Systematic Review

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Polyunsaturated Fatty Acid Supplementation in Athletes: A Systematic Review

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Background: This study aims to summarize the evidence regarding the effects of polyunsaturated fatty acids (PUFAs) supplementation on both amateur and professional athletes.
Objective: The aim is to elucidate the impacts of PUFAs supplementation on physical performance, inflammatory response, biochemical profile, anthropometric/body composition, and performance outcomes in athletes.
Methods: Articles published up to December 2023 were retrieved from databases including Cochrane Library, PubMed/Medline, Scopus, and Embase. Selected articles met eligibility criteria and quality methodology. Data on inflammatory response, biochemical markers, anthropometric/body composition, and neuromuscular indicators were extracted.
Results: Twenty-one studies were included in this systematic review. PUFAs supplementation resulted in decreased levels of certain inflammatory markers (interferon-gamma, interleukin 1, prostaglandin E2, and tumor necrosis factor alpha). However, no significant differences were observed in interleukin 4, 6, 8, 10, and matrix metalloproteinase 9. Additionally, there were no differences in glycemic (glucose and insulin) and lipid metabolism (high density lipoprotein (HDL)) cholesterol, low density lipoprotein (LDL), triglycerides). A reduction in reactive oxygen species levels was noted. No significant differences were found in muscle fatigue markers and anthropometry. Some performance parameters (neuromuscular and aerobic) improved following supplementation, including performance on the Yo-Yo distance test, resting energy expenditure, exercise time to exhaustion, and maximum oxygen consumption/maximum heart rate.
Conclusion: Supplementation with PUFAs (600–3150 mg) in athletes led to reductions in inflammation and oxidative stress markers, as well as improvements in specific aerobic performance parameters. However, no significant effects were observed on glycemic and lipid profiles, anthropometric profiles, or body composition.

Keywords: polyunsaturated fatty acids; performance; athletes; physical activity; sports nutrition

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Introduction

Lipids are molecules responsible for energy reserves and structural components, primarily for the formation of plasma membranes. They also play a crucial role in signaling and regulation through changes in the concentration of specific lipids, resulting in repercussions on cellular functions [1,2].

Malonyl coenzyme A (malonyl-CoA) synthesis is a crucial step in the formation of fatty acids and serves as a carbon donor for the elongation of these molecules. However, in humans, the production of certain fatty acids, such as alpha-linolenic acid (ALA) and linoleic acid (LA), either does not occur or is insufficient because of the absence of the enzymes responsible for their synthesis. Therefore, an exogenous intake is required [3]. These fatty acids give rise to others and are classified as polyunsaturated fatty acids (PUFAs), including essential unsaturated fatty acids. Thus, the main PUFAs, such as omega-3 (ω-3) and omega-6 (ω-6), are primarily obtained through diet [4,5].

Three fatty acids belong to the ω-3 group: ALA, docosahexaenoic acid (DHA), and eicosapentaenoic acid (EPA). In contrast, the ω-6 group comprises LA, conjugated linoleic acid (CLA, which belongs to a group of positional isomers of LA) [6], and arachidonic acid (AA). Eicosapentaenoic acid (EPA) and DHA are produced through ALA metabolism during elongation, whereas LA metabolism produces AA [7]. PUFAs have been associated with health benefits such as increasing anti-inflammatory factors, reducing blood pressure, arterial plaque accumulation, risks of cardiovascular diseases, symptoms of neurodegenerative diseases, positively impacting cognitive function, and helping defend against autoimmune pathologies and infections [8,9].

The anti-inflammatory action of PUFAs occurs by decreasing the release of pro-inflammatory cytokines, leukocyte chemotaxis, and the expression of adhesion molecules [10]. Furthermore, the cardioprotective effects result from a reduction in plasma triglyceride levels, low-intensity chronic inflammation, and functional remodeling of the cardiac tissue, which is reflected in contractility.

In the field of sports, both professional and amateur athletes generally exhibit fatty acid levels that are below the ideal value (approximately 8%) [11–14]. This deficiency is primarily caused by inadequate intake, and supplementation may be a viable option. The benefits of PUFA supplementation include those already mentioned in addition to indirectly improving performance through injury recovery, reducing oxidative stress, increasing antioxidant action, optimizing energy metabolism, and enhancing mood and reaction time.

Engaging in intense physical activity promotes an increase in the formation of pro-inflammatory cytokines and matrix metalloproteinases (MMPs), especially MMPs present in muscles (such as MMP2 and MMP9), which facilitate the adaptation of skeletal muscles to injuries and increased contractile effort [15]. Physical exercise also induces significant metabolic changes, primarily in the cellular components involved in bioenergetics, and attenuates the levels of hormones such as cortisol, testosterone, and estradiol [16].

Therefore, PUFA supplementation can play a fundamental role in health, particularly in terms of the cardiovascular aspects and inflammatory responses. Moreover, they can directly and indirectly influence sports performance, reduce the risk of chronic inflammatory processes, and stimulate metabolic adaptations, thereby optimizing energy metabolism and enhancing the efficiency of substrate utilization during sports practice.

This study aimed to elucidate the effect of PUFA supplementation on physical performance and its effects on inflammatory and biochemical profiles, anthropometric/body composition, and performance outcomes in professional and amateur athletes.

Materials and Methods

The present study followed the Preferred Report Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. Additionally, complete the PRISMA Checklist, aiming to describe the location of each component during the preparation of this review and this is available as part of the submitted material for the present study **(Supplementary Material).**

Study Selection and Eligibility Criteria

The establishment of eligibility criteria were previously selected to minimize the occurrence of systematic biases. The inclusion and exclusion criteria followed the Population/Intervention/Control/Outcomes/Study Design (PICOS, Table 1). Thus, the following inclusion criteria were applied: (a) Only studies published in English, (b) without restriction on publication date, (c) involving athletes at different levels (amateur and professional/elite), (d) receiving polyunsaturated fatty acid supplementation, (e) both sexes, (f) withing age range 18–40 years old, (g) studies with a Placebo group as a comparator, (h) assessing inflammatory response, biochemical, and anthropometric/body composition outcomes, and (i) evaluating neuromuscular, aerobic performance, and physical effort load outcomes. Exclusion criteria: (a) articles not involving PUFAs supplementation or without a placebo group, (b) athletes subjected to pharmacological and other nutritional strategies, as well as those who presented associated physical or psychological pathologies, (c) studies not assessing athletes, neuromuscular and aerobic performance components, (d) studies carried out with below 18 years old and above 40 years old, and (e) studies involving animals of any species, comments, review publications, letters, duplicates, and missing data used in different studies.

Table 1. Population/Intervention/Control/Outcomes/Study Design (PICOS) strategy.

	Inclusion criteria	Exclusion criteria
Population	Amateur and professional/elite athletes	Any other population
Intervention	PUFAs supplementation	No PUFAs supplementation
Comparator	Placebo	Any other comparison group
Outcomes	Inflammatory response, biochemistry, anthropometric/body composition, neuromuscular and aerobic performance outcomes	Any other outcome
Study design	Intervention Studies	Animal's Studies; Commentary: review, letters, duplicates, and missing data used in different studies were excluded.

PUFAs, polyunsaturated fatty acids.

Information Sources and Search Strategy

The search strategy was developed from November to December 2023. The following databases were used to select and include articles: Cochrane Library, PubMed/Medline, Scopus and Embase, using the following search equation: ((((Acids, Unsaturated Fatty) OR (Unsaturated Fatty Acids)) OR (Unsaturated Fatty Acid)) OR (Polyunsaturated Fatty Acids)) AND ((((((Athlete Professional) OR (Professional Athletes)) OR (Elite Athletes)) OR (Elite Athletes)) OR (Athlete College)) OR (Athletes)).

Selection and Data Collection Process

The screening of studies involved reviewing the title, abstract, and full text. The selection of studies was carried out independently by the researchers (MSSF and GCJS). Discrepancies were resolved by a third evaluator. Data collection process were conducted by two independent researchers. All the selection process is described in Fig. 1.

Data Items

In the present systematic review, information related to the description of the sample was extracted including author and year, sample size, sex (male and female), sport modality, and level of experience in sport (amateur or professional/elite). Data on PUFAs supplementation included dose, type of PUFA used in supplementation, frequency, route of administration, and duration (days or weeks), as well as description of the substance used by the placebo group. In addition, data on inflammatory response markers were extracted, such as: interferon-gamma (IFN-γ); IFN-γ/IL-4 ratio; interleukin-1 beta (IL-1β); interleukin1-ra (IL1-ra); interleukin-2 (IL-2); interleukin-4 (IL-4); interleukin-6 (IL-6); interleukin-8 (IL-8); interleukin-10 (IL-10); matrix metalloproteinase-2 (MMP2); matrix metalloproteinase-9 (MMP9), prostaglandin E2 (PGE2); tumor necrosis factor alpha (TNF-α). biochemistry parameters included: catalase; carbonyls index; creatine kinase (CK); creatine phosphokinase (CPK); Cu/Zn-superoxide dismutase (SOD), glucose; glutathione peroxidase (GPx); high density lipoprotein (HDL); insulin; lactate dehydrogenase (LDH); low density lipoprotein (LDL); malonaldehyde (MDA); myeloperoxidase (MPO); MnSOD; nitric oxide (NO); reduced glutathione (GSH); reactive oxygen species (ROS); superoxide dismutase (SOD); triglycerides (TG); total cholesterol (TC). Anthropometric/Body composition parameters included: body fat (%); body mass index (BMI); body weight (BW); fat mass (kg); free fat mass (kg); lean body mass (kg); muscle mass (kg).

In addition, neuromuscular outcomes including Back Squat; Counter Movement Jump (cm); Dominant Leg Extension one-repetition maximum (1RM) (Kgs); Dominant Leg Extension (repetitions); Dominant Leg Press Muscular Endurance (repetitions); Dominant Leg maximal voluntary isometric contractions (MVC) (N.m); Maximal Voluntary Isometric Contraction (MCV); Mean Power (W); Non-Dominant Leg press (Kgs); Non-Dominant Leg MCV (N.m); Non-Dominant Leg Extension and Muscular Endurance (repetitions); Non-Dominant Leg Extension 1RM (Kgs); Peak Torque Extension ($N.m^2$); Peak Torque Flexion ($N.m^2$); Peak Power (W); Power ($\%W_{max}$); Push up (repetitions); Vertical Jump Height (cm); Squat Jump (cm); Wingate Average Power (W); Wingate Power Drop (%); Wingate PP; 1RM Left and Right (kg) were extracted. Data related to aerobic performance included Anaerobic Threshold (km/h); Change in Yo-Yo distance (m); Yo-Yo distance (m); Exercise Time to Exhaustion (sec); Heart Rate (HR) in beats per minute; HR max (bpm); Mean HR (bpm); Mean VO_{2max}; Peak HR (bpm); Race Duration (min); Resting HR (bpm); Resting Energy Expenditure (%), Speed Race (km/h); Sprint Time (Sec); Training Volume; 10 Km-Time Trial (min); 250 kj Trial (sec) VO_{2max} (mL/kg/min); VO_{2max} (%); VO_{2max}; VO_{2max}/HR_{max}. Finally, physical effort outcome such Ratings of Perceived Exertion (RPE) was included.

Methodological Quality Assessment

The Joanna Briggs Institute Critical Appraisal Checklist for analytical randomized controlled trial and non-randomized experimental studies was used to verify the methodological quality of the included articles. This tool comprises eight questions that assess the methodological quality. Responses to these questions were recorded as "Yes", "No", or "Unclear". A scored was assigned for "Yes" responses, while no score was given for "No" or "Un-

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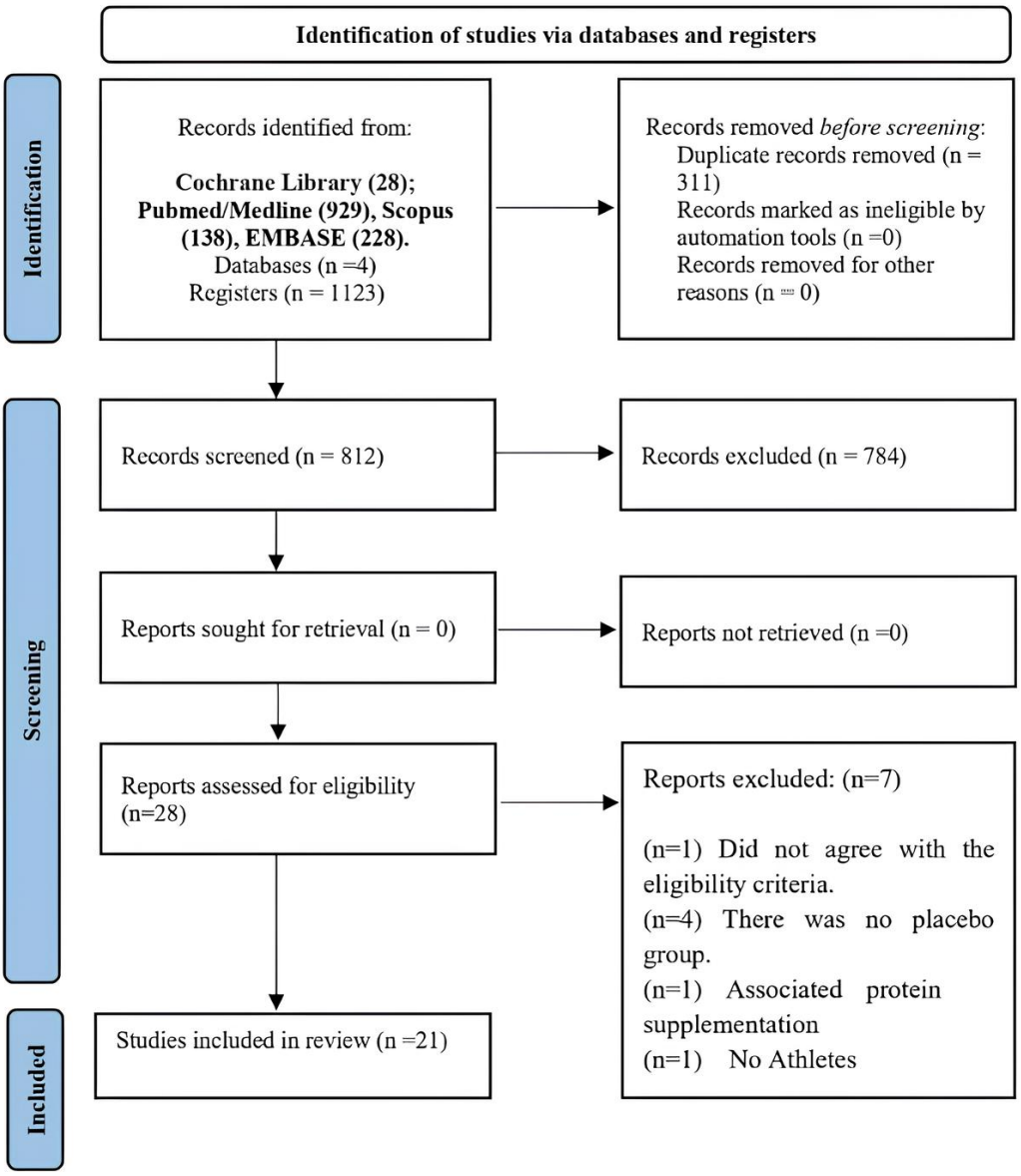

Fig. 1. PRISMA 2020 flow diagram for new systematic reviews which included searches of databases and registers only. PRISMA, Preferred Report Items for Systematic Reviews and Meta-Analyses.

clear" responses. The total score for each article was calculated as a percentage and categorized as high (80–100%), fair (50–79%), or low (50%). Two reviewers independently evaluated all studies, and any discrepancies between them were resolved through consensus (Table 2, Ref. [10,13–15,17–33]).

Results

Search Results

A total of 1123 studies were identified through searches in the databases [Cochrane Library (n = 28); PubMed/Medline (n = 929); Scopus (n = 138); and Embase (n = 228)]. After removing duplicates (n = 311), 812 articles were screened for the inclusion process. Subsequently, 784 publications were excluded based on the title/abstract, leaving 28 studies for full-text review. Finally, 21 studies were included in the present systematic review. The process of search, selection, and inclusion of studies was summarized in the flow diagram of the PRISMA statement (Fig. 1).

Methodological Quality Assessment

All included studies demonstrated fair quality (75%). Identification and control of confounders were not evaluated in all studies. However, inclusion criteria, description of participant context, reliable and valid measurements, and an adequate statistical analysis process were considered (Table 2).

Table 2. Methodological quality assessment for Non-Randomized and Randomized Studies - Joanna Briggs Institute.

Author, Year	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	%
Andrade, 2007 [13]	Y	Y	Y	Y	N	N	Y	Y	75
Baghi, 2016 [15]	Y	Y	Y	Y	N	N	Y	Y	75
Campo, 2020 [29]	Y	Y	Y	Y	N	N	Y	Y	75
Capó, 2015 [17]	Y	Y	Y	Y	N	N	Y	Y	75
Delfan, 2015 [28]	Y	Y	Y	Y	N	N	Y	Y	75
Drobnic, 2021 [27]	Y	Y	Y	Y	N	N	Y	Y	75
Filaire, 2010 [26]	Y	Y	Y	Y	N	N	Y	Y	75
Gravina, 2017 [18]	Y	Y	Y	Y	N	N	Y	Y	75
Jost, 2022 [21]	Y	Y	Y	Y	N	N	Y	Y	75
Lewis, 2015 [30]	Y	Y	Y	Y	N	N	Y	Y	75
Martorell, 2015 [14]	Y	Y	Y	Y	N	N	Y	Y	75
Martorell, 2014 [19]	Y	Y	Y	Y	N	N	Y	Y	75
Moradi, 2021 [31]	Y	Y	Y	Y	N	N	Y	Y	75
Nieman, 2009 [10]	Y	Y	Y	Y	N	N	Y	Y	75
Philpott, 2019 [33]	Y	Y	Y	Y	N	N	Y	Y	75
Raastad, 1997 [20]	Y	Y	Y	Y	N	N	Y	Y	75
Santos, 2013 [22]	Y	Y	Y	Y	N	N	Y	Y	75
Terasawa, 2017 [32]	Y	Y	Y	Y	N	N	Y	Y	75
Tomczyk, 2023 [23]	Y	Y	Y	Y	N	N	Y	Y	75
Zebrowska, 2015 [25]	Y	Y	Y	Y	N	N	Y	Y	75
Zebrowska, 2021 [24]	Y	Y	Y	Y	N	N	Y	Y	75

Notes: Y, YES; N, No; U, Not clear. Q1: Were the inclusion criteria well defined? Q2: Have participants and context been described in detail? Q3: Were the measurements collected in a valid and reliable way? Q4: Were standardized and objective inclusion criteria used? Q5: Were any confounding variables found? Q6: Were strategies used to deal with confounding variables? Q7: Were the results measured validly and reliably? Q8: Was the statistical analysis used adequate?

Characteristics of Included Studies

The studies included were published between 1997 and 2022 (Table 3, Ref. [10,13–15,17–33]). The number of participants ranged from 10 to 36 athletes. Out of the 21 included studies, 18 were conducted with male athletes, and 3 studies included both genders. The participants' mean age varied from 18 to 39.7 years old. Various sports modalities were observed in included studies. Five studies solely assessed soccer players [14,17–20], four studies were exclusively conducted with runners [21–24], two studies evaluated cyclists [10,25]. Each of the following modalities was represented by one study: Swimmers [13], judo athletes [26], CrossFit athletes [27], paddlers [28], endurance athletes [29], athletes in rowing, sailing, triathlon, and running [30], soccer, volleyball, and swimming athletes [31], basketball, volleyball, and swimming athletes [32], and athletes in strength and endurance modalities [33]. Eleven studies were conducted with elite athletes [13,14,17,19,20,22,25,26,28,30,31], and ten included studies were conducted with amateur athletes [10,15,18,21,23,24,27,29,32,33]. Various countries were identified in the included studies: Spain (n = 5) [14,17,19,27,29], Poland (n = 4) [21,23–25], Iran (n = 3) [15,28,31], Canada (n = 2) [30,33], Brazil (n = 2) [13,22], Japan (n = 1) [32], France (n = 1) [26], Scotland (n = 1) [18], and Norway (n = 1) [20].

Polyunsaturated Fatty Acid Supplementation Protocol

Different PUFAs supplementation protocols were observed in the included studies (Table 4, Ref. [10,13–15,17–33]). Various substances were used in the placebo group. Seven included studies used only olive oil in the placebo group [14,17,19,20,27,29,30], 2 studies used paraffin [15,31], 2 studies used only mineral oil [13,28], 2 studies used medium chain triglycerides [21,23], 1 study used only vegetable oil and 1 study included a composition of substances such as gelatin, glycerin, and water [26]. Another study used caprylic, capric, lauric, and palmitic acids [18], while 1 study used soybean oil, natural flavors, tocopherols, canola oil, and citric acid [10]. One study used carbohydrates and proteins [33], 1 study used magical ace powder [32], one study used lactose monohydrate [25], and 1 study used microcrystalline cellulose, magnesium stearate, and lactose monohydrate as a placebo [24].

Regarding the types of PUFAs used in the included studies, it was observed that 19 studies used ω-3 in the

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Table 3. Sample description.

Author, Year	*n*	Sex	Age (y)	Sport modality	Level	Country
Andrade, 2007 [13]	20	M	20–35	Swimmers	Elite	Brazil
Baghi, 2016 [15]	23	M	18–24	Non-informed	Amateur	Iran
Campo, 2020 [29]	15	M	18–45	Endurance	Amateur	Spain
Capó, 2015 [17]	15	M	19.3 ± 0.3	Soccer	Elite	Spain
Delfan, 2015 [28]	22	M	23.3 ± 1.4	Paddlers	Elite	Iran
Drobnic, 2021 [27]	35	F/M	33.1 ± 8.8	Crossfit	Amateur	Spain
Filaire, 2010 [26]	20	M	22.5 ± 1.4	Judo	Elite	France
Gravina, 2017 [18]	26	F/M	24.0 ± 5.0	Soccer	Amateur	Scotland
Jost, 2022 [21]	26	M	37.0 ± 3.0	Endurance Runners	Amateur	Poland
Lewis, 2015 [30]	30	M	25.0 ± 4.6	Rowing, sailing, triatlon, running	Elite	Canada
Martorell, 2015 [14]	15	M	39.7 ± 0.4	Soccer	Elite	Spain
Martorell, 2014 [19]	15	M	19.7 ± 0.4	Soccer	Elite	Spain
Moradi, 2021 [31]	36	M	21.8 ± 3.1	Soccer, volleyball, swimming	Elite	Iran
Nieman, 2009 [10]	23	F/M	25.5 ± 2.6	Cyclism	Amateur	United States
Philpott, 2019 [33]	20	M	23.0 ± 1.0	Strenght, and Resistance	Amateur	Canada
Raastad, 1997 [20]	28	M	23.5 ± 3.0	Soccer	Elite	Norway
Santos, 2013 [22]	21	M	36.5 ± 3.5	Marathon runners	Elite	Brazil
Terasawa, 2017 [32]	10	M	19.3 ± 1.4	Baseball, volleyball, swimming	Amateur	Japan
Tomczyk, 2023 [23]	26	M	37.0 ± 3.5	Long Distance Runners	Amateur	Poland
Zebrowska, 2015 [25]	13	M	23.1 ± 5.4	Cyclism	Elite	Poland
Zebrowska, 2021 [24]	24	M	34.1 ± 6.3	Recreacional runners	Amateur	Poland

Notes: F, Female; M, Male; *n*, Number of participants; y, Years old.

forms of EPA, DHA, and DPA [8,10,13–15,17–20,22–30,33]. However, only 2 studies utilized conjuged linoleic acid (CLA) as a supplementation strategy [31,32]. Supplementation was administered in capsule in 16 included studies [10,13,15,18,20–28,30–32], 4 studies observed administration through beverages [14,17,19,33], and 1 included study used soft gels [29]. The quantities in milligrams (mg) and grams (g) of the substances used were heterogeneous. The amounts of EPA varied from 200 mg to 2.4 g, DHA levels ranged from 240 mg to 2.4 g, DPA varied from 20 mg to 230 mg, and finally, CLA quantities ranged from 900 mg to 5.4 g. All PUFAs supplementation protocols were administered orally, with the administration duration ranging from 2 weeks to 12 weeks.

Impacts of PUFA Supplementation on Biological Outcomes

To understand the impacts of PUFAs supplementation on athletes across various sports, we extracted data related to inflammatory response, biochemical and anthropometric/body composition parameters (Table 5, Ref. [10,13–15,17–33]).

Inflammatory Response

Within the included articles, 9 studies evaluated various factors related to the inflammatory response in blood samples from athletes [8,10,13,15,19,22,24,28,29]. These parameters were essentially divided into pro- and anti-inflammatory categories. Among the pro-inflammatory factors, serum levels of interferon-gamma (IFN-γ), interleukin-1 beta (IL-1β), interleukin-1 receptor antagonist (IL-1ra), interleukin-6 (IL-6), interleukin-8 (IL-8), matrix metalloproteinase-9 (MMP9), prostaglandin E2 (PGE2), and tumor necrosis factor alpha (TNF-α) were assessed. For anti-inflammatory factors, IL-4 and IL-10 were observed. Additionally, three indicators of the pro- and anti-inflammatory balance were analyzed, including IFN-γ/IL-4, IL-2, and MMP2 (Fig. 2).

Pro-Inflammatory Markers

Two included studies evaluated IFN-γ levels [13,28], and it was observed that PUFAs supplementation in athletes significantly reduce levels compared to the placebo. Only 1 study assessed the effects of PUFAs supplementation on IL-1β levels [29], which significantly decreased compared to the placebo group. Only 1 included study evaluated IL-1ra levels [10], and 5 studies assessed IL-6 levels after PUFAs supplementation [10,15,24,28,29]; however, no statistically significant differences were observed compared to the placebo. Similarly, 2 included studies also did not demonstrate significant effects on IL-8 after the PUFA supplementation protocol [10,29], and 1 study that analyzed MMP9 levels after PUFAs supplementation did not observe any significant difference [15]. However, 2 included studies that assessed PGE2 identified a significant decrease in the group of athletes who used PUFAs supplementation compared to the placebo [13,19]. Finally, 6 studies evaluated TNF-α levels after PUFAs supplementation

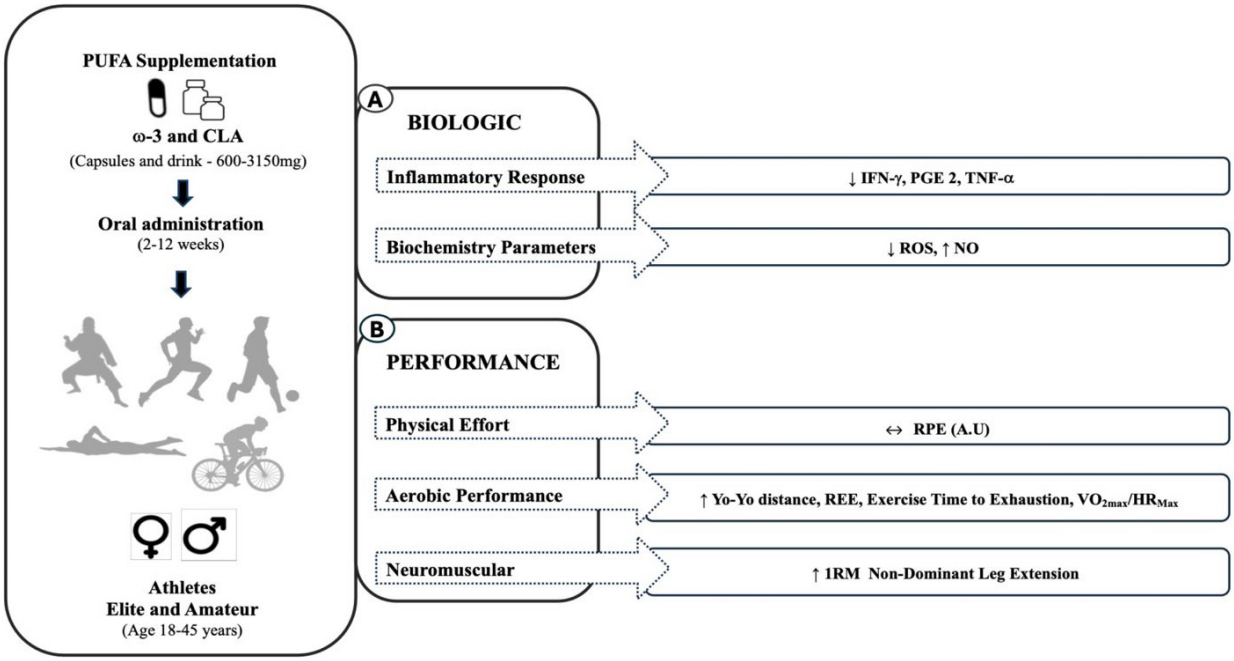

Fig. 2. Impacts of Polyunsaturated Fatty Acid Supplementation on (A) Biological and (B) Performance outcomes in athletes.
Notes: IFN-γ, interferon-gamma; TNF-α, tumor necrosis factor alpha; PGE2, prostaglandin E2; ROS, reactive oxygen species; NO, nitric oxide; REE, resting energy expenditure; RPE (A.U), ratings of perceived exertion; $VO2_{max}$, maximum oxygen consumption; HR_{max}, maximum heart rate; Resting HR, resting heart rate; CLA, conjugated linoleic acid; RM, maximum repetition.

[13,15,22,24,28,29]. Three studies did not observe significant differences between the groups, but 3 studies observed a significant decrease after the supplementation protocol compared to the placebo, demonstrating the capacity of different PUFAs supplementation protocols to reduce markers linked to inflammation.

Anti-Inflammatory Factors

Only two anti-inflammatory factors were assessed in the included studies, IL-4, and IL-10. Three included studies evaluated IL-4 levels after PUFAs supplementation and did not observe significant differences compared to the placebo group [13,22,28]. Two included studies assessed IL-10 levels following PUFAs use in these athletes [22,28]. One study noted a significant increase in IL-10 levels. However, another study observed a significant decrease compared to the placebo. These results indicate that the use of PUFAs supplementation was not effective in enhancing the production of indicators related to the anti-inflammatory response in athletes at different levels of competition.

Indicators of the Pro- and Anti-Inflammatory Balance

Three indicators related to the regulation of inflammatory balance were assessed in the included studies, namely IFN-γ/IL-4, IL-2, and MMP2. One included study evaluated IFN-γ/IL-4 levels and demonstrated a significant reduction after the PUFAs supplementation protocol [28]. Two included studies analyzed IL-2 levels; one study showed a significant decrease in IL-2 levels compared to the placebo, while the other study did not find significance between the groups [22]. Finally, one included study assessed MMP2 levels and did not observe significant differences between the groups after PUFAs supplementation [15].

Biochemistry Parameters

Within the studies included in this systematic review, 12 studies assessed indicators related to glycemic metabolism (Glucose and Insulin), lipid profile (HDL, LDL, TG, and TC), markers of oxidative stress (Carbonyl index, NO, MDA, ROS levels) , antioxidant defenses (Catalase, SOD and their associations with cofactors Cu/Zn-SOD and MnSOD, GPx, GSH, MPO, and nitric oxide), and biochemical compounds related to muscle fatigue (CPK, CK, and LDH) [10,13–15,17,19,20,24–26,29,32].

Glycemic Metabolism

Five included studies analyzed glucose levels in both amateur and elite athletes exposed to PUFAs supplementation [13,24–26,32]. Four studies did not observe significant differences in glucose levels compared to the placebo [13,24,25,32]. Nevertheless, only 1 study noted a significant increase in glucose after PUFAs supplementation. Additionally, two studies assessed insulin levels [13,26]. One study showed an increase in insulin levels in athletes compared to the placebo. However, one study did not show significant differences. According to these findings, it can be concluded that PUFAs supplementation was not effective in regulating glucose and insulin in athletes.

Table 4. Description of the PUFA supplementation protocol in athletes.

Author, Year	Placebo	Type of PUFA	PUFA supplementation protocol	Route and time of administration
Andrade, 2007 [13]	Mineral oil	w-3	Capsules containing 950 mg of eicosapentaenoic acid (EPA) and 500 mg of docohexaenoic acid (DHA) per day	OA, 6 wks
Baghi, 2016 [15]	Paraffin	CLA	Capsules containing 5.6 g of CLA supplement per day	OA, 2 wks
Campo, 2020 [29]	Olive oil	w-3	Soft Gel with 2.1 g of DHA and 240 mg of EPA, totaling 2.34 g per day	OA, 10 wks
Capó, 2015 [17]	Olive oil	w-3	Drink containing 0.6% refined olive oil and 0.2% DHA-S market per day	OA, 8 wks
Delfan, 2015 [28]	Mineral oil	w-3	Capsules containing 1.2 g of DHA and 2.4 g of EPA totaling a daily dose of 6 g	OA, 4 wks
Drobnic, 2021 [27]	Olive oil	w-3	Capsules containing 2.5 g/day of Neptune krill oil (550 mg EPA/DHA and 150 mg choline)	OA, 12 wks
Filaire, 2010 [26]	Gelatin, glycerin and water	w-3	Capsules containing 600 mg EPA and 400 mg DHA per day	OA, 6 wks
Gravina, 2017 [18]	Caprylic, capric, lauric and palmitic acids	w-3	Capsules of 1000 mg contained (EPA, 70%), (DHA, 20%), docosapentaenoic acid (DPA) (2%) and vitamin E (0.02 mg)	OA, 4 wks
Jost, 2022 [21]	Medium-chain triglycerides	w-3	Capsules contained a total of 2234 mg of EPA + 916 mg of DHA per day	OA, 12 wks
Lewis, 2015 [30]	Olive oil	w-3	Capsules contained 5 mL seal oil, 375 mg of EPA, 230 mg of DPA, 510 mg of DHA, per day	OA, 4 wks
Martorell, 2015 [14]	Olive oil	w-3	1 liter of the experimental drink for 5 days a week provided 1.14 g DHA/day	OA, 8 wks
Martorell, 2014 [19]	Olive oil	w-3	Experimental drink contained 1.14 g of DHA/day	OA, 8 wks
Moradi, 2021 [31]	Paraffin	w-3	Capsules per day containing 240 mg of DHA, 360 mg of EPA	OA, 3 wks
Nieman, 2009 [10]	Soybean oil, natural flavors, tocopherols, canola oil, and citric acid	w-3	Capsules contained 2000 mg of EPA, and 400 mg of DHA	OA, 6 wks
Philpott, 2019 [33]	Carbohydrates and proteins	w-3	Drink containing $\sim$1 g of EPA and $\sim$1 g of DHA	OA, 6 wks
Raastad, 1997 [20]	Corn oil	w-3	Capsules contained 1.60 g/day EPA and 1.04 g/day DHA	OA, 10 wks
Santos, 2013 [22]	Vegetable oil	w-3	Capsules containing 1.5 g DHA, 0.3 g EPA, and 18 mg α-tocopherol per day	OA, 60 days
Terasawa, 2017 [32]	Magical ace powder	CLA	Capsules with 1.8 g/day of CLA (0.9 g/day)	OA, 2 wks
Tomczyk, 2023 [23]	Medium-chain triglycerides	w-3	Capsules containing 2234 mg of EPA and 916 mg of DHA per day	OA, 12 wks
Zebrowska, 2015 [25]	Lactose monohydrate	w-3	Capsules with 660 mg of EPA, 440 mg of DHA, 200 mg other acids and 13.4 mg vitamin E per day	OA, 3 wks
Zebrowska, 2021 [24]	Microcrystalline cellulose, magnesium stearate and lactose monohydrate	w-3	Capsules contained 852 mg EPA, 1602 mg of DHA, and 72 mg and 30 µg of vitamin E and D per day	OA, 3 wks

Notes: EPA, eicosapentaenoic acid; DHA, docosahexaenoic acid; DPA, docosapentaenoic acid; OA, oral administration; wks, weeks; CLA, conjuged linoleic acid; mg, miligrams; g, grams; mL, milliliter.

Table 5. Supplementation of polyunsaturated fatty acids on the inflammatory response, biochemical and anthropometric parameters, and body composition in athletes.

Author, Year	Inflammatory Response	Biochemistry Parameters	Anthropometric/Body composition
Andrade, 2007 [13]	↓ IFN-γ, PGE2; ↔ IL-2, IL-4, TNF-α	↔ Glucose, Insulin	-
Baghi, 2016 [15]	↔ MMP2, MMP9, IL-6; ↓ TNF-α	↔ HDL, LDL, TC, TG	↔ BW (kg), BMI
Campo, 2020 [29]	↓ IL-1β; ↔ IL-6, IL-8, TNF-α	↓ CPK, LDH	-
Capó, 2015 [17]	-	↔ Catalase, Cu/Zn-SOD, GPx, MnSOD; ↓ ROS	↔ BW (kg), BMI, FFM (%)
Delfan, 2015 [28]	↓ IFN-γ, IFN-γ/IL-4 ratio; ↑ IL-10; ↔ IL-1β, IL-4, IL-6, TNF-α	-	↔ BW (kg), BMI, BF (%), LBM (kg)
Drobnic, 2021 [27]	-	-	↔ BMI, BF (%)
Filaire, 2010 [26]	-	↓ TG; ↑ Insulin, MDA, NO; ↔ GPx	↔ BW (kg), BMI, BF (%)
Gravina, 2017 [18]	-	-	↔ BW (kg)
Jost, 2022 [21]	-	-	↔ BW (kg)
Lewis, 2015 [30]	-	-	↔ BW (kg), BF (kg)
Martorell, 2015 [14]	-	↔ MDA, Carbonyls index, Catalase, Cu/Zn-SOD, GPx, MnSOD	↔ BW (kg), BMI, BF (%), FFM (%)
Martorell, 2014 [19]	↓ PGE2	↔ MDA, Carbonyls index, Catalase, SOD, HDL, LDL, TC, LDH, CPK, Glucose	-
Moradi, 2021 [31]	-	-	↔ BW (kg), BF (%), FM (kg), FFM (kg)
Nieman, 2009 [10]	↔ IL-1ra, IL-6, IL-8	↔ CK, MPO	↔ BW (kg), BF (%)
Philpott, 2019 [33]	-	-	↔ BW (kg), BF (%), LBM (kg)
Raastad, 1997 [20]	-	↔ TG	↔ BW (kg)
Santos, 2013 [22]	↓ IL-2, TNF-α, IL-10; ↔ IL-4	-	↔ BW (kg), BMI, BF (%)
Terasawa, 2017 [32]	-	↔ CK, Glucose, LDH, TG	↔ BM (kg), BF (%)
Tomczyk, 2023 [23]	-	-	↓ BW (kg)
Zebrowska, 2015 [25]	-	↔ HDL, LDL, TC, TG; ↑ Glucose	-
Zebrowska, 2021 [24]	↔ IL-6; ↓ TNF-α	↑ SOD; ↔ HDL, LDL, TG, Glucose, Catalase, GPx, GSH, MDA	↔ BW (kg), BMI, BF (%), MM (kg)

Notes: IFN-γ, interferon-gamma; TNF-α, tumor necrosis factor alpha; MMP2, matrix metalloproteinase-2; MMP9, matrix metalloproteinase-9; IL-6, interleukin-6; HDL, high density lipoprotein; LDL, low density lipoprotein; TC, total cholesterol; TG, triglyceride; BW, body weight; BMI, body mass index; BF (%), body fat percentage; MM (kg), skeletal muscle mass; MDA, malondialdehyde; SOD, superoxide dismutase; GPx, glutathione peroxidase; GSH, glutathione; CK, creatine phosphokinase; MPO, myeloperoxidase; CPK, creatine phosphokinase; NO, nitric oxide; LBM, lean body mass; FFM, fat-free mass; IL-2, interleukin-2; IL-4, interleukin-4; IL-10, interleukin-10; IL-1β, interleukin-1 beta; IL-8, interleukin-8; Cu/Zn-SOD, copper/zinc superoxide dismutase; MnSOD, manganese superoxide dismutase; ROS, reactive oxygen species; IL-1ra, interleukin-1 receptor antagonist. ↓, significant decrease; ↑, significant increase; ↔, no significant differences.

Table 6. Impacts of polyunsaturated fatty acid supplementation on neuromuscular, aerobic, and physical effort performance outcomes in athletes.

Author, Year	Neuromuscular Outcomes	Aerobic Performance	Physical Effort
Andrade, 2007 [13]	-	-	-
Baghi, 2016 [15]	-	-	-
Campo, 2020 [29]	↔ Peak Torque Flexion (N/m^2), Peak Torque Extension (N/m^2)	-	↔ RPE (A.U)
Capó, 2015 [17]	-	↔VO_{2max} (mL/kg/min)	-
Delfan, 2015 [28]	-	↔VO_{2max} (mL/kg/min)	-
Drobnic, 2021 [27]	-	↔ HR_{max} (bpm), Resting HR (bpm); VO_{2max} (mL/kg/min)	↔ RPE (A.U)
Filaire, 2010 [26]	-	↔Mean HR (bpm); VO_{2max} (mL/kg/min)	-
Gravina, 2017 [18]	↔ Vertical Jump Height (cm); 1RM Left Leg (kg), 1RM Right Leg (kg)	↔ Change in Yo-Yo distance (m), Sprint Time (Sec); ↑ Yo-Yo distance (m)	-
Jost, 2022 [21]	-	-	-
Lewis, 2015 [30]	↔ Back Squat (Rpts), Push up (Rpts), Counter Movement Jump (cm), MVC (%), Squat Jump (cm), Wingate PP, Wingate Average Power (W); ↓ Wingate Power Drop (%)	↔VO_{2max} (mL/kg/min), 250 Kj Trial (sec)	-
Martorell, 2015 [14]	-	↔VO_{2max} (mL/kg/min)	-
Martorell, 2014 [19]	-	-	-
Moradi, 2021 [31]	-	↔VO_{2max} (mL/kg/min); ↑ REE (%)	-
Nieman, 2009 [10]	↔ Mean Power (W), Power (%Wmax)	↔ Mean HR (bpm), HR (%HR_{max}), Mean VO_{2max} (mL/kg/min), VO_{2max} (%), 10 Km-Time Trial (min)	-
Philpott, 2019 [33]	↔ D-Leg Extension and Leg Press 1RM (Kgs), N.D Leg Press (Kgs), D-Leg MVC (N/m), D-Leg Extension and Leg Press Muscular Endurance (Rpts), N.D Leg Extension and Leg Press Muscular Endurance (Rpts); ↑ Non-D-Leg Extension 1RM (Kgs), ↓ N.D Leg MVC (N/m)	-	-
Raastad, 1997 [20]	-	↔Peak HR (bpm), VO_{2max} (%), VO_{2max} (mL/kg/min), Running Time to Exhaustion (min), Anaerobic Threshold (km/h)	-
Santos, 2013 [22]	-	↔ Race Duration (min), Speed Race (km/h)	-
Terasawa, 2017 [32]	-	↔ HR (bpm); ↑ Exercise Time to Exhaustion (sec)	↔ RPE (A.U)
Tomczyk, 2023 [23]	-	↔ VO_{2max} (mL/kg/min) at 12 Km/h, VO_2 peak(mL/kg/min)	-
Zebrowska, 2015 [25]	↔ Peak Power (W)	↔ HR (bpm), ↑ VO_{2max} (mL/kg/min), VO_{2max}/HR_{max}; ↓ HR_{max} (bpm)	-
Zebrowska, 2021 [24]	-	↔ HR (bpm), Training Volume, VO_{2max} (mL/kg/min)	-

Notes: 1RM, one-repetition maximum; MVC, maximal voluntary isometric contractions; Wingate PP, Wingate test-peak power; D-Leg, dominant leg; N.D Leg, non-dominant leg; VO_{2max}, maximum oxygen consumption; HR_{max}, maximum heart rate; Resting HR, resting heart rate; Mean HR, mean heart rate; REE, resting energy expenditure; RPE (A.U), ratings of perceived exertion (arbitrary units). ↓, significant decrease; ↑, significant increase; ↔, no significant differences.

Lipid Profile

Seven studies assessed the responses of PUFAs supplementation on components of the lipid profile [15,19,20,24–26,32]. 4 studies evaluated the responses of this supplementation on HDL, and no significant differences were identified compared to the placebo [15,19,24,25]. 4 studies analyzed LDL levels, and none of them observed statistically significant differences after the supplementation protocol [15,19,24,25]. 6 studies examined the responses of PUFA supplementation on serum TG levels, and no significant differences were identified between the groups [15,20,24–26,32]. Finally, 3 studies assessed TC where no significant differences were identified [15,19,25]. These data suggest that the use of PUFA as a supplement does not impact the lipid profile of athletes at diverse competition levels.

Oxidative Balance

Six studies analyzed indicators related to oxidative balance (markers of oxidative stress and/or related to antioxidant defenses) [10,14,17,19,24,26]. 4 included studies assessed MDA levels after PUFA supplementation [14,19,24,26], and 3 studies did not observe significant differences between the groups. However, 1 study noted a significant increase in MDA after the PUFA supplementation intervention in athletes. 2 studies examined the indicator of protein oxidation carbonyls [14,19], and after PUFA supplementation, no significant differences were observed. 1 included study evaluated the levels of ROS produced after the PUFA supplementation protocol, and the results showed a reduction in ROS levels. Therefore, we identified that PUFA supplementation can reduce ROS levels in athletes [17].

Several markers related to antioxidant defenses were evaluated in 5 included studies [14,17,19,24,26]. Two studies assessed SOD activity, with one study observing a significant increase after the use of PUFA supplementation, while another study did not find significance between the groups [19,24]. 2 studies analyzed the activity of Cu/ZnSOD and Mn/SOD and did not observe differences between the groups [14,17]. Additionally, 4 studies assessed catalase activity, where no statistical differences were observed between the groups after PUFA supplementation [14,17,19,24]. 1 study evaluated GPx levels [26], 1 study assessed GSH [24], 1 study MPO [10], and 1 study analyzed NO levels [26]; however, none of these studies found significant differences between the groups after PUFA supplementation.

Muscle Fatigue Markers

Parameters related to muscle fatigue were evaluated in the studies included after PUFA supplementation. 2 studies included evaluated CPK levels, 1 study observed a decrease in CPK after supplementation, another study did not observe significant differences [14,29]. 2 studies analyzed CK levels, and similarly did not find statistical significance [10,32]. Finally, 3 studies evaluated the levels of the LDH enzyme [19,29,32], 1 study observed a decrease in its levels after PUFA supplementation in athletes, the other 2 did not demonstrate differences between the groups.

Anthropometric, and Body Composition Components

Aiming to analyze the impacts of PUFAs supplementation on anthropometric and body composition parameters, data from BW, BMI, BF, FFM; muscle mass and lean body mass were extracted. 16 included studies evaluated BW in kilograms [10,14,15,17,18,20–24,26,28–31,33], 16 studies did not observe significant differences after PUFAs supplementation, however only 1 study demonstrated a significant decrease in BW in relation to placebo. 8 studies evaluated the BMI, no significant differences were observed between the groups [14,15,17,22,24,26–28]. 11 included studies analyzed PUFAs supplementation responses on BF levels, none of the studies found differences between groups [10,14,22,24,26–28,30–33]. 3 studies evaluated FFM, in which no statistical differences were identified between the groups [14,17,31]. 1 study only evaluated muscle mass levels. No significant differences were seen after PUFAs supplementation when compared to placebo [24]. Finally, 2 included studies evaluated lean body mass. Similarly, no differences were identified between the groups [17,33]. The findings indicate that the use of PUFAs did not have significant impacts on anthropometric parameters and body composition of amateur and elite athletes.

PUFA Supplementation on Performance Parameters

To observe the different responses of PUFAs supplementation in neuromuscular, aerobic, and physical exertion performance parameters, the included studies were extracted (Table 6, Ref. [10,13–15,17–33]).

Neuromuscular Outcomes

Six included studies evaluated different neuromuscular parameters linked to the performance of amateur and elite athletes after PUFAs supplementation [10,18,25,29,30,33]. 1 study evaluated the number of repetitions performed in the back squat exercise, where there were no significant differences after PUFA supplementation [30]. 1 study analyzed performance in the counter movement jump test in centimeters and did not observe statistical significance between the groups [30]. 1 study evaluated extension in 1 RM, leg extension in repetitions, leg press muscle endurance and MVC in the dominant leg, demonstrating no statistical significance between the groups [33]. In the same included study, no significant differences were observed in the non-dominant leg in the variables in 1 RM, leg extension in repetitions, and leg press muscle endurance [33]. However, in the non-dominant leg extension 1 RM test there was a significant increase in athletes who used PUFAs supplementation compared to placebo. Finally, when MVC was eval-

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uated in the non-dominant leg, a significant decrease was observed in the group of athletes supplemented with PUFA [33].

1 study included evaluated the mean power in watts, with no significance observed between the groups [10]. 1 study analyzed peak torque extension and flexion in both variables, with no statistically significant differences observed [22]. 1 study evaluated peak power, also not observing significant differences between the groups [25]. 1 study analyzed power in % $watts_{Max}$ and similarly no significant differences were observed [10]. 1 study evaluated performance in repetitions of the push-up exercise after PUFAs supplementation, without identifying statistical significance [30]. 1 study evaluated performance in vertical jump height and found no significance [18]. 1 study evaluated the squat jump and similarly found no significance [30]. 1 study evaluated Wingate average power and Wingate PP, identifying no significant differences between the groups [30]. However, there was a significant decrease in Wingate power drop in percentage in athletes who used PUFAs supplementation. These results demonstrate that PUFAs supplementation was responsible for the improvement in 1RM performance in the non-dominant leg extension, and the decrease in non-dominant leg MVC, and Wingate power drop in percentage in athletes.

Aerobic Performance

Aiming to elucidate the effects of PUFAs supplementation on aerobic performance, different parameters were evaluated. 10 included studies evaluated VO_{2max} levels (mL·kg·min) after PUFA supplementation [14,17,20,23–28,30]. 1 study included observed a significant increase in VO_{2max} when compared to placebo, however 9 studies did not observe significant differences between the groups [14,17,20,23,24,26–28,30]. 2 studies evaluated VO_{2max} as a percentage, observing no differences between groups [10,20]. 1 study evaluated the levels of VO_{2max} produced at a speed of 12 km/h, similarly, no statistical significance was observed [23]. 1 study observed the average VO_{2max}, after the PUFAs supplementation protocol, no significant differences were observed. 1 study included analyzed the ratio between VO_{2max}/HR_{max} and did not observe significant differences in athletes when compared to placebo [25]. 1 study included evaluated VO_2 peak levels, similarly, no statistical significance was observed between the groups [23].

2 included studies evaluated HR_{max} in beats per minute in response to PUFA supplementation [25,27]. 1 study did not observe significant differences. However, 1 study included observed a significant decrease after using the supplement. 3 studies evaluated HR levels in athletes compared to placebo, no significant differences were observed [24,25,32]. 1 study analyzed HR (%HR_{max}) [25], no statistical significance was also observed. Finally, 1 study included observed Peak HR in beats per minute, without showing statistical differences [20]. 1 study evaluated performance in seconds in the 250 Kj test, without observing differences between the groups [30]. 1 study analyzed the REE in percentage, after the PUFA supplementation protocol, demonstrating a significant increase in athletes when compared to the placebo group [20]. 1 study included evaluated performance in the 10 km-time tests in minutes after PUFA supplementation, without observing statistical differences between the groups [10]. 1 study evaluated running time to exhaustion, also showing no significance between the groups [20]. 1 study evaluated the anaerobic threshold (km/h) in athletes supplemented with PUFA, compared to placebo, and did not observe statistically significant differences. 1 study included evaluated the race duration in minutes and speed race (km/h) after supplementation with PUFA and did not observe significance in athletes in relation to placebo [20]. 1 included study evaluated the change in Yo-Yo distance in meters and sprint time in seconds, in both variables no statistically significant differences were observed when compared to placebo [18]. 1 study included after PUFA supplementation, analyzed Yo-Yo distance in meters and demonstrated a significant increase when compared to placebo [18]. 1 study evaluated Exercise time to exhaustion in seconds, the authors identified a significant increase in the group of athletes supplemented with PUFA compared to placebo [32]. Finally, training volume was evaluated, and no statistically significant differences were observed between the groups after supplementation.

Physical Effort

Finally, we evaluated the responses produced by PUFA supplementation on RPE in arbitrary units. 3 studies analyzed RPE (A.U) after PUFA use [27,29,32]. Similarly, no significant differences were observed compared to the placebo group. Demonstrating that PUFA supplementation was not effective in modulating RPE in athletes.

Discussion

The present review sought to elucidate the impacts of PUFAs supplementation in professional and amateur athletes on physical performance, inflammatory and biochemical profile, anthropometric/body composition, and performance results. The present results demonstrated that oral supplementation could promote improvements in the inflammatory profile, reactive oxygen species levels, and aerobic performance outcomes mainly.

PUFAs are characterized by the presence of a double bond in their chemical structure, which provides greater stability due to low interactions between molecules. ALA is responsible for forming ω-3 PUFAs, which can be derived into EPA and DHA [34]. These fatty acids are classified as essential, as there is a need to ingest them exogenously, as the organism is not capable of synthesizing them. Among adult individuals, international recommendations

recommend a daily intake of 0.6–1.2% of the energy percentage coming from ω-3 [35]. In this review, most studies used ω-3 as a PUFA supplement.

Several pieces of evidence have highlighted the role of ω-3 PUFA on the inflammatory profile [36–38]. Its effects have been related to the production of anti-inflammatory mediators, reduction of leukocyte chemotaxis, expression of adhesion molecules, and production of eicosanoids. It is known that the inflammatory process is fundamental for protection against invading pathogens and for the repair and regeneration of damaged tissues [39–41]. During physical exercise, exercise-induced muscle damage can result in acute inflammation, and consequently reduced performance [42]. Given this perspective, the present review demonstrated that supplementation with ω-3 PUFA was able to promote the reduction of inflammatory markers; however, there were no changes in anti-inflammatory mechanisms.

In healthy individuals, the beneficial effects of ω-3 on reducing the inflammatory response have occurred through effects on lipid mediators and cytokine secretion by T lymphocytes [43]. In a study that carried out ω-3 PUFAs supplementation through the consumption of enriched eggs in 40 individuals aged between 19–28 years, it predicted an increase in pro-resolvins, a reduction in serum levels of prostaglandins, peripheral lymphocytes, and IL-6 [44].

In addition to the benefits on the inflammatory profile, PUFAs has been related to a lower risk of developing metabolic diseases through improvements on the lipid and glycemic profile [45]. In individuals with type 2 diabetes mellitus and non-alcoholic fatty liver disease, PUFAs supplementation has demonstrated benefits through greater insulin sensitivity and changes in the intestinal microbiota [46,47]. These effects have been more evident in pathological cases. However, in healthy individuals, PUFAs supplementation does not promote changes in lipid and glycemic markers [48].

PUFAs supplementation has also demonstrated positive effects on oxidative stress through the reduction of ROS [49]. Low concentrations of ROS have important cellular functions. However, its excess can cause adverse effects, causing oxidative stress, which can even activate inflammation pathways [50]. Moderate physical exercise has demonstrated beneficial effects on oxidative balance [51]. However, vigorous exercise contributes to imbalance. Therefore, PUFAs supplementation has been shown to be effective in reducing ROS through its antioxidant and anti-inflammatory potential [47].

PUFAs supplementation has also been correlated with improvements in cardiovascular function via NO production [52]. NO is the molecule responsible for promoting vasodilation and antiatherosclerosis action [53]. The increase in oxidative stress can promote a reduction in NO bioavailability through endothelial dysfunction. Thus, the greater production of NO after supplementation with PUFA can be explained both by the reduction in oxidative stress and by the greater expression of endothelial nitric oxide synthase (eNOS) [54].

In the present review, no differences were observed regarding body composition parameters. The lack of differences may have occurred due to comparisons between the intervention group vs. placebo, which mostly used vegetable oils, such as olive oil. Vegetable oils such as olive oil, soybean oil and corn oil contain PUFA in their composition [55]. In this way, comparisons between groups can bring insignificant results, although the concentrations are different.

Supplementation with olive oil has demonstrated benefits on cardiometabolic parameters [56–58]. The same was observed in a randomized trial carried out by healthy men and women who ingested 50 g of olive oil daily in the diet or as a supplement. No significant differences were observed between weight, BMI, central adiposity, fasting blood glucose, systolic or diastolic blood pressure when compared to the control [59]. Therefore, the comparison with a placebo group using other vegetable oils creates a confusing factor.

Next, we analyzed outcomes related to aerobic, neuromuscular performance, and physical effort. The data demonstrated that PUFAs supplementation promoted improvements in parameters related to aerobic performance. However, the different supplementation protocols were not effective in enhancing neuromuscular performance and modulating RPE. It is known that aerobic physical effort is dependent on the effective performance of oxidative metabolism, which mainly relies on the bioavailability of lipids in the form of fatty acids as sources of ATP production [60]. This production occurs mainly due to mitochondrial beta-oxidation, which consists of the transport of fatty acids to be oxidized inside the mitochondria, promoting large amounts of ATP molecules [61,62]. This energy balance is fundamental for the execution of aerobic exercises since they have long duration and low intensity. Deficiencies in oxidative metabolism and energy supply during physical effort are capable of drastically reducing performance, as well as promoting mitochondrial dysfunction and stress in the endoplasmic reticulum, culminating in deleterious effects such as the emergence of metabolic and infectious diseases, mainly in athletes [62].

On the other hand, the lack of neuromuscular results can be explained by the absence of changes in body composition after PUFAs supplementation in athletes, especially in muscle mass levels. According to scientific literature, the amount of skeletal muscle is directly related to greater effectiveness in neuromuscular variables such as muscular strength and power [33,63–65]. The standardization of supplementation protocols with this type of macronutrient (amount in milligrams, duration, type of substance used) may also be behind the absence of these neuromuscular results [33]. However, Huang and collaborators in a meta-analysis demonstrated that in non-athletes, more

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precisely in the elderly, ω-3 supplementation in amounts greater than 2 grams/day was responsible for significantly increasing muscle mass levels, as well as walking speed. This demonstrates that in conditions of progressive physiological degradation such as aging, PUFAs supplementation was effective.

Finally, there were no differences in RPE after PUFA supplementation. It is a subjective method of evaluating perceived exertion, which does not effectively clarify the real explanations behind the absence of these effects in athletes. Furthermore, original studies must be carried out with the aim of relating direct physiological measures related to physical effort in athletes to confirm the real causes and mechanisms behind perceptual regulation, since athletes exposed to exhaustive working hours of effort can alter their subjective perception, thus adding a possible bias to the results [66].

The present study is the first systematic review of the scientific literature to address the impacts of different supplementation protocols with PUFAs (w-3 e CLA) on biological outcomes (inflammatory response, biochemical and anthropometry/body composition parameters), as well as neuromuscular, aerobic, and physical effort performance outcomes in amateur and elite athletes. One of the main objectives of sports supplementation is to meet nutritional demands that cannot be met by food in a logistically viable way, since athletes at different levels are always exposed to demands in training, and competitions. Secondly, findings from the present study demonstrated that PUFAs supplementation did not significantly alter anthropometric and body composition outcomes. It is known that drastic changes in body weight, BMI, fat percentage, as well as muscle mass levels can harm the establishment of determining physical capabilities including strength, speed, agility, power, and others. Third, the articles included in this review point to effective improvements in reducing the expression of indicators responsible for signaling inflammation and oxidative stress. Containing these processes is essential to avoid a decline in sports performance, mainly because it is associated with chronic pain, voluntary muscle fatigue and bioenergetic dysregulations. Finally, we observed that PUFAs supplementation was effective mainly for outcomes linked to aerobic performance, which can be explained by the interaction between lipid metabolism and the production of chemical energy in the form of ATP, through mitochondrial pathways that occur in the presence of oxygen, culminating in high bioavailability of energy during physical effort. Some limitations were observed in the included studies that make up this systematic review. Initially, we observed a heterogeneity in the amount of PUFA offered in each study, making it difficult to standardize protocols, which would be useful for sports nutrition professionals to understand the dose necessary to promote physiological and performance-related benefits. Another limitation needs to be highlighted is the scarcity of studies that specifically observe the impacts of PUFA supplementation only in female athletes. Including such studies would enable us to deepen discussions about the biological individuality and unique physiological mechanisms of each gender in response to the practiced sport, as well as their association with the PUFA supplementation protocol. It is imperative to conduct studies that meet these criteria. Other limitation is the lack of standardization of the substance used in the placebo group. The diversity of these substances used can confound the study due to their potential interactions within the organism and may interfere with the emergence of expected results. Finally, the presence of quantitative data, as well as greater homogeneity of markers and measurement units, for example, could assist in preparing confirmatory statistics analyzes with a lower degree of heterogeneity.

Exposure to constant and exhausting physical exertion can induce detrimental changes throughout the body, including inflammatory processes and those associate with oxidative stress. These interconnected processes may result in performance and illness, mainly due to infectious processes, depending on the frequency of exposure to such diseases and the high volume and intensity demands. Furthermore, we highlight the effects of PUFA supplementation on aerobic performance tests and parameters, indicating a promising path for observing responses and mechanisms that occur because of these interactions. It is strongly recommended that studies with original data standardize their placebo group, including the substance used and its dosage, to ensure consistency and comparability across studies.

Conclusion

We observed that PUFA supplementation, with doses ranging from 600 to 3150 mg, led to a reduction in levels of markers associated with inflammation and oxidative stress in athletes. Furthermore, improvements were observed in test performance and indicators related to aerobic performance, such as the Yo-Yo distance test, REE, exercise time to exhaustion, and the ratio of VO_{2max}/HR_{max}. However, PUFA supplementation did not show significant effectiveness in modulating glycemic and lipid profiles, anthropometric profiles, body composition, or neuromuscular performance.

Availability of Data and Materials

The data and materials are available in the databases used in this systematic review.

Author Contributions

Conceptualization: MSSF, JMC, GB, GCJS, DGMS, CJL, FHY, RFS; Methodology: MSSF, JMC, FHY, JST and RFS; Investigation and Data curation: MSSF, JMC, GB, RMS, FTGF, RFS, JST and CJL. Writing - original

draft: MSSF, JMC, GB, GCJS, RMS, FTGF, DGMS, CJL, JST, FHY, RFS; Writing – editing & review draft: MSSF, JMC, GB, FHY, and CJL; Resources and Project administration: MSSF, JMC, FHY, CJL and RFS; Writing - review & editing final version: MSSF, JMC, GB, CJL, FHY, RFS. All authors read and approved the final manuscript. All authors had full access to all the data in the study and take responsibility for the integrity and the accuracy of the all data analysis.

Ethics Approval and Consent to Participate

Not applicable.

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Conflict of Interest

Georgian Badicu is serving as one of the Guest Editor of this journal. We declare that Georgian Badicu was not involved in the peer review of this article and has no access to information regarding its peer review. Other authors declare no conflict of interest.

Supplementary Material

Supplementary material associated with this article can be found, in the online version, at https://doi.org/10.23812/j.biol.regul.homeost.agents.20243806.367.

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