2011]. Its anti-inflammatory properties also contribute to the prevention of atherosclerosis, which can lead to heart attacks and strokes [Schuchardt *et al.* 2014]. DHA is a crucial component of the retina, where it supports visual function and protects against age-related macular degeneration (AMD), a leading cause of blindness in older adults [SanGiovanni and Chew 2005]. DHA exerts significant anti-inflammatory effects through the production of specialized pro-resolving mediators (SPMs), including resolvins and protectins, which promote the resolution of inflammation [Calder 2017, Djuricic and Calder 2021]. These mediators support the resolution of chronic inflammation, which is implicated in the development of various chronic diseases, including cardiovascular disease, cancer, and autoimmune disorders [Bazinet and Layé 2014]. DHA's immune-modulating effects are also beneficial in conditions such as asthma, inflammatory bowel disease, and rheumatoid arthritis, where chronic inflammation plays a key role in disease progression [Calder 2017].

Impact on Animal Health

Omega-3 fatty acids have significant benefits for animal health. They support immune function, reduce inflammation, and improve cardiovascular health in animals [Bauer 2011]. In pets like dogs and cats, omega-3s can enhance skin and coat quality, reducing dryness and shedding [Lenox and Bauer 2013]. Additionally, these fatty acids promote joint health, especially in aging animals, and are also linked to better cognitive function [Watson 2009, Stelmasiak *et al.* 2018].

The growing number of research on omega-3 fatty acids has expanded significantly over the past few decades, reflecting increased scientific and public interest in their health-promoting properties. This research spans a wide range of fields, including nutrition, medicine, biochemistry, and public health. This study aims to perform a comprehensive bibliometric analysis of omega-3 fatty acid research, utilizing the Web of Science Core Collection database and VOSviewer software to visualize key trends and influential contributors. This study provides a better understanding of the current state of research on omega-3 fatty acids and highlights future directions for exploration.

Material and methods

The online Web of Science (WoS) Core Collection database was queried on 7 May 2024 with the following search string: TS = ("omega-3 fatty acid*" OR "omega-3 polyunsaturated fatty acid*" OR "ω−3 fatty acid*" OR "ω−3 polyunsaturated fatty acid*" OR "n−3 fatty acid*" OR "n−3 polyunsaturated fatty acid*" OR "omega−3 oil*"). This search string identified publications mentioning omega-3 fatty acid or its word variants in titles, abstracts, or keywords. The query returned 35,575 papers. The search did not set limitations to other publishing aspects such as publication year, document type or language. The basic publication and citation data were exported directly from the WoS platform, whereas the full records of the 35,575 papers were exported to VOSviewer [van Eck and Waltman 2009] for further bibliometric analyses. VOSviewer was the software used to generate a term map that visualized terms appearing in >1% (n = 356) of the titles and abstracts of the 35,575 papers and showed their publication count and citations per paper (CPP). A similar term map was generated to visualize author keywords that appeared in >0.1% (n = 36) of the papers. Except for these customized thresholds, default settings from VOSviewer were applied.

Results

The analyzed literature set contained 35,575 papers, which has demonstrated a literature body that experienced steady growth since the 2000s (Fig. 1). Most of the papers were classified as original articles by WoS (n = 26,381, 74.2%) and the rest were mainly reviews (n = 4861, 13.7%). The original article-to-review ratio was 5.4:1. The top 5 most productive authors, affiliations, countries, journals, and journal categories are listed in Table 1.

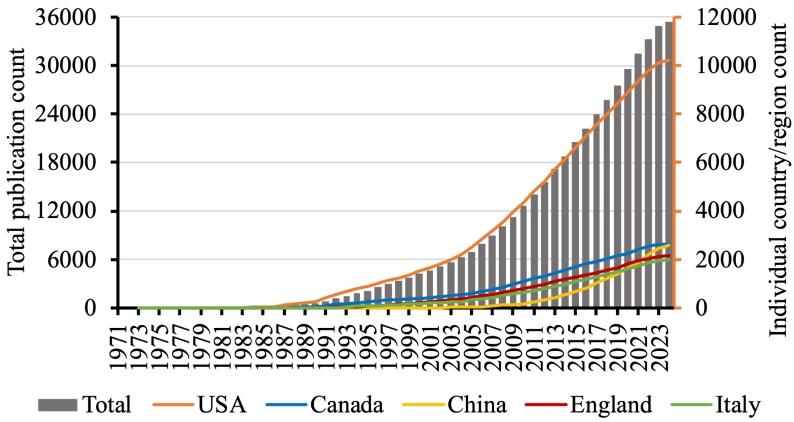

Fig. 1. Cumulative publication counts for the overall literature and the top 5 most productive countries/regions.

Table 1. The top-five most productive authors, affiliations, countries/regions, journals, and journal categories

Entity	Number of papers (% of 35,575)	Citations per paper (CPP)
Author		
Philip C Calder	347 (1.0)	89.5
William Stephen Harris	288 (0.8)	68.2
Erik Berg Schmidt	182 (0.5)	30.5
Jingxuan Kang	160 (0.5)	68.3
Robert K McNamara	126 (0.4)	22.6
Affiliation		
Harvard University	1310 (3.7)	74.6
University of California system	819 (2.3)	53.1
French National Institute of Health and Medical Research (INSERM)	688 (1.9)	40.1
French National Research Institute for Agriculture, Food and Environment (INRAE)	578 (1.6)	42.0
United States National Institute of Health (NIH)	504 (1.4)	70.0
Country/region		
United States	10,260 (28.8)	45.0
Canada	2652 (7.5)	39.8
China	2598 (7.3)	20.5
England	2182 (6.1)	54.4
Italy	1990 (5.6)	40.1
Journal		
Nutrients	797 (2.2)	25.0
Prostaglandins Leukotrienes and Essential Fatty Acids	661 (1.9)	33.2
American Journal of Clinical Nutrition	579 (1.6)	102.0
Lipids	538 (1.5)	42.4
FASEB Journal	478 (1.3)	8.3
Journal category		
Nutrition Dietetics	8187 (23.0)	38.9
Biochemistry Molecular Biology	5006 (14.1)	35.2
Food Science Technology	3974 (11.2)	26.8
Endocrinology Metabolism	2314 (6.5)	31.6
Cell Biology	1993 (5.6)	29.2

The most productive author was Professor Philip C Calder (n = 347, CPP = 89.5) from University of Southampton. The United States (n = 10,260, CPP = 45.0) had contributions to nearly 30% of the papers, with Harvard University being the leading affiliation (n = 1310, CPP = 74.6). Among the top 5 most productive countries, China was a relatively newcomer that began to publish in 1990 and might overtake Canada as the 2nd most productive country in the near future (Fig. 1). Nutrients was the most productive journal (n = 797, CPP = 25.0) but American Journal of Clinical Nutrition had the highest CPP among the top 5 (n = 579, CPP = 102.0). Overall, Nutrition & Dietetics was the most productive journal category and had the highest CPP among the top 5 (n = 8187, CPP = 38.9).

Figure 2 shows a term map that visualized the recurring terms in the titles and abstracts of the papers. Fish is a common source of omega-3 fatty acids, with fish oil (n = 5135, CPP = 42.7) and fish (n = 3689, CPP = 45.0) being 2 recurring terms. Upon closer examination of the data, other common food sources mentioned included olive oil (n = 690, CPP = 47.8), corn oil (n = 634, CPP = 40.2), soybean oil (n = 576, CPP = 27.3), flaxseed (n = 500, CPP = 33.5), microalgae (n = 471, CPP = 38.2), linseed oil

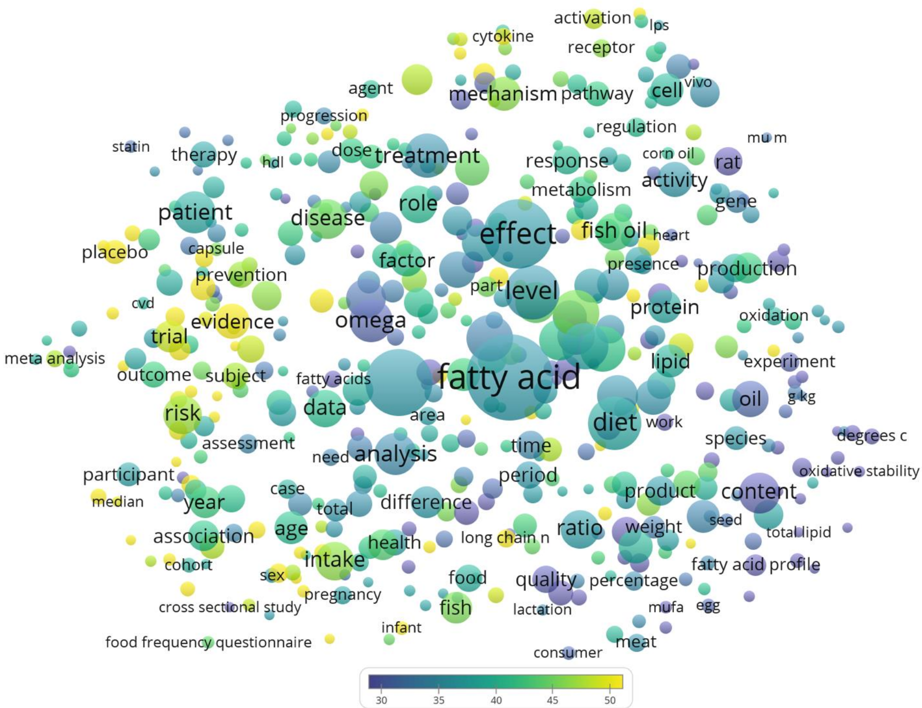

Fig. 2. A term map that visualizes the recurring terms in the titles and abstracts of the omega-3 fatty acids papers. The node color indicates the citations per paper (CPP) of the terms, the node size indicates the number of papers, and the inter-node distance indicates the frequency of co-occurrence of the terms in the same papers.

Table 2. Recurring medical conditions identified from the titles and abstracts of the omega-3 fatty acids papers

Medical conditions	Number of papers (% of 35,575)	Citations per paper (CPP)
Inflammation	3464 (9.7)	47.1
Cardiovascular disease	2208 (6.2)	53.8
Cancer	2057 (5.8)	49.8
Obesity	1418 (4.0)	42.8
Depression	1089 (3.1)	48.6
Diabetes	996 (2.8)	42.7
Insulin resistance	822 (2.3)	47.8
Atherosclerosis	770 (2.2)	42.0
Hypertension	664 (1.9)	48.0
Coronary heart disease	632 (1.8)	72.7
Myocardial infarction	622 (1.7)	74.8
Alzheimer (Alzheimer's disease)	563 (1.6)	55.5
Stroke	512 (1.4)	72.1
Hypertriglyceridemia	509 (1.4)	32.3

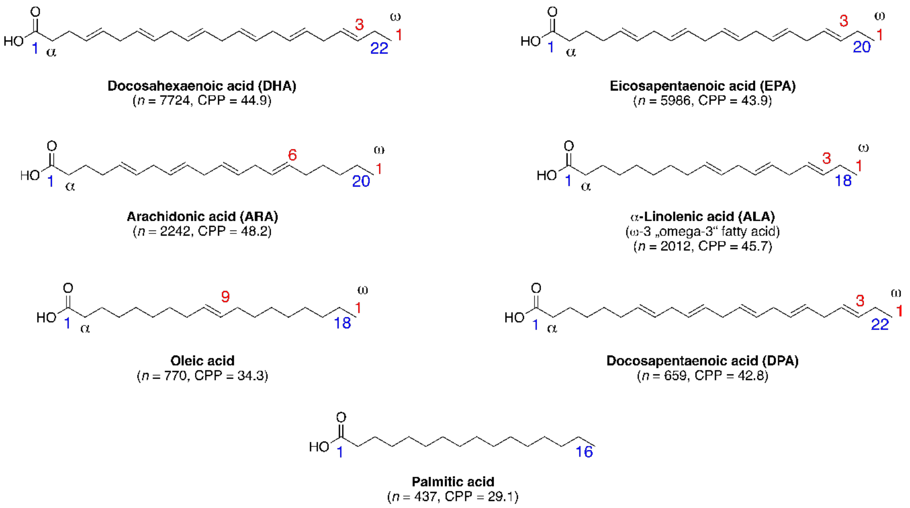

Fig. 3. Chemical structures of frequently mentioned acids. In brackets are indicated the number of papers (n) in which the respective acid was cited and the citations per paper (CPP).

(n = 440, CPP = 28.1), vegetable oil (n = 440, CPP = 52.0), and seafood (n = 431, CPP = 58.1). Recurring medical conditions identified from the titles and abstracts are listed in Table 2. Nearly 10% of the papers mentioned inflammation (n = 3464, CPP = 47.1), with cardiovascular disease (n = 2208, CPP = 53.8), cancer (n = 2057, CPP = 49.8), obesity (n = 1418, CPP = 42.8), depression (n = 1089, CPP = 48.6), and diabetes (n = 996, CPP = 42.7) being the mostly mentioned diseases. Recurring acids mentioned in the titles and abstracts were docosahexaenoic acid (DHA, n = 7724, CPP = 44.9), eicosapentaenoic acid (EPA, n = 5986, CPP = 43.9), arachidonic acid (n = 2242, CPP = 48.2), alpha-linolenic acid (ALA, n = 2012, CPP = 45.7), linolenic acid (n = 1438, CPP = 43.9), oleic acid (n = 770, CPP = 34.3), docosapentaenoic acid (n = 659, CPP = 42.8), and palmitic acid (n = 437, CPP = 29.1) (Fig. 3).

Figure 4 visualizes the recurring author keywords. Ten most recurring keywords (excluding omega-3 fatty acids and its word derivatives) included docosahexaenoic acid (n = 2283, CPP = 48.7), fish oil (n = 2130, CPP = 42.3), eicosapentaenoic acid (n = 1638, CPP = 46.1), inflammation (n = 1472, CPP = 44.3), polyunsaturated fatty acids (n = 1196, CPP = 38.4), diet (n = 964, CPP = 45.5), nutrition (n = 951, CPP = 39.0), oxidative stress (n = 662, CPP = 26.8), obesity (n = 579, CPP = 33.4), and alpha-linolenic acid (n = 570, CPP = 53.4).

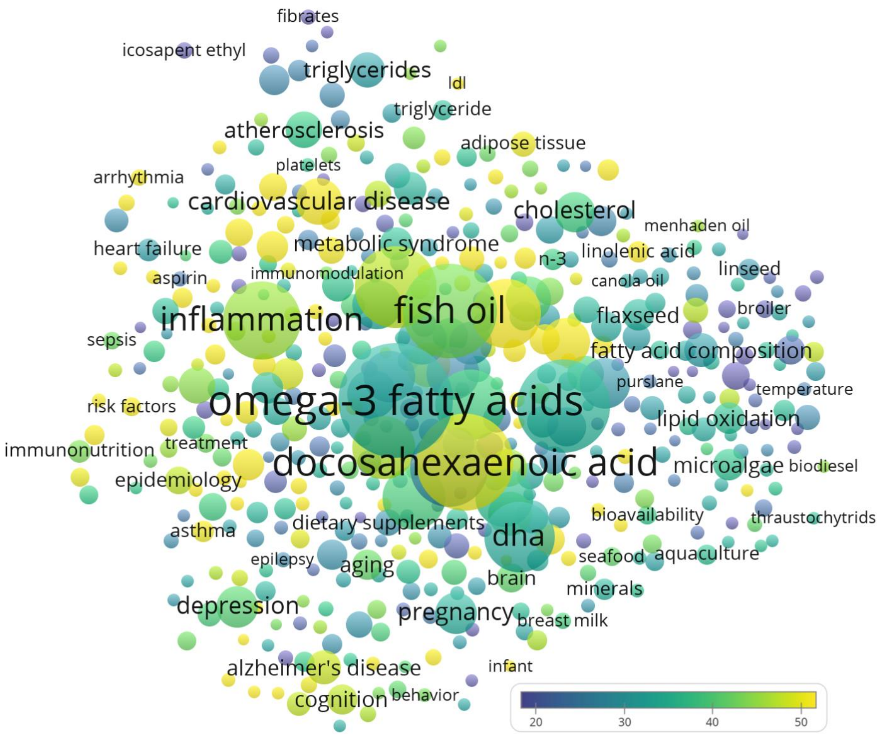

Fig. 4. Term map of recurring author keywords of the papers. The node color indicates the citations per paper (CPP) of the terms, whereas the node size indicates the number of papers, and the inter-node distance indicates how frequently the terms co-occurred with each other in the same papers.

Discussion

Omega-3 fatty acids, particularly alpha-linolenic acid (ALA), eicosapentaenoic acid (EPA), and docosahexaenoic acid (DHA), have been extensively studied for their wide-ranging health benefits. The existing literature underscores their essential role in promoting cardiovascular health, supporting neurological and cognitive function, enhancing immune response, and even improving animal health and productivity. The mechanisms by which these fatty acids exert their effects, alongside their dietary sources and required intake levels, are key areas of ongoing research.

Analyzed data

The substantial part of literature on omega-3 fatty acids, represented by the analysis of 35,575 publications (Fig. 1), underscores the growing global interest in their health-promoting properties, particularly their potential therapeutic roles in managing chronic conditions such as cardiovascular diseases, inflammatory disorders, obesity, and mental health pathologies [Mozaffarian and Wu 2011, Calder 2020]. The increase in publications since the 2000s may also reflect broader shifts in dietary trends and public health priorities, particularly as the global burden of lifestyle-related diseases continues to rise [Rimm *et al.* 2018a].Most of the papers (n = 26,381, 74.2%) were classified as original research articles, with the remainder mainly comprising review papers (n = 4861, 13.7%). The original article-to-review ratio of 5.4:1 highlights the active generation of new empirical data in the field, which is vital for expanding knowledge about omega-3 fatty acids' mechanisms and health impacts. The relatively lower percentage of reviews indicates that, while there is a wealth of original research, there may be a need for more synthesis and integration of these findings. Given the rapidly expanding nature of omega-3 research, more comprehensive reviews could help synthesize current knowledge and provide clearer guidance on topics such as optimal intake levels, therapeutic uses, and implications for public health [Simopoulos 2016a].

Leading Authors and Institutions

The analysis of the top contributors to the omega-3 fatty acid research literature, provides key insights into the leading figures, institutions, countries, journals, and categories driving scientific inquiry in this field (Tab. 1). The authors who have dedicated the most articles to omega-3 fatty acids are: Philip C Calder, William Stephen Harris, Erik Berg Schmidt, Jingxuan Kang and Robert K McNamara. The identification of the most productive author, Professor Philip C. Calder from the University of Southampton, highlights the central role played by individual researchers who have significantly shaped our understanding of omega-3 fatty acids and their health benefits. Professor Calder's contribution of 347 papers and his high citation per publication (CPP) of 89.5 reflect his influence in advancing knowledge, particularly in the areas of omega-3s' impact on inflammation, immune function, and cardiovascular health [Calder 2020].

At the institutional level, Harvard University leads in omega-3 research with 1310 papers and a citation per paper (CPP) of 74.6, followed by the University of California (819 papers, 53.1 CPP) and the French National Institute of Health and Medical Research (688 papers, 40.1 CPP), respectively. Harvard's prominence in omega-3 research aligns with its reputation as a leader in public health and biomedical research. Harvard's significant output and high CPP highlight its role in producing influential research on essential nutrients like omega-3s. These all listed institutions emphasize health prevention through evidence-based nutrition, addressing global health challenges like cardiovascular disease and obesity [Rimm *et al.* 2018a].

Geographically, the United States leads in omega-3 research with 10,260 papers, accounting for nearly 30% of global contributions, and a CPP of 45.0. The next two countries are Canada and China, whose articles account for only 7% of the global contribution in this field. The United States' dominance in the field is driven by substantial funding, robust academic infrastructure, and a strong focus on evidence-based dietary guidelines aimed at improving population health outcomes. However, it is worth noting that China, which began publishing research on omega-3 fatty acids in 1990, is rapidly gaining ground. The country's growing research output suggests that it may soon surpass Canada as the second most productive country. China's increasing investment in research and development, coupled with its focus on improving public health, likely contributes to this trend.

Journals and Categories

The analysis of journal contributions further underscores the breadth and depth of omega-3 research. Nutrients, the most productive journal with 797 publications and a CPP of 25.0, reflects the growing focus on nutrition research in open-access formats, which increases accessibility and dissemination of findings across a broad audience. While Nutrients publishes a high volume of papers, the American Journal of Clinical Nutrition (AJCN) stands out for its higher impact, with 579 papers and the highest CPP among the top five journals at 102.0. AJCN's influence suggests that it publishes highly cited, high-quality research, cementing its position as a leading journal in the field of clinical nutrition.

In terms of journal categories, Nutrition & Dietetics was the most productive category, contributing 8,187 papers with a CPP of 38.9. This reflects the central role of nutrition science in understanding the health impacts of omega-3 fatty acids [Calder 2013]. The high productivity and CPP in this category indicate a strong alignment between dietary research and public health outcomes, reinforcing the importance of omega-3s as a focus for dietary guidelines and therapeutic interventions [Kris-Etherton and Innis 2007].

Key Food Sources

The term map presented in Figure 2 provides valuable insight into the recurring themes in the literature on omega-3 fatty acids, highlighting the importance of specific food sources as well as the focus on health-related applications. The visualization of frequently mentioned terms in the titles and abstracts of the analyzed papers reinforces the central role of fish and fish oil as primary sources of omega-3 fatty acids.

Fish oil (n = 5135, CPP = 42.7) and fish (n = 3689, CPP = 45.0) lead in omega-3 research due to their high levels of EPA and DHA. Fish oil is typically derived from fatty fish such as salmon, mackerel, sardines, and anchovies. Mackerel is one of the richest sources, with 4580 mg of omega-3s per 100g, along with vitamin B12 and selenium. Salmon, especially the wild varieties (2260 mg omega-3s/100g) is also popular, providing additionally ample vitamin D [Kris-Etherton *et al.* 2002]. Herring (2366 mg omega-3s/100g), anchovies (2113 mg omega-3s/100g and also providing iron and calcium), farmed rainbow trout (2026 mg omega-3s/100g), and sardines (1480 mg omega-3s/100g also a good source of calcium, especially when eaten with the bones) are other nutrient-dense fish that are excellent omega-3 sources [Mozaffarian and Rimm 2006, Gogus and Smith 2010].

Studies on plant-based omega-3 sources like olive oil (n = 690, CPP = 47.8), corn oil (n = 634, CPP = 40.2), and soybean oil (n = 576, CPP = 27.3) highlight a growing interest in alternative sources of essential fatty acids. These oils are rich in alpha-linolenic acid (ALA), a shorter-chain omega-3 that can convert to EPA and DHA, though with limited efficiency [Jump 2011].

Olive oil, while beneficial in the Mediterranean diet due to its monounsaturated fats (particularly oleic acid), contains minimal ALA (0.5-1%). Instead, olive oil is primarily rich in monounsaturated fats, particularly oleic acid (omega-9 fatty acid) [Pérez-Jiménez and Ruano 2006]. Corn oil is primarily omega-6, with linolenic acid composing 50–60% of its content and only trace ALA (typically less than 1%), which can contribute to an inflammatory profile when omega-6 is high relative to omega-3 [Harris and Mozaffarian 2010]. In turn, soybean oil contains 7-8% ALA and is common in processed foods, cooking oils, and margarine due to its high smoke point and neutral flavor. It is also found in salad dressings, and baked goods. However, its omega-6 to omega-3 ratio (7:1) may influence health outcomes if consumed excessively.

Flaxseed (n = 500, CPP = 33.5) and linseed oil (n = 440, CPP = 28.1) come from the seeds of *Linum usitatissimum* and stand out as key plant-based omega-3 sources, especially for their high content of alpha-linolenic acid (ALA). Flaxseed, widely used as a dietary supplement and functional food ingredient, supports digestive health and lowers cholesterol due to its soluble and insoluble fiber content. Linseed oil, extracted from flaxseeds, offers a concentrated source of omega-3 ALA but lacks fiber and lignans removed during extraction. Rich in ALA, linseed oil promotes heart health by reducing inflammation, supporting cholesterol balance, and improving heart function. Linseed oil's fatty acid composition includes 40-60% ALA, 12-17% linolenic acid, 13-19% oleic acid, 5-8% palmitic acid, and 2-4.5% stearic acid, with polyunsaturated fatty acids (PUFA) making up about 73% of the oil's lipids [Walkowiak *et al.* 2022]. The oil's favorable n-6:n-3 ratio of 0.3:1 also makes it a key choice for vegetarian and vegan diets where marine sources of EPA and DHA are limited [Simopoulos 2016b].

The notable appearance of microalgae (n = 471, CPP = 38.2) in the term map highlights its role as a sustainable source of omega-3 fatty acids, particularly EPA and DHA. As the original producers of these omega-3s in the marine food chain, microalgae offer the same health benefits as fish-derived sources, making them ideal for plant-based or vegan diets [Rymer *et al.* 2010]. Compared to fish oil, microalgae farming has a lower environmental impact, avoiding issues like fish stock depletion and bycatch (the unintentional capture of non-target species during fishing) [Gordon *et al.* 2021]. Cultivated in controlled environments, microalgae oil is also free from contaminants such as heavy metals, dioxins, and PCBs.

Available in liquid or capsule form, microalgae oil serves as a vegan alternative to fish oil and is being explored for uses in dairy substitutes, snack bars, and baby formulas. Additionally, microalgae-derived omega-3s are used in aquaculture to improve the nutritional quality of farmed fish, reducing the need for wild fish in their diets.

Vegetable oil (n = 440, CPP = 52.0) and seafood (n = 431, CPP = 58.1) highlight the diversity of omega-3 sources. The general term vegetable oil covers several types of oils that are rich sources of omega-3 acids. These include primarily linseed oil, canola oil, and soybean oil, which were discussed earlier. However, it is impossible not to mention perilla oil or hemp seed oil, which are less commonly used but are also rich in omega-3 acids.

Perilla oil (Perilla frutescens (L.) var. frutescens), though less common, contains 50-60% omega-3 and has a favorable omega-6 to omega-3 ratio of about 1:6, which is considered optimal for reducing inflammation [Kim *et al.* 2019]. Popular in Korean and Japanese cuisine, perilla oil has a mild, nutty flavor and is used in salad dressings or as a finishing oil. Due to its delicate fatty acids, it is unsuitable for high-heat cooking. In skincare, perilla oil aids in hydration and reducing inflammation [Lempert 2021].

In turn, hemp seed oil contains about 15-25% ALA with an omega-6 to omega-3 ratio of about 3:1, and is ideal for dietary balance [Callaway 2004]. Rich in antioxidants like vitamin E, it supports skin health and is commonly used in skincare for hydration and treating dryness. Hemp seed oil has a nutty flavor and is best for raw or lightly cooked dishes, such as salads and smoothies, to preserve its delicate fatty acids.

Seafood's high CPP (58.1) underscores its association with omega-3 benefits, especially for heart and brain health, with a focus on shellfish like oysters, mussels, and clams. Oysters, with 329 mg of omega-3s per serving, are rich in zinc and support heart health, reducing inflammation, and benefiting cognitive function. Mussels offer 500-600 mg of omega-3s per 3-ounce serving and are also rich in vitamin B12, iron, and selenium, making them a nutritious and sustainable seafood choice packed with health benefits. Clams provide 200-300 mg of omega-3s per serving, supporting cardiovascular and brain health and delivering protein, iron, and vitamin B12 [Kris-Etherton *et al.* 2009].

Health Conditions

The analysis of recurring medical conditions in omega-3 research shows significant health benefits (Tab. 2). With nearly 10% of studies mentioning inflammation (n = 3464, CPP = 47.1), omega-3s play a key role in modulating inflammatory responses [Calder, 2020]. Omega-3s reduce inflammation through several mechanisms: EPA competes with omega-6s to produce anti-inflammatory eicosanoids; EPA and DHA are converted into anti-inflammatory resolvins and protectins; they regulate cytokine production to prevent chronic inflammation, and also they influence gene expression to reduce pro-inflammatory protein production. This means they help "turn off" genes that produce pro-inflammatory proteins and "turn on" genes that help reduce inflammation.

Cardiovascular disease (n = 2208, CPP = 53.8) is a major focus in omega-3 research due to strong evidence of its cardioprotective effects. Omega-3s, particularly EPA and DHA, help lower risk factors for heart disease and stroke by reducing triglycerides by 15-30%, increasing HDL (good cholesterol), and lowering blood pressure by 2-5 mmHg [Mozaffarian and Wu 2011]. Omega-3s also stabilize heart rhythms, reduce blood clot formation, and slow atherosclerosis by reducing arterial inflammation. Omega-3s help reduce blood clot formation by making platelets in the blood less sticky. This effect helps prevent heart attacks and strokes. These benefits are reflected in dietary guidelines, such as those from the American Heart Association, which advocate for omega-3s in cardiovascular health.

Cancer (n = 2057, CPP = 49.8) is another frequently studied condition in relation to omega-3 fatty acids, with studies investigating their anti-tumor potential, particularly in reducing inflammation, modulating cell proliferation, and inducing apoptosis [Patterson *et al.* 2012]. Omega-3s, especially EPA, help lower pro-inflammatory molecules like cytokines and eicosanoids that can fuel tumor growth. They may also inhibit cancer progression by promoting apoptosis and preventing angiogenesis (the formation of new blood vessels tumors need to grow). Additionally, omega-3s may improve the effectiveness of cancer treatments like chemotherapy and radiation.

The significant presence of obesity in the literature (n = 1418, CPP = 42.8) highlights growing concerns about metabolic diseases and dietary roles in managing obesity. Omega-3 fatty acids have been shown to impact lipid metabolism, improve insulin sensitivity, and reduce inflammation-key factors in obesity, metabolic syndrome, and type 2 diabetes [Jump 2011]. While not a standalone solution, including omega-3s in a balanced diet may support metabolic health and weight management.

The frequent mention of depression in the literature (n = 1089, CPP = 48.6) reflects growing evidence linking omega-3 fatty acids, especially DHA, to brain health and mood regulation. Omega-3s, essential for neuronal membranes, play roles in neurotransmission and neuroinflammation. These essential fats are believed to aid brain function by modulating neurotransmitters like serotonin and dopamine, which are linked to mood regulation [Sublette *et al.* 2011]. Studies suggest that omega-3 supplementation may reduce depressive symptoms, especially alongside standard treatments [Grosso *et al.* 2014, Appleton *et al.* 2021]. Additionally, omega-3s help reduce inflammation in the brain, a factor that some studies associate with depression [Hibbeln 2009]. Research indicates that individuals with depression often show lower omega-3 levels, and supplementation, especially with higher EPA ratios, may help alleviate symptoms [Carlezon *et al.* 2005, Mischoulon and Freeman 2013]. Rich dietary sources like fatty fish may support mental well-being, with omega-3s offering potential benefits as part of a holistic approach to managing depression [Appleton *et al.* 2021].

Diabetes (n = 996, CPP = 42.7) is often discussed in omega-3 research for its potential to improve insulin sensitivity and reduce inflammation, key factors in managing type 1 and type 2 diabetes [Bhan and Arora 2021]. While effects on glycemic control remain debated, omega-3s offer broader cardiovascular benefits, making them valuable in diabetic dietary management [Rimm *et al.* 2018b]. Omega-3s may enhance insulin sensitivity and support better glycemic control, with potential reductions in insulin resistance [Esmaillzadeh and Mirmiran 2021]. Given the elevated cardiovascular risks in diabetes [Hooper and Sweeney 2020], omega-3s' benefits on triglycerides, blood pressure, and inflammation make them supportive for metabolic health [Brenner and Aasly 2020, Kwak and O'Connor 2020].

Focus on Specific Fatty Acids

The data highlights eight fatty acids that were most frequently mentioned in the titles and abstracts of scientific publications (Fig. 3).

Docosahexaenoic acid (DHA) is the most frequently cited omega-3, with 7,724 mentions and a Citations per Paper (CPP) of 44.9. Known for its vital role in brain development and retinal function [Tou *et al.* 2011], DHA is essential for cognitive function and visual health, especially in infants and children [Calder and Yaqoob 2009, Lauritzen *et al.* 2016]. Research also links DHA to a reduced risk of age-related macular degeneration [Shirai *et al.* 2006a]. Eicosapentaenoic acid (EPA), with 5,986 mentions and a CPP of 43.9, plays a key role in inflammation regulation, blood clotting, and immune response [Jump *et al.* 2012, Calvo *et al.* 2017]. Beneficial for cardiovascular health, EPA helps lower triglycerides, reduce blood pressure, and decrease heart disease risk [Lee and Jeong 2010].It also supports brain health, potentially aiding conditions like depression and cognitive decline [Shirai *et al.* 2006b, Calder 2015, Ghanbari *et al.* 2018].

Arachidonic acid (n = 2,242, CPP = 48.2), an omega-6 fatty acid, is frequently cited for its role in immune regulation and inflammation [Simopoulos 2008]. It serves as a precursor for both pro- and anti-inflammatory eicosanoids (prostaglandins, thromboxanes, and leukotrienes), which are key to immune function and conditions involving inflammation [Serhan 2014]. Found in cell membrane phospholipids, arachidonic acid contributes to brain health, supporting neuronal structure, neurotransmission, cognitive functions, and mood modulation [Meyer *et al.* 2018].

Oleic acid (n = 770, CPP = 34.3), a monounsaturated fat abundant in olive oil, was less frequently cited but is notable for its cardiovascular benefits, including cholesterol reduction and heart disease risk reduction, central to the Mediterranean diet [Schwingshackl and Hoffmann 2014].

Docosapentaenoic acid (DPA) (n = 659, CPP = 42.8), an omega-3 found in fish oil and algae, also supports cardiovascular health [Kaur *et al.* 2011]. It can also be synthesized in the body from EPA.

Palmitic acid (n = 437, CPP = 29.1), a saturated fat common in animal and plant fats, is associated with metabolic disorders and plays a role in energy metabolism and cell membrane structure [Poirier *et al.* 2009]. It can be synthesized by the body from carbohydrates.

Keyword Analysis and Emerging Themes

Figure 4 highlights the most frequently recurring author keywords in the literature, excluding terms directly related to omega-3 fatty acids and their derivatives. The most prominent keyword was "docosahexaenoic acid" (DHA), mentioned 2,283 times with a Citations per Paper (CPP) value of 48.7. DHA's recurring presence is well justified by its critical role in brain development, cognitive function, and cardiovascular health, which has been extensively documented in studies [Innis 2007, Swanson *et al.* 2012].

"Fish oil" was the second most frequent keyword (n = 2,130, CPP = 42.3). As a common source of DHA and EPA, fish oil supports various health benefits, particularly reducing inflammation and promoting heart health [von Schacky 2014]. Its frequent study inclusion highlights its role in improving cardiovascular outcomes and reducing chronic disease risks, such as heart disease and arthritis [Mozaffarian and Wu 2011].

The keyword "eicosapentaenoic acid" (EPA) appeared 1,638 times (CPP = 46.1). Known for its anti-inflammatory properties, EPA helps prevent cardiovascular disease by reducing pro-inflammatory eicosanoids [Calder 2017]. This makes it a common focus in research on heart health and inflammatory diseases.

The keyword "inflammation" appeared frequently (n = 1,472, CPP = 44.3) due to the role of omega-3s like DHA and EPA in regulating inflammation. These fatty acids inhibit inflammatory molecules, highlighting their therapeutic potential in chronic conditions such as cardiovascular disease and arthritis [Calder 2010, Serhan 2014].

The term "polyunsaturated fatty acids" (PUFAs) appeared 1,196 times (CPP = 38.4). PUFAs, including omega-3 and omega-6, are widely studied for their health impacts. Maintaining a balance between these fatty acids is essential, as imbalances are linked to inflammation and chronic diseases [Simopoulos 2011].

Keywords such as "diet" (n = 964, CPP = 45.5) and "nutrition" (n = 951, CPP = 39.0) highlight the role of diets rich in essential fatty acids. A balanced diet, especially with omega-3s, is crucial for preventing and managing chronic diseases like cardiovascular disease and obesity [Estruch *et al.* 2013, Mozaffarian 2016].

"Oxidative stress" (n = 662, CPP = 26.8) and "obesity" (n = 579, CPP = 33.4) were also prominent keywords. Omega-3 fatty acids help reduce oxidative damage, lowering risks for conditions like cardiovascular disease and cancer [Ross 2014]. Obesity, linked to chronic inflammation and metabolic syndrome, is also studied in relation to fatty acids, as omega-3s can reduce inflammation and improve metabolic health [Peyron-Caso *et al.* 2002]. Finally, "alpha-linolenic acid" (ALA) appeared 570 times, with the highest CPP of 53.4. ALA is a plant-based omega-3 fatty acid, often researched for its conversion into DHA and EPA and its cardiovascular benefits. Although its conversion efficiency is limited, ALA has been associated with reduced risks of cardiovascular disease [Pan *et al.* 2012].

Omega-3 Fatty Acids in Animal Farming

Omega-3 fatty acids, traditionally linked to fish, are now valued in animal farming for improving animal health, productivity, and the nutritional quality of products like meat, milk, and eggs. Supplementing livestock diets with omega-3s benefits health and productivity by reducing inflammation, supporting immunity, and enhancing reproductive performance. Omega-3s are crucial for brain development in young animals and help pregnant and lactating animals supports optimal neurological development in offspring [Crawford *et al.* 2013]. They also enhance the immune system of farm animals and improve immune responses and manage infections [Jenkins and McGuire 2006, Calder 2010]. Moreover, omega-3 fatty acids support cardiovascular health by reducing blood lipid levels and supporting heart function, and improve skin hydration, skin and coat quality [Bauer 2011]. Studies show that omega-3s improve growth, fertility, and milk production in cows [Moallem *et al.* 2018], reduce metabolic issues like ketosis and fatty liver [Grainger and Beauchemin 2011, Silvestre *et al.* 2011], and decrease mastitis risk [Lessard *et al.* 2003]. Also in dairy cows, omega-3 supplementation has been associated with improved fertility and reduced early embryonic loss [Silvestre *et al.* 2011], whereas in calves, they contribute to better weight gain and overall development [Gitto *et al.* 2002]. In poultry, omega-3 fatty acids help decrease the severity of inflammatory diseases such as avian coccidiosis [Khatibjoo *et al.* 2020], and to reduce stress-related behaviors such as feather pecking and aggression [Scheideler *et al.* 1997], while in broiler chickens, they enhance growth rates and improve feed efficiency [Scheideler *et al.* 1997]. In turn, in pigs, omega-3 fatty acids contribute to larger litter sizes and healthier piglets, it can lower cortisol levels, a hormone associated with stress and help manage chronic inflammatory conditions such as arthritis [Rooke *et al.* 2001]. Adding omega-3s can enhance welfare and sustainability of animal farming [Jenkins and McGuire 2006], as feeds like flaxseed, chia seeds, algal oil or agricultural by-products rich in omega-3s, like flaxseed meal, are eco-friendly [Sprague *et al.* 2017, Rodriguez-Alcala and Fontecha 2018] and additionally enrich animal products for human consumption [Woods and Fearon 2009]. Omega-3-enriched products, such as DHA-rich eggs and pork, meet the growing demand for healthier foods [Surai *et al.* 2001, Wood *et al.* 2008, Turner *et al.* 2014]. Challenges exist in integrating omega-3s into animal farming, primarily due to the higher cost of omega-3-rich feeds, which can impact farm profitability, especially for smaller farms. Additionally, omega-3s are prone to oxidation, reducing their nutritional value [Brenna 2009]. Research aims to address these issues by developing more stable feed formulations and using affordable plant-based sources to make omega-3 supplementation more accessible. They will be crucial for the future of animal farming.

Conclusions

Within the limitations of this study, the literature analysis showed that the omega-3 fatty acids literature had a steady growth since the 2000s. The United States had contributions to nearly 30% of the papers, whereas China was a relatively newcomer that began to publish in 1990 and might overtake Canada as the 2nd most productive country in the near future. Fish is a common source of omega-3 fatty acids mentioned by the literature, as well as olive oil, corn oil, soybean oil, flaxseed, microalgae, linseed oil, vegetable oil, and seafood. Recurring medical conditions mentioned by the literature included inflammation, cardiovascular disease, cancer, obesity, depression, and diabetes.

Conflict of interest

The authors declare no conflict of interest.

Author contributions

AWKY and AGA conceived the work. AWKY performed data collection and analyses. AWKY and MS drafted the manuscript. All authors critically reviewed and revised the manuscript, and approved its submission for publication in the journal Animal Science Papers and Reports.

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