GRASAS Y ACEITES 75 (2)
April-June 2024, 1995
ISSN-L: 0017-3495
https://doi.org/10.3989/gya.0650231.1995

Metabolic effects of chia oil in experimental models: a narrative review

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Submitted: 30 June 2023; Accepted: 22 March 2024; Published: 02 July 2024

SUMMARY: Chia seeds are a promising food for society and the scientific community because they contain polyunsaturated fatty acids, such as alpha-linolenic acid omega-3, antioxidants, and bioactive compounds. This study aimed to investigate the metabolic effects of chia oil in experimental models which have already been described in the literature. Twenty-two preclinical studies were selected, mostly with rats. The results showed that there is still no consensus on what oil dosage is ideal for generating health benefits, with the doses ranging from 0.1g/mL to 111.1g/mL and supplementation time of 1 to 33 weeks. The studies reported increased liver omega-3 contents, an improved lipid profile, increased HDL-c, and decreased total cholesterol levels. Improved glucose tolerance and insulin sensitivity, and improved antioxidant status. It is concluded that chia oil has shown beneficial metabolic effects in organisms in preclinical studies, acting on glycemic homeostasis, lipid profiles, and oxidative stress markers.

KEYWORDS: *Omega 3; Oxidative stress; Polyunsaturated fatty acid; Salvia hispanica.*

RESUMEN: ***Efectos metabólicos del aceite de chia en modelos experimentales: una revisión narrativa.*** Las semillas de chía son un alimento prometedor para la sociedad y la comunidad científica porque contienen ácidos grasos poliinsaturados, como el ácido alfa-linolénico omega-3, antioxidantes y compuestos bioactivos. Este estudio tuvo como objetivo investigar los efectos metabólicos del aceite de chía en modelos experimentales descritos en la literatura. Se seleccionaron veintidos estudios preclínicos, en su mayoría con ratas. Los resultados mostraron que todavía no hay consenso sobre qué dosis de aceite es ideal para generar beneficios para la salud, con dosis que oscilan entre 0,1 g/mL y 111,1 g/mL y tiempos de suplementación de 1 a 33 semanas. Los estudios mostraron un mayor contenido de omega-3 en el hígado, un perfil lipídico mejorado, un aumento del HDL-c y una disminución de los niveles de colesterol total. Mejora de la tolerancia a la glucosa y sensibilidad a la insulina, y mejora del estado antioxidante. Se concluye que el aceite de chía ha mostrado efectos metabólicos beneficiosos en organismos en estudios preclínicos, actuando sobre la homeostasis glucémica, perfiles lipídicos y marcadores de estrés oxidativo.

PALABRAS CLAVE: *Ácido graso poliinsaturado; Estrés oxidativo; Omega 3; Salvia hispánica.*

Citation/Cómo citar este artículo: Leão ER, Marques SMS, Porto Pimenta LCJ, Castro IC. 2024. Metabolic effects of chia oil in experimental models: a narrative review. *Grasas Aceites* **75** (2), 1995. https://doi.org/10.3989/gya.0650231.1995

1. INTRODUCTION

Chia (*Salvia hispanica* L.) is an annual herbaceous plant belonging to the family *Lamiaceae* and to the genus species *Salvia*, and is native to Mexico and parts of South America. Chia seeds are 2 mm long and are notable due to their high nutritional and functional value (Coelho and Salas-Mellado, 2014; Fonte-Faria *et al*., 2019). In recent years, the importance of chia seeds concerning human health and nutrition has increased because of their high α-linolenic fatty acid content and the beneficial effects of omega-3 fatty acid consumption on human health (Ayerza, 2011).

Chia seeds contain 25-38% oil by weight, with polyunsaturated fatty acids (PUFAs) being the main fatty acid type, particularly omega-3 fatty acids. The seeds are also an important source of protein, dietary fiber, minerals (including iron and calcium), and bioactive compounds (such as tocopherols and phenolic compounds), increasing their potential beneficial effects on human health (Fernández-López, 2018; Ayerza, 2011).

The Western diet, characterized by the excessive intake of saturated fatty acids and polyunsaturated omega-6 (n-6 PUFA) and trans fatty acids with decreased intake of omega-3 polyunsaturated fatty acids (n-3 PUFA), increases the n-6:n-3 ratio (range, 10:1 to 20:1) and may play a role in the pathogenesis of obesity and other related diseases (Simopoulos, 2016).

The human body can synthesize some fatty acids, but not linoleic acid (LA; n-6) or α-linolenic acid (ALA; n-3), which must be consumed in the diet. α-linolenic acid is a precursor to eicosapentaenoic acid (EPA - C20:5n-3) and docosahexaenoic acid (DHA - C22:6n-3) in the human body (Albracht-Schulte *et al*., 2018). Both the consumption of ALA and the activity of the enzyme fatty acid desaturase determine the plasma levels of n-3 PUFA (Vessby, 2003).

The 3 largest n-3 PUFAs, α-linolenic acid (ALA; C18:3n-3), eicosapentaenoic acid (EPA; C20:5n-3), and docosahexaenoic acid (DHA; C22:6n-3), can produce distinctly different responses on the risk factors for metabolic syndrome (Poudyal *et al*., 2011).

EPA and marine DHA are not as widely available as plant-derived ALA because of the cost and limited supply of seafood compared to plant foods. The effect of ALA on endothelial function is therefore of considerable importance, particularly for populations with low fish intake or availability (Sierra *et al*., 2015).

Sierra *et al*. (2015) demonstrated that dietary supplementation with chia oil can improve vascular dysfunction under hypercholesterolemic conditions. However, little evidence has been found on the beneficial effects of oils derived from plants which are rich in omega-3.

Thus, chia is a promising food for society and the scientific community because it contains fatty acids, antioxidants, and bioactive compounds which prevent or modify metabolic disorders resulting from chronic diseases.

The objective of this study was to investigate the metabolic effects of chia oil in experimental models which have already been described in the literature.

2. MATERIALS AND METHODS

2.1. Literature research, study selection, and data extraction

This study is a narrative review that sought studies on supplementing chia oil in experimental models of metabolic disturbances, throughout the period of 2010 to 2024. The Capes, PubMed, Scopus, and Web of Science databases were used for this end. The keywords used were "chia oil" AND "supplementation", "chia oil and supplementation" NOT "seed", "salvia hispanica", "salvia hispanica" OR "supplementation" OR "oil". Articles which used only chia seed or flour, studies with humans, studies related to food technology, and review articles were excluded. At the end of the search and exclusion of those studies that did not fit the purpose of this review, 22 articles were selected.

3. RESULTS

3.1. Chia oil

Chia essential oil has significantly higher contents of α-linolenic (55-66%) and linoleic acids (16-22%) than linseed, canola and soybean oils (Ayerza, 2011). PUFAs have been associated with an improved lipid profile, the attenuation of cardiometabolic risk, and decreased inflammation (Lesna *et al*., 2013).

Studies have shown that chia seed and oil can be rich sources of bioactive compounds because of their high polyphenolic compound contents, such as chlorogenic acid, caffeic acid, myricetin, quercetin and kaempferol, and lipolytic compound contents, such as tocopherols, phytosterols, carotenoids and phospholipids (Martínez-Cruz and Paredes-López, 2014).

Obesity impairs the antioxidant enzymatic system, with reduced catalase (CAT), superoxide dismutase (SOD), glutathione peroxidase (GPx) and glutathione reductase (GRd) activities, and affects the nonenzymatic antioxidant system (reduced thiol, minerals, vitamins, and polyphenols) which play an essential role in many antioxidant mechanisms (Brambilla *et al*., 2008; Fernández-Sánchez *et al*., 2011). Several studies have shown that the consumption of natural dietary sources (fruits, nuts, and vegetables) with bioactive antioxidant compounds (polyphenols, tocopherols, carotenoids, vitamins) can help prevent oxidative stress and can be a natural alternative for chronic disease prevention and control (Avignon *et al*., 2012; Bulló *et al*., 2011; Landete, 2012).

3.2. Chia oil and blood lipid profile

Studies with rodents have shown that the ingestion of chia oil can reduce serum cholesterol, low-density lipoprotein (LDL), and triglycerides, increase liver levels of ALA, EPA, and DHA, and decrease the n-6/n-3 ratio (Ayerza and Coates, 2007; Valenzuela *et al*., 2012; Han *et al*., 2020). Another study has also shown decreased blood glucose, triglycerides, and body weight in Wistar rats fed with a high-fat and high-fructose diet after treatment with *Salvia hispanica* (Moreira *et al*., 2022; Batista *et al*., 2023).

Capobianco *et al.* (2018) reported that pregnant rats with gestational diabetes supplemented with chia oil exhibited a lower increase in cholesterol than did the group that did not receive supplementation. The fetuses of these animals had lower glycemic and triglyceride indices and lower lipid peroxidation. Fonte-Faria *et al.* (2019) also observed better glucose and insulin tolerance, with decreased serum levels of fasting insulin in groups of rats supplemented with chia oil.

EPA and DHA are associated with beneficial changes in lipid metabolism, altering serum cholesterol concentrations, reducing triglyceride and LDL-c levels, and increasing plasma HDL-c levels (da Silva *et al*., 2019).

Poudyal (2012) showed that ALA from chia oil does not reduce total body fat but induces lipid redistribution away from the abdominal area, improving glucose tolerance and insulin sensitivity and attenuating dyslipidemia and hypertension. In a subsequent study, ALA supplementation from chia oil increased DHA concentrations but induced different physiological responses to EPA and DHA. This result strongly suggests that ALA has independent effects on metabolic syndrome that are not dependent on DHA metabolism. In addition, De Souza *et al.* (2020) demonstrated that daily ingestion of chia oil promoted the browning process in subcutaneous adipose tissue, and an increase in the expression of genes involved in mitochondrial biogenesis, as well as an increase in the expression of Uncoupling Protein 1 (UCP-1).

Gallegos *et al.* (2018) reported that hepatic ALA and n-3 PUFA contents increased the levels of LA and decreased n-6 PUFA. Also, significant rises in the expression of the peroxisome proliferator-activated receptors alpha (PPAR-α) gene and the sterol regulatory element-binding protein 1 (SREBP-1c) gene were observed when animals were supplemented with chia oil. In contrast to this finding, another study observed an increased expression and DNA-binding activity of the transcription factor PPAR-α but decreased expression and binding activity of the transcription factor SREBP-1c. This transcription factor up-regulates lipogenesis in the liver along with acetyl-CoA carboxylase 1 (ACC1), concomitant with the down-regulation of genes involving fatty acid oxidation like carnitine palmitoyl-transferase 1a (Cpt1a), adiponectin receptor 2 (Adipor 2), and PPAR-α. Moreira *et al.* (2022) demonstrated that chia oil led to the down-regulation of SREBP-1c genes and up-regulation of Cpt1a and Adipor 2 genes in rats fed with a high-fat and high-fructose diet (Rincón-Cervera *et al*., 2016; González-Mañán *et al*., 2012; Catrysse and Van Loo, 2017).

PUFAs, especially those in the n-3 family, can activate PPAR-α. PPAR-α increases β-oxidation by regulating genes that encode several key enzymes involved in the process and decreases the gene expression of ACC and fatty acid synthase (FAS), the target genes of SREBP-1c, thus resulting in the inhibition of lipogenesis. PPAR-γ is related to the control of glucose metabolism and, therefore, to improvements in insulin sensitivity (Calder, 2012; Gallegos *et al*., 2018).

3.3. Chia oil and inflammatory markers

Obesity is a chronic disease that can be characterized as an excess accumulation of body fat (Furukawa *et al.,* 2017). The prevalence of obesity has increased considerably in recent years, affecting 25.9% of the Brazilian adult population (IBGE, 2020). The consumption of a high-fat diet and high consumption of

Table 1. Summary of studies using chia oil in experimental models

Article	Chia Oil	Control Oil	Supplementation Time	Study	Results
Ayerza and Coates, 2007	53.4 g/kg diet 59,3g/ml	Corn oil	4 weeks	Investigated the influence of n-3 fatty acids on plasma composition. Chia seed, chia flour and chia oil were used.	Improved serum fatty acid profile. Increased n–3 PUFA (18: 3n–3, 20: 5n–3, and 22: 6n–3) plasma contents, and lower n–6 PUFA (18: 2n–6 and 20: 4n–6) contents.
González-Mañán *et al*., 2012	100 g/kg diet (6.3 g of ALA) 10,71 g/mL	Sunflower oil	3 weeks	Evaluated the hepatic bioconversion of ALA to EPA and DHA, the expression of PPAR-α, ACOX-1 and CAT-1, and the accumulation of EPA and DHA in plasma and adipose tissue in Sprague-Dawley rats.	Increased levels of ALA, EPA and DHA in plasma, adipose tissue, and liver. Decreased n-6:n-3 ratio. Increased PPAR-α, COX1, and CAT-I expression.
Poudyal *et al.*, 2013	30 mL/kg diet	EPA and DHA oil	8 weeks	Compared the cardiovascular, hepatic and metabolic responses to n-3 fatty acids in the diet (ALA; EPA; and DHA).	Reduced heart and liver inflammation, cardiac fibrosis and hepatic steatosis. Suppressed stearoyl-CoA 1 desaturase activity. Increased DHA concentrations
Sierra *et al*., 2015	10%	Cholesterol	5-6 weeks	Evaluated the effects of dietary supplementation with chia oil on the vascular function of hypercholesterolemic rats.	Protection of vascular function against the deleterious effects of early hypercholesterolemia.
Marineli *et al*., 2015	40 g/kg diet 4,28 g/mL	Soybean oil	6 or 12 weeks	Investigated the effect of chia seeds and oil on the plasma and oxidative status of the liver in rats with diet-induced obesity.	Increased plasma levels of GSH and plasma catalase and GPx activities. Improved glutathione reductase activity in liver tissue. Reduced plasma TBARS. Plasma and liver antioxidant capacity increased by approximately 47% in groups that received the chia oil, compared to the HFF group.
Rincón-Cervera *et al*., 2016	100 g/kg diet (6.3 g of ALA) 10,71 g/mL	Sunflower oil	3 weeks	Evaluated the hepatic and epididymal uptake and the biosynthesis of long-chain n-3 PUFAs, the activity and expression of Δ-5 and Δ-6 desaturases, the expression and activity of PPAR-α and SREBP-1c DNA binding, parameters of oxidative stress and activity of antioxidant enzymes in rats fed sunflower oil (control, 1% ALA); canola oil (10% ALA); rosehip oil (30% ALA), sacha inchi oil (49% ALA) and chia oil (64% ALA), as the only lipid source.	Increased hepatic ALA content Increased tissue accumulation of DHA and EPA and reduced n-6 deposition Consistent reduction in the activity of Δ-5 and Δ-6 desaturase enzymes Increased expression and DNA-binding activity of PPAR-α Decreased expression and binding activity of SREBP-1c Improved antioxidant status Improved fat oxidation capacity Reduced lipogenesis activity
Capobianco *et al*., 2018	11 g/100 g diet 1,18 g/mL	Safflower oil	1 week	Studied the effects of PUFA supplementation in rats with gestational diabetes (F0) fed a diet enriched with 6% safflower oil from day 1 to 14, followed by a diet enriched with 6% chia oil from day 14 of gestation to term (21 days).	Improved glycemic control Better lipid profile Lower placental PPAR-γ levels Lower lipid peroxidation Lower activation of mTOR signaling pathways

Article	Chia Oil	Control Oil	Supplementation Time	Study	Results
Gallegos *et al*., 2018	4.71% of ALA	Soybean oil	~ 14 weeks (it is not clear in the article)	Evaluated the effect of oral supplementation of ALA from chia oil and anthocyanins from a purple corn extract (PCE) on SREBP-1c, PPAR-α, and Δ5 and Δ6 desaturase gene expression in the liver and liver lipid profile, in 36 female Sprague-Dawley rats.	Increased PPAR-α and SREBP-1c gene expression. Increased ALA and long-chain n-3 PUFA content and decreased linoleic acid and long-chain n-6 PUFA levels.
Valenzuela *et al*., 2012	9,6 g/mL	Sunflower oil	3 weeks	Evaluated the hepatic bioconversion of ALA into EPA and DHA and liver damage (histology and transaminase) in Sprague-Dawley rats fed different vegetable oils.	Increased hepatic levels of ALA, EPA and DHA. Decreased the n-6/n-3 ratio.
Syeda *et al*., 2018	90 g/kg diet 9,64g/mL	Soybean oil	28 weeks	Explored whether inclusion of bioactive food in the diet may impact central pathological markers of Alzheimer's disease by modulation of the gut microbiota.	Improved cognition and reduced A aggregates and tau hyperphosphorylation Decreased MDA levels, astrocyte and microglial activation, PSD-95, synaptophysin, GluR1 and ARC protein levels in transgenic mice. Increased levels of pGSK-3. Restored gut microbiota composition, LPS, and propionate levels to control values.
Fonte-Faria *et al*., 2019	15 g/kg of diet 1,61 g/mL	Soybean oil	11 weeks	Evaluated the effect of chia oil supplementation on body composition and insulin signaling in the skeletal muscle of obese rats.	Improved glucose and insulin tolerance. Decreased fasting serum insulin levels Reduced serum leptin and triacylglycerol levels. Increased HDL-c. Changed body composition (increased lean mass and decreased fat mass).
De Souza *et al*., 2020	15 g/kg of diet 1,61 g/mL	Soybean oil	10 weeks or 27 weeks	Evaluated whether chia oil supplementation would promote browning of adipose tissue and improve glucose metabolism in animals subject to an obesogenic diet.	Animals supplemented with chia oil since weaning (21-130 days) showed an improvement in glucose metabolism, browning of subcutaneous adipose tissue.
Han *et al*., 2020	Three doses: low (1,05 g/mL kg^{-1} b.w.) medium (2,11 g/mL kg^{-1} b.w.); high (4,22 g/mL kg^{-1} b.w.)	Lard	5 weeks	Evaluated the effects of chia oil on hyperlipidemia induced by high fat diet and oxidative stress in mice.	Decreased body weight, Reduced total cholesterol, triglyceride, and low-density lipoprotein cholesterol. Elevated superoxide dismutase and GPx activities and reduced MDA content in serum and liver. Improvement of hepatic steatosis and reduced lipid deposition. Chia oil upregulates the expression of PPAR-α and CAT-1 in the liver

Article	Chia Oil	Control Oil	Supplementation Time	Study	Results
Alarcon *et al*., 2020	3%	8% lard or 10% corn oil	6 weeks	Evaluated the isocaloric partial replacement of corn oil with chia oil into a high-fat diet on metabolic parameters and vascular alterations in a model of metabolic syndrome.	Reduced the rise in triacylglycerol and n-6/n-3 fatty acids ratio high-fat diet-induced Reversed the HFD-induced endothelial dysfunction and sensitized aortic tissues to angiotensin II. The deleterious effects of HFD on fasting glucose, abdominal obesity, and glucose tolerance were worsened.
Ahmed *et al*., 2021	2,25 g/mL and 4,5 g/mL	None	1 week	Investigated the cardioprotective potential of chia oil against doxorubicin-induced (DOX) cardiotoxicity in Wistar rats.	Pre-treatment with chia oil defended against DOX-induced rise of serum CK and AST levels. Inhibited GSH depletion and elevation of MDA.
Moreira *et al*., 2022	40 g/kg diet 4,28 g/mL	Soybean oil	10 weeks	Investigated whether chia oil and flour improves metabolic disorders in the liver of Wistar rats fed a high-fat and high-fructose diet.	Increased the liver total antioxidant capacity and superoxide dismutase Decreased nitric oxide levels and liver steatosis. Promoted upregulation CPT-1 and Adipor2 and downregulated SREBF1. Decreased blood glucose, triglycerides and body weight.
Syeda *et al*., 2022	3%	Soybean oil	12 weeks	Investigated whether a combination of functional foods could reverse cognitive damage and to what extent it would be associated with changes in gut microbiota and liver.	Increased a cluster of bacteria with anti-inflammatory capacity. Decreased serum LPS levels and increased serum eicosapentaenoic acid (EPA). Increased antioxidant enzymes. Decreased lipogénesis. Reduced inflammation mediated by the TLR4-TNFα pathway. Decreased in body fat, glucose intolerance Reduced neuroinflammation in the brain Working memory improved.
Batista *et al*., 2023	15 g/kg 1,61 g/mL	Soybean oil	33 weeks	Evaluated the hepatic antioxidant activity of a high-fat diet supplemented with chia oil in mice.	Chia oil improved antioxidant status in high-fat diet fed mice. Chia oil ameliorated plasma lipid peroxidation increased by high-fat diet. Chia oil up-regulated Nrf2 and PPAR-gamma in the liver of high-fat fed mice. Obese animals treated with chia oil exhibit increased antioxidant activity in the liver.

Article	Chia Oil	Control Oil	Supplementation Time	Study	Results
Alarcon *et al*., 2023	11,11g/mL (ALA 5,8-11,6g/day)	Cholesterol	5-6 weeks	Investigated the effects of cold-pressed chia seed oil supplementation on certain hematological and biochemical biomarkers in both normal and hypercholesterolemic rabbits.	Achieved control of the hypercholesterolemia-induced increase in mean arterial blood pressure. Reduced n-6/n-3 polyunsaturated fatty acid ratios and arachidonic/linolenic fatty acid ratios both in erythrocytes and fat from normal and hypercholesterolemic rabbits. The increase in linolenic fatty acid into the retroperitoneal fat was about 9 times higher than its respective controls.
Dalginli *et al*., 2023	1g/kg 0,1g/mL	None	2 weeks	Investigated the hypoglycemic antioxidative/nitrosative, oxidative DNA damage and adenosine deaminase effects of chia seed oil on streptozotocin (STZ) induced diabetes in rats.	Chia oil regulated body weight Decreased glucose level increased with STZ treatment.
El Makawy *et al*., 2024	100 and 200 mg/kg b.w.	Corn oil	4 weeks	Assessed the repressive effect of chia and quinoa seeds oil nanocapsules against mammary tumors in rats. Rat models of chemically-induced mammary tumors were gavaged with chia and quinoa nanocapsules for one month.	Inhibited tumors in response to quinoa and chia nanocapsules. Reduced TNF-α levels, proliferation capability, and motivation for apoptosis. Repressed the activation of the MYC and PIK3CA genes. Nanocapsules modulated the liver enzymes and kidney function alterations induced in mammary tumor animals.
Amin *et al*., 2024	3%, 5%, and 7%	None	6 weeks	Explored the therapeutic effect of chia seed oil (CSO) based ice cream against coronary heart disease (CHD). CSO-based ice cream was developed by using different concentrations of CSO (G_2 3%, G_3 5%, and G_4 7%).	Decreased TG level in G_3. Increased HDL level. Decreased LDL level.

HDL-c: high-density lipoprotein; ALA: α-linolenic acid; EPA: eicosapentaenoic acid; DHA: docosahexaenoic acid; SREBP-1c: sterol regulatory element-binding protein 1; ACOX-1: peroxisomal acyl-coenzyme A oxidase 1; CAT-1: carnitine palmitoyltransferase 1; GSH: glutathione; GPx: glutathione peroxidase; TBARS: thiobarbituric acid reactive substances; PPAR-α: peroxisome proliferator-activated receptor alpha; MDA: malondialdehyde; CPT-1: carnitine palmitoyltransferase 1a; Adipor2: adiponectin receptor 2; SREBF1: sterol regulatory element binding transcription factor 1; PIK3CA: phosphatidylinositol-4, 5-bisphosphate 3-kinase catalytic subunit alpha.

fructose is correlated with inflammation, resulting in adipocyte hypertrophy and subsequent infiltration of macrophages and resulting in the activation of specific signaling pathways (Catrysse and Van Loo 2017; Moreira *et al.,* 2022).

These pathways lead to the production of inflammatory substances, including nuclear factor kappa B (NF-κB), interleukin 1 beta (IL-1β), and tumor necrosis factor-alpha (TNF-α) (Morettini *et al.,* 2015). Thus, the consumption of a high-fat diet contributes to the activation of inflammatory pathways, the dysregulation of lipid metabolism, changes in protein expression, and increased oxidative stress (Silva *et al.,* 2019). Oxidative stress suppresses PPAR-γ mRNA expression in 3T3-L1 adipocytes and inhibits the nuclear translocation of PPAR-γ in combination with nitrates, as demonstrated by Furukawa *et al.* (2017).

Poudyal *et al.* (2013) compared the cardiovascular, hepatic, and metabolic responses to n-3 fatty acids (ALA, EPA, and DHA) and reported that ALA (derived from chia oil), as well as EPA and DHA oil, reduced heart and liver inflammation, cardiac fibrosis and hepatic steatosis. Additionally, for the groups supplemented with oil, all tissues showed complete inhibition of stearoyl-CoA desaturase-1 (SCD-1) ac-

tivity. The increase in SCD-1 expression and activity has been related to cardiovascular diseases, insulin resistance, and obesity (Poudyal *et al.,* 2012).

Syeda *et al*. (2022) reported an increase in a cluster of bacteria with anti-inflammatory capacity and a reduction in inflammation mediated by the TLR4-TNFα pathway in male Wistar rats fed a high-fat-5% sucrose diet for 4 months, and later fed for 1 month with bioactive foods (dried nopal, soy protein, chia seed oil, and turmeric).

Furthermore, chia oil improves hepatic steatosis and reduces lipid deposition. Also, it was suggested that dietary chia oil may modulate lipid metabolism by regulating PPAR-α and CPT-1a protein expressions in the liver (Han *et al*., 2020).

3.4. Chia oil and oxidative stress

Rincón-Cervera *et al.* (2016) studied different sources of ALA (canola, rosehip, sacha inchi, and chia) and reported that the antioxidant status of the liver was modified in groups supplemented with chia oil, showing increased levels of reduced glutathione (GSH) and a highly reduced glutathione/oxidize glutathione (GSH/GSSG) ratio compared to the control (sunflower oil). Reduced glutathione is one of the most relevant nonenzymatic cellular antioxidants, both for its antioxidant role and for being a cofactor of the glutathione peroxidase (GPx) enzyme.

Higher ALA content, such as that provided by chia oil, was shown to reduce lipid peroxidation, and result in higher activities of antioxidant enzymes, such as those involved in protection against oxidative stress, e.g., superoxide dismutase (SOD), plasma catalase (CAT), glutathione peroxidase (GPx) and GR (glutathione reductase). The results observed in that study reinforce the concept that ALA improves the protective status of liver oxidative stress (Rincón-Cervera *et al.,* 2016; Santos-López *et al*., 2018).

Da Silva Marineli *et al.* (2015) induced obesity in rats through a high-fructose and high-fat (HFF) diet supplemented with chia seed and oil and observed increased plasma levels of reduced thiol (GSH) and CAT and GPx activity. There was no change in CAT and GPx activity in the liver; however, improvement in GR activity was observed.

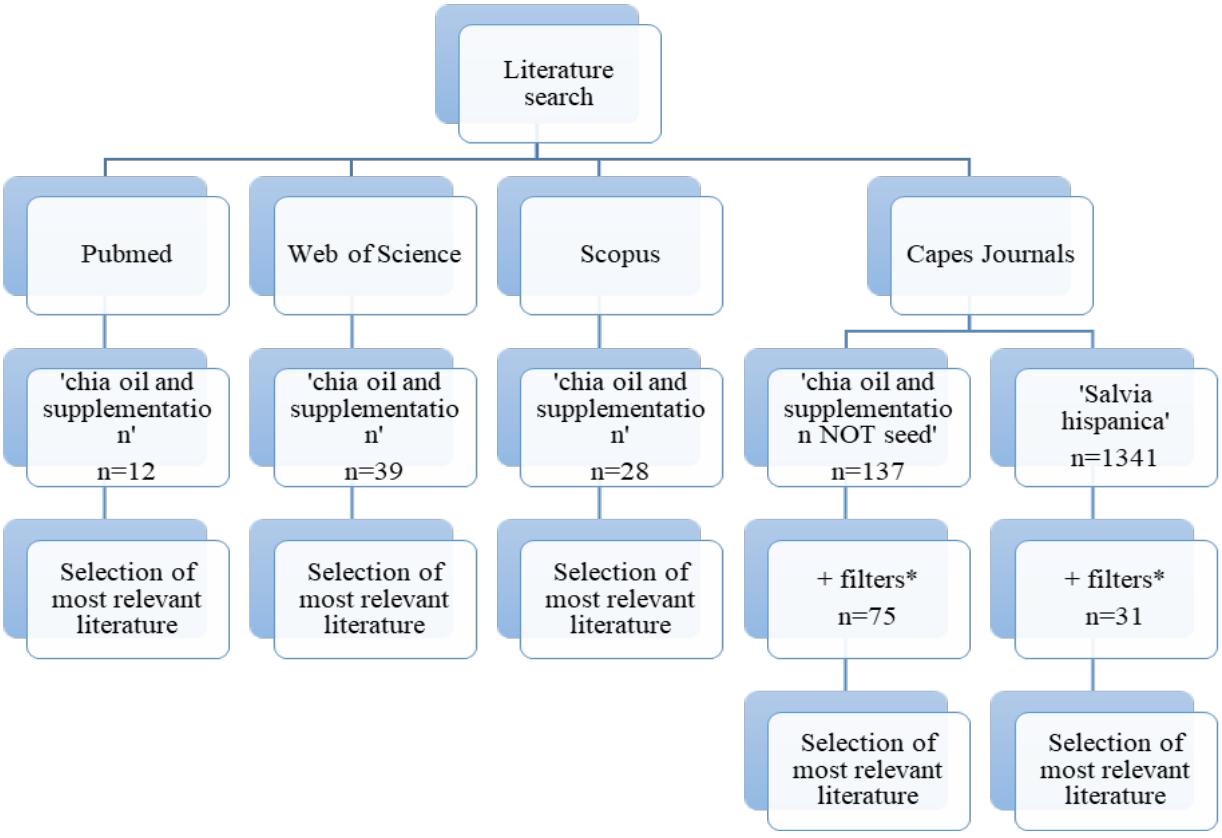

Figure 1. Literature search. * years (2010 - 2024); animals; exclusion (fish oil and humans)

The ingestion of chia oil and seeds reduced plasma thiobarbituric acid reactive substances (TBARS), and compared to those in the group that did not receive supplementation, the plasma and liver antioxidant capacity values increased in the chia seed and oil groups by approximately 35 and 47%, respectively, suggesting that both the seed and the oil can act as antioxidants and neutralize the pro-oxidative effects caused by the consumption of an HFF diet.

Batista *et al*. (2023) showed that animals supplemented with chia oil for 45 days showed increased activity of antioxidant enzymes in the liver. The animals fed with a high-fat diet and supplemented with chia oil had reduced plasma F2-isoprostane, a specific marker of oxidative damage, and reduced lipid and protein liver oxidation. Chia oil increased the content of nuclear factor-erythroid 2 related factor 2 (Nrf2) in the liver, which is related to the regulation of the antioxidant enzymes SOD, catalase, and GPx in the liver (Han *et al*., 2020; Syeda *et al*., 2022).

Therefore, these results indicate that chia oil mitigates oxidative damage in the liver resulting from a high-fat diet consumption by activating Nrf2 and PPAR-γ, which can induce the endogenous antioxidant defense system (Batista *et al*., 2023). Also, chia oil may be a potential lipid-lowering oil, especially to prevent and treat high-fat diet-induced hyperlipidemia and oxidative stress (Han *et al*., 2020).

4. CONCLUSIONS

There is still no consensus on what dosage of chia oil is ideal for generating health benefits, with doses ranging from 0.1g/mL to 111.1g/mL and supplementation times of 1 to 33 weeks.

The studies reported increased liver ALA, EPA, and DHA contents, a decreased n-6:n-3 PUFA ratio, an improved lipid profile, increased HDL-c, and decreased total cholesterol. Increased PPAR-α gene expression, improved glucose tolerance and insulin sensitivity, and improved antioxidant status through the increased activity of antioxidant enzymes, such as SOD, plasma CAT, GPx, and GR, were also observed.

It is concluded that chia oil has shown beneficial metabolic effects on organisms in preclinical studies, acting on glycemic homeostasis, lipid profiles and oxidative stress markers.

ACKNOWLEDGMENTS

The authors thank the Coordination of Superior Level Staff Improvement (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil - CAPES).

DECLARATION OF COMPETING INTEREST

The authors of this article declare no financial, professional or personal conflicts of interest that could have inappropriately influenced this work.

FUNDING SOURCES

This study was financed in part by the Minas Gerais Research Funding Foundation (Fapemig).

AUTHORSHIP CONTRIBUTION STATEMENT

E.R. Leão: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Writing – original draft. S.M. S. Marques: Formal analysis, Methodology, Writing – original draft. L.C.J. Porto Pimenta: Formal analysis, Investigation, Methodology, Writing – review & editing. I.C. Castro: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing.

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