CLINICAL NUTRITION
DOI: 10.12957/demetra.2026.90683

DEMETRA
Alimentação, Nutrição & Saúde

e-ISSN:2238-913X

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This article originated from the master's thesis entitled "Impact of avocado oil supplementation and nutrients on calcium and vitamin D levels in obese adolescents," authored by Ciro Pacheco de Mello Filho and supervised by Priscila Sala Kobal, presented in 2025 to the São Camilo University Center, São Paulo-SP, Brazil.

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Assistant Editor
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Impact of avocado oil supplementation on calcium and vitamin D levels in adolescents with obesity

Impacto da suplementação do óleo de abacate nos níveis de cálcio e vitamina D em adolescentes com obesidade

Abstract

Introduction: Obesity in adolescents might be associated with calcium and vitamin D deficiencies. Although avocado oil does not contain high amounts of these nutrients, it is rich in bioactive compounds that may improve their absorption, potentially assisting in obesity management. *Objective:* To evaluate the effects of avocado oil supplementation on serum calcium and vitamin D levels in adolescents with obesity. *Methods:* In a randomized, double-blind, placebo-controlled clinical trial, 30 post-pubertal adolescents with obesity, aged 13 to 19, were allocated into three groups: 2G (n=9), supplemented with 2 g/day of avocado oil; 1G (n=12), supplemented with 1 g/day of avocado oil; and Placebo (n=9), supplemented with 1 g/day of mineral oil. The intervention lasted 12 weeks. Dietary intake of calcium and vitamin D was assessed using a 3-day 24hR, and their serum levels were evaluated at the beginning and end of the study. Statistical analysis was performed using JAMOVI software (version 2.3). *Results:* There were no significant changes in serum vitamin D levels, nor in the dietary intake of vitamin D and calcium. Avocado oil supplementation resulted in a significant increase in serum calcium levels in the group that received 1 g/day (Pre: 9.23±0.22 vs. Post: 9.6±0.25; p = 0.014). *Conclusion:* Supplementation with 1 g/day of avocado oil significantly increased serum calcium levels in adolescents with obesity, with no impact on vitamin D. Despite the modest effect, the findings suggest a possible influence of avocado oil on mineral metabolism, reinforcing the need for further studies with larger sample sizes and longer intervention periods.

Keywords: Avocado. Obesity. Adolescent. Calcium. Vitamin D.

Resumo

Introdução: A obesidade em adolescentes pode estar associada a deficiências de cálcio e vitamina D. Embora o óleo de abacate não contenha grandes quantidades desses nutrientes, ele é rico em compostos bioativos que podem melhorar sua absorção, auxiliando no manejo da obesidade. *Objetivo:* Avaliar os efeitos da suplementação com óleo de abacate nos níveis séricos de cálcio e vitamina D em adolescentes com obesidade. *Métodos:* Em um ensaio clínico randomizado, duplo-cego e controlado por placebo, 30 adolescentes com

obesidade, pós-púberes,com idades entre 13 e 19 anos, foram alocados em três grupos: 2G (n=9), suplementados com 2g/dia de óleo de abacate; 1G (n=12), 1g/dia de óleo de abacate; e Placebo (n=9), suplementados com 1g/dia de óleo mineral. A intervenção foi realizada por 12 semanas. O consumo alimentar de cálcio e vitamina D, por meio de um recordatório alimentar de 3 dias, e seus níveis séricos foram avaliados no início e no final do estudo. A análise estatística foi feita com o *software* JAMOVI (versão 2.3). ***Resultados:*** Não houve alteração significativa nos níveis séricos de vitamina D, bem como no consumo alimentar de vitamina D e cálcio. A suplementação com óleo de abacate resultou em aumento significativo nos níveis séricos de cálcio no grupo que recebeu 1g/dia (Pré: 9,23±0,22 e Pós: 9,6±0,25; p = 0,014). ***Conclusão:*** A suplementação com 1 g/dia de óleo de abacate aumentou significativamente os níveis séricos de cálcio em adolescentes com obesidade, sem impacto na vitamina D. Apesar do efeito discreto, os achados sugerem possível influência do óleo de abacate sobre o metabolismo mineral, reforçando a necessidade de novos estudos com maior amostra e tempo de intervenção prolongado.

Palavras-chave: Abacate. Obesidade. Adolescente. Cálcio. Vitamina D.

INTRODUCTION

Obesity is a complex clinical condition that affects children at all stages of their development. During puberty, there is a decrease in insulin sensitivity, regardless of weight status. However, it is common for overweight adolescents, due to the impact on ß-cell function, to develop greater insulin resistance and exhibit a decline in the compensatory secretory responses of this hormone, without fully recovering by the end of this period.[1–3]

Lipid imbalances, such as cholesterol, triglycerides, and high-density lipoprotein (HDL), are also widely recognized biomarkers in obesity. In the data, the prevalence of dyslipidemia among overweight children was 50.4%, with the main findings being the presence of hypertriglyceridemia (31.9%) and low HDL (29.7%). Increased waist circumference (55.4%) was the most detected risk factor in the study conducted by Casavalle et al.[4] and has been directly linked to hypertension in adolescents.[5]

Recent evidence shows a significant relationship between dietary habits and the prevention, as well as the development, of obesity and its complications. These studies reinforce the importance of food security standards as an essential strategy to mitigate risk factors.[6,7] Many adolescents may present nutritional alterations, such as vitamin D and calcium deficiency, which exacerbates their health conditions. These micronutrients are closely linked to obesity and the previously mentioned associated disorders, such as insulin resistance, arterial hypertension, and dyslipidemia, which, together, characterize metabolic syndrome (MS).[8–10]

Obesity has been associated with lower serum concentrations of 25-hydroxyvitamin D [25(OH)D], possibly due to the sequestration of this vitamin by adipose tissue, which acts as a reservoir and reduces its bioavailability.[11,12] Furthermore, the presence of vitamin D receptors in pancreatic ß-cells suggests its role in insulin secretion, such that insufficient levels may contribute to insulin resistance and glycemic dysfunction.[13,14] Vitamin D deficiency has also been implicated in the activation of the renin-angiotensin-aldosteronesystem and endothelial dysfunction, favoring an increase in blood pressure and cardiovascular risk.[15,16] Moreover, studies indicate an inverse correlation between 25(OH)D levels and triglycerides, as well as a positive association with HDL, highlighting its role in lipid regulation and metabolic protection.[17]

In addition to the various functional relationships previously mentioned, within the intestinal environment, 1,25-dihydroxyvitamin D [1,25$(OH)_2$D] plays an essential role in the transcellular transport of calcium, highlighting the close connection between these nutrients.[18] This relationship is also reflected in the impact of calcium on body composition. Tylavsky et al.[19] observed that female adolescents with calcium intake below 314 mg/day had a higher body fat percentage compared to those with intake ≥ 634 mg/day. Similar results were found by Jurimae et al.,[20] who identified an inverse association between calcium intake and total body adiposity in male adolescents ($p<0.05$).

According to these results, Das & Choudhuri[21] observed that rats fed a high-fat diet and supplemented with calcium (1.0%) for 12 weeks showed a significant reduction ($p <0.01$) in adiposity index, glucose, insulin, HOMA-IR, adiponectin, and hepatic lipid accumulation, highlighting the benefits of calcium on metabolism.

These findings highlight the role of calcium not only in metabolism but also in arterial hypertension, a link between obesity and cardiovascular disorders.[22] Chen et al.,[23] in a study with 1,580 participants, observed that elevated serum calcium levels were significantly associated with increased systolic blood pressure, reinforcing this interrelation.

Benefits of avocado oil

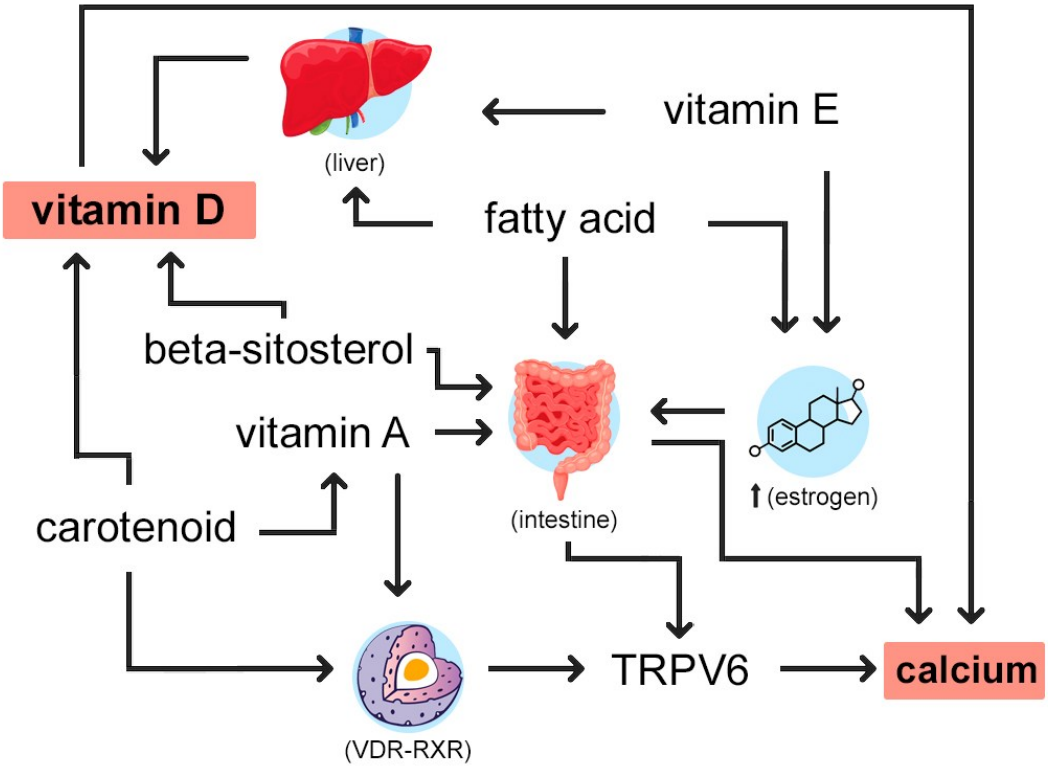
Studies demonstrate that avocado oil supplementation can improve insulin sensitivity and reduce hepatic fat and triglyceride accumulation in experimental models of obesity.[24] In the cardiovascular context, the intake of the oil significantly reduced the levels of triglycerides, very-low-density lipoprotein (VLDL), and low-density lipoprotein (LDL) in rats with sucrose-induced metabolic alterations.[25] Furthermore, Tan et al.[26] reported that the oral intake of extra virgin avocado oil (900 mg/kg/day) showed effects comparable to those of simvastatin, promoting a significant reduction ($p < 0.05$) in LDL and triglyceride levels, in addition to increasing high-density lipoprotein (HDL) levels. In an experimental model of hypertension, Márquez-Ramírez et al.[27] observed that avocado oil supplementation reduced diastolic and systolic blood pressure by 21.2% and 15.5%, respectively, in addition to mitigating adverse renal effects.

The adoption of dietary approaches focused on nutrients, such as calcium and vitamin D, or foods that provide them, such as avocado oil, can positively influence the management of obesity and its comorbidities. The avocado stands out for its high lipid content (61.27 – 62.66%), with a predominance of monounsaturated fatty acids.[28] Oleic acid is the primary fatty acid, accounting for approximately 55% of its composition. Among the bioactive compounds found, β-sitosterol, α-tocopherol, and lutein are noteworthy, representing sterols, tocopherols, and carotenoids, respectively.[29]

The inclusion of avocado in the diet has been associated with improved diet quality, higher nutrient intake, and a reduction of up to 50% in the risk of MS compared to individuals who do not consume this fruit. Thus, its oil has sparked growing interest in the fields of nutrition, the food industry, and cosmetics, due to its potential health benefits.[30]

Although avocado oil does not act directly on the regulation of serum calcium and vitamin D levels, its bioactive compounds, such as carotenoids, vitamin E, β-sitosterol, and fatty acids, may influence the metabolism of these nutrients, especially in individuals with obesity, in whom insulin resistance, hypertension, and dyslipidemia are aggravating factors that contribute to the development of MS.[31–35] Figure 1 presents a summary of the potential benefits of avocado oil on calcium and vitamin D metabolism.

Figure1 - Overview of the potential metabolic pathways of avocado oil bioactive compounds regarding calcium and vitamin D homeostasis.



Note: Provitamin A carotenoids play a role in the synthesis of retinoid X receptors (RXR), which, when associated with the vitamin D receptor (VDR), form a complex responsible for the transcription of genes related to calcium absorption, such as TRPV6 (transient receptor potential vanilloid subtype 6) in the small intestine. Vitamin A and beta-sitosterol play a crucial role in maintaining intestinal integrity, while fatty acids increase paracellular permeability. Furthermore, estrogen regulates calcium absorption in the duodenum, where fatty acids and vitamin E ensure stable levels of this hormone. Hydroxylation processes are essential for the activation and metabolism of vitamin D, which also plays a fundamental role in calcium absorption. Carotenoids, beta-sitosterol, fatty acids, and vitamin E collaborate to optimize this process. Figure created based on references[31–35].

However, further studies are needed to fully understand the effects of avocado oil in adolescents with obesity. Thus, the present study aimed to evaluate the impact of avocado oil supplementation on serum calcium and vitamin D levels in adolescents with obesity after a 12-week intervention, in addition to analyzing the intake of these nutrients and their correlation with serum levels.

METHODS

This study was conducted at the Centro de Promoção e Reabilitação em Saúde e Integração Social (PROMOVE) from the Centro Universitário São Camilo. The research protocol was registered (Platform Brasil ID: 7,297,222) and approved by the institution's Research Ethics Committee.

All participants were included in the study upon the signing of the Informed Consent Form by their parents or caregivers, and the Informed Assent Form by the adolescents. Adolescents aged 13 to 19, post-pubertal, referred by the pediatrics specialty at PROMOVE with a diagnosis of obesity, were recruited. Exclusion criteria included a diagnosis of familial hypercholesterolemia, chronic diseases, endocrine disorders, or inflammatory bowel diseases; excessive consumption of alcohol or drugs; the use of supplements or medications that could interfere with body composition; the practice of intense physical activity (more than three times per week); allergy to any component of the formula; and participation in a recent interventional study. These criteria were also established because the present study is part of a larger project aimed at evaluating the effect of the intervention on weight loss and body composition, the preliminary data of which have already been previously published by the research group.[36]

This study was designed as a randomized, double-blind, placebo-controlled clinical trial, conducted with a non-probabilistic sample consisting of adolescents with obesity. Participants were randomly assigned to three intervention groups:

- Group 2G: Supplemented with four capsules/day containing 500 mg of avocado oil, totaling 2 g/day,
- Group 1G: Supplemented with two capsules/day containing 500 mg of avocado oil, totaling 1 g/day,
- Placebo Group: Supplemented with two capsules/day containing 500 mg of mineral oil, totaling 1 g/day.

Randomization was conducted by an independent researcher using a sequence generated by software (GraphPad Statistical Software; QuickCalcs, La Jolla, CA - USA). The intervention lasted 12 weeks, during which all participants received a handbook with general guidelines on healthy eating. Patients and their guardians were informed that the capsules could be consumed at any time of the day, according to individual preference, provided that all scheduled doses were ingested by the end of the day. Splitting the intake was also permitted to facilitate protocol adherence, considering the potential difficulty in consuming two or four capsules at once. Adherence was monitored through periodic contacts, every one to two weeks, to check on the participants' well-being and confirm the regularity of supplement consumption. However, there were no dietary interventions, and participants were not instructed to modify their eating habits. They were simply instructed to maintain their usual diet, without specific restrictions or monitoring of avocado consumption. The avocado oil capsules were provided by the company Flor do Abacate Comércio e Indústria LTDA.® The nutritional and phytochemical composition of the oil is described in Table 1.

Table 1. Nutritional composition of avocado oil. São Paulo-SP, 2025.

Determination	Result
ß-sitosterol (mg/100g)	359.19 (7.68)[a]
ß-carotene (µg/100g)	10.12 (0.86)[a]
Vitamin A (IU/100g)	6
Total carotenoids expressed as lutein (mg/100g)	1.20 (0.13)[a]
Ergocalciferol (µg/100g)	ND < 0.30[b]
Vitamin D2 (IU/100g)	ND < 12[b]
Alpha-tocopherol (mg/100g)	10.50 (0.23)[a]
ß-tocopherol (mg/100g)	ND 0.02[b]
Gamma-tocopherol (mg/100g)	1.77 (0.09)[a]
Total tocopherol (mg/100g)	0.091 (0.001)[a]
Vitamin E (IU/100g)	12
Vitamin E expressed as alpha-tocopherol (mg/100g)	10.74
Fatty acids (g)	100mL
Saturated	20.14
Monounsaturated	55.53
Polyunsaturated: Omega-3	0.55
Polyunsaturated: Omega-6	10.90
Fatty acid composition (g)	100mL
C 16:0 palmitic	19.22
C 17:1 cis-10-heptadecenoic	0.07
C 18:0 stearic	0.84
C 18:1 omega-9: oleic	50.41
C 18:2 omega-6: linoleic	10.90
C 20:0 arachidic	0.10
C 18:3 omega-3: alpha-linolenic	0.55
C 20:1 omega-11: cis-11-eicosenoic	0.13

Footnotes: [a]mean and standard deviation estimate; [b],not detected.
Source: Flor do Abacate®, 2024.

Assessments were conducted at the beginning and end of the 12-week intervention and included anthropometric analysis, dietary intake assessment, and blood collection. Anthropometry was performed by a trained registered dietitian and included the measurement of weight (kg) and height (cm) to calculate the body mass index (BMI). BMI classification was performed using Z-scores, adjusted for the participants' age and sex. The criteria adopted were: underweight (-3 ≤ z-score < -2), normal weight (-2 ≤ z-score < +1), overweight (+1 ≤ z-score < +2), and obesity (z-score ≥ +2).[37] Dietary intake was assessed using a three-day 24 dietary recall (24hR), administered and guided by the nutrition team. The 24hR covered two weekdays and one weekend day and was completed by the adolescents with the assistance of their parents or guardians. Dietary intake was analyzed using the Nutrition Data System for Research (NDSR, 2023 version, Nutrition Coordinating Center, University of Minnesota, Minneapolis, MN, USA). Blood collection was performed by peripheral forearm venipuncture after an 8-hour fast. Samples were analyzed at the Hospital São Camilo-Ipiranga Laboratory using enzymatic colorimetric methods to quantify serum vitamin D and calcium levels.

Data normality was initially verified using the Shapiro–Wilk test. Intragroup comparisons were performed using the paired t-test for variables with normal distribution and the Wilcoxon test for non-parametric variables. For between-group comparisons, repeated-measures ANOVA was used, considering both intra- and inter-subject effects. When a significant effect was identified, the Tukey post-hoc test was applied to determine specific differences between groups. Correlations between biochemical and dietary variables were tested using Pearson and Spearman coefficients, according to the data distribution. All analyses were conducted using JAMOVI® software (version 2.3), adopting a significance level of $p<0.05$.

According to CNS Resolution No. 466/2012, the study was classified as presenting minimal risk. Avocado oil, a natural substance extracted from the fruit, has no reported adverse effects in the literature. Participants were monitored by the medical team and were instructed to discontinue the supplementation should any adverse reaction occur.

RESULTS

A total of 34 adolescents with obesity were included in the study. However, four participants did not complete the protocol and were excluded from the analysis. The final sample consisted of 30 adolescents (20 females and 10 males) distributed into three groups: 2 g of avocado oil (n=9), 1 g of avocado oil (n=12), and placebo (n=9) (Table 2). The treatment was well-tolerated, and no adverse effects were reported throughout the study period. Additionally, there was missing data in the 3 24hR for some participants, both at baseline and post-intervention, resulting in only 15 adolescents (50%) having complete dietary intake data (Table 3). The tables present the effects of avocado oil supplementation on different nutritional aspects of adolescents with obesity, including a comparison of serum calcium and vitamin D levels before and after supplementation, as well as changes in dietary intake, with a focus on variations in the nutrients present in the oil consumed during the pre- and post-intervention periods..

Table 2. Changes in anthropometric measurements and serum calcium and vitamin D parameters before and after avocado oil and placebo supplementation. São Paulo-SP, 2025.

Variables	Baseline (n = 30)		Group 2G (n = 9)		Group 1G (n = 12)		Placebo (n = 9)	
	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention
Anthropometry								
Weight (kg)	95.7±20.3	97.4±21.5	101.6±24.9	102.7±25.5	95.3±19.9	97.1±21.0*	90.4±15.4	91.8±15.3
Height (m)	1.6±0.1	1.6±0.1	1.6±0.1	1.6±0.1	1.6±0.1	1.6±0.1	1.6±0.1	1.7±0.1
BMI (kg/m²)	35.8±6.4	36.2±6.5	37.6±8.4	37.8±8.8	36.7±6.9	37.2±7.1	32.8±4.0	33.4±3.8
BMI/age	1.5±0.5	1.5±0.6	1.6±0.5	1.7±0.5	1.4±0.5	1.6±0.7	1.4±0.5	1.3±0.5
Serum values								
Calcium (mg/dL)	9.4±0.3	9.7±0.3	9.5±0.4	9.8±0.3	9.2±0.2	9.6±0.3*	9.4±0.3	9.7±0.4
Vitamin D (ng/mL)	17.5±5.3	19.1±6.8	18.5±5.4	20.0±8.6	16.4±6.0	18.4±5.7	17.7±3.4	19.6±6.1

Note: "Post" values correspond to data collected after 12 weeks of intervention. Values are expressed as mean ± standard deviation. *$p < 0.05$.

Table 3. Changes in total nutrient intake (diet + supplementation) before and after avocado oil supplementation. São Paulo-SP, 2025.

Variables	Group 2G (n = 4)		Group 1G (n = 5)		PLACEBO (n = 6)	
	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention
Vitamin A (IU)	1741.4±955.4	1835.6±1738.9	1483.5±960.9	1257.5±707.5	2101.8±1522.2	1574.7±1589.2
ß-carotene (mcg)	334.6±314.7	623.1±854.3	709.5±588.2	446.3±308.7	931.2±917.5	588.5±834.4
Vitamin D (mcg)	9.0±8.3	4.1±1.8	2.4±2.5	2.1±0.7	2.0 ± 0.9	2.7±1.9
Calcium (mg)	783.3±304.5	636.2±332.1	339.0±135.2	414.8±145.9	426.4 ± 321.2	524.6±329.4
Palmitic acid (g)	15.6±4.7	11.4±2.2	8.3±3.5	11.0±2.9	12.2 ± 7.9	11.9±5.0
Oleic acid (g)	21.8±6.8	17.3±3.7	14.6±7.2	16.0±3.7	18.2 ± 11.6	17.7±7.5
Lutein and zeaxanthin (mcg)	243.4±130.7	574.0±840.9	190.0±116.2	362.6±298.0	690.2 ± 606.8	762.2±1309.8
Vitamin E (IU)	10.5±3.5	7.5±3.1	4.3±2.0	6.2±2.5	6.4 ± 5.4	7.7±4.9
Linoleic acid (g)	17.5±5.1	12.6±5.3	7.8±3.7	11.8±4.2	11.1±8.3	12.3±7.2

Note: “Post" values correspond to data collected after 12 weeks of intervention. Values are expressed as mean ± standard deviation.

Avocado oil supplementation did not have a significant effect on serum vitamin D levels in adolescents with obesity, nor did it result in an increase in the dietary intake of this vitamin throughout the study. A significant increase in serum calcium levels was observed in the group that received 1 g/day of avocado oil ($p = 0.014$), whereas the 2 g/day dose did not present the same effect. In the Tukey post-hoc analysis, Group 1 (1 g of avocado oil) showed a significant difference in serum calcium levels compared to Group 2 (2 g of avocado oil), with $p = 0.012$. Dietary calcium intake remained constant, suggesting that the elevation in serum calcium levels may be associated with the supplementation.

Weight increased significantly in the 1G group, while height and BMI did not show significant changes. These data, including other anthropometric measurements, have already been detailed in a study published by our research group. These results suggest that avocado oil supplementation did not promote significant changes in the body composition of the adolescents during the study period.[36]

A detailed analysis of the nutrients recorded in the 3 24hR, including the nutrients present in the oil for the supplemented groups, did not reveal a significant increase in the intake of these nutrients.

DISCUSSION

The results of this study indicate that avocado oil supplementation had no significant impact on serum vitamin D levels in adolescents with obesity. However, a positive effect on calcium levels was observed, especially in those who received the 1 g/day dose. This finding is reinforced by the 3 24hR analysis, which showed no increase in dietary calcium intake throughout the study, suggesting that the supplementation may have contributed to the elevation of serum levels of this mineral. Nevertheless, the absence of a similar effect at the 2 g/day dose raises the hypothesis of a non-linear relationship between the supplement dose and its efficacy.

Although statistically significant, the observed effect should be interpreted with caution, as serum calcium levels are influenced by various factors, including age, BMI, exposure to pollutants, medication use, and lifestyle habits such as smoking, dietary patterns, alcohol consumption, and physical activity.[38] Even though higher calcium intake might be associated with higher serum levels, its regulation is strongly mediated by the parathyroid hormone (PTH).

PTH maintains calcium homeostasis by stimulating osteoclastic bone resorption and increasing the conversion of 25(OH)D to $1,25(OH)_2D$ in the kidneys, thereby promoting intestinal calcium absorption.[39] Alternatively, calcitonin reduces serum calcium levels by inhibiting bone resorption. Thus, the concentration of calcium in the blood does not depend exclusively on dietary intake, but rather on a complex hormonal balance.[40]

In this context, Ferrone et al.[41] identified that, in individuals under 38 years of age, 25(OH)D is one of the primary regulators of PTH, highlighting the relevance of vitamin D in this process. Additionally, Byrne et al.[42] demonstrated that serum calcium levels may remain stable regardless of dietary intake or supplementation, suggesting that a normal serum calcium concentration does not exclude the possibility of excessive or ineffective intake.

The restriction of moderate or vigorous physical activity (>3 times per week) during the study was a strategy to minimize external interference, as exercise can modulate PTH secretion and, consequently, circulating calcium levels.[43] However, BMI may also play a relevant role in this context. Studies indicate that

an increase in BMI is associated with elevations in PTH levels, which may result in greater conversion of 25(OH)D to its active form and, consequently, changes in calcium homeostasis.[44,45]

Furthermore, individuals with obesity require higher doses of vitamin D to achieve serum concentrations equivalent to those of eutrophic individuals.[46] Although no increase in dietary vitamin D intake was identified throughout the study, the contribution of food sources, even the richest ones, such as fish (5–25 µg/100 g), mushrooms (21.1–58.7 µg/100 g), reindeer lichen (87 µg/100 g), and fish liver oils (250 µg/100 g), may not be sufficient to promote significant elevations in serum levels of this vitamin.[47,48]

Endogenous factors play an essential role in the regulation of calcium and vitamin D. However, avocado oil may positively influence the metabolism of these nutrients. Its bioactive compounds not only assist in the absorption and utilisation of calcium and vitamin D, but may also contribute to the management of obesity and comorbidities associated with metabolic syndrome, factors that impact the bioavailability of these micronutrients.[31–35]

The nutritional and phytochemical composition of avocado oil is detailed in Table 1. One tablespoon (13 mL) of this oil provides a wide range of nutrients and phytochemicals, including ß-sitosterol (46.7 mg),ß-carotene (1.3 µg), lutein (0.2 mg), vitamin A (0.8 IU), vitamin E (1.6 IU), and saturated (2.62 g), monounsaturated (7.2 g), and polyunsaturated (1.49 g) fatty acids, represented by palmitic acid (2.5 g), oleic acid (6.6 g), and linoleic acid (1.4 g). Despite the inclusion of the oil's nutrients in the dietary intake analysis (Table 3) for the groups supplemented with 1 g and 2 g, there was no significant increase in the intake of these compounds. Even so, the presence of these components in avocado oil may influence the absorption and metabolism of essential nutrients, suggesting the need for more in-depth investigations into the mechanisms by which avocado oil may impact calcium and vitamin D homeostasis.

Carotenoids: ß-carotene and lutein

Carotenoids play an essential role in human health, being widely recognized as precursors to retinol (vitamin A). Furthermore, evidence suggests that higher plasma levels of carotenoids are associated with a reduction in adiposity, greater weight loss, and an improved cardiometabolic profile in adolescents who are overweight or obese.[49,50]

In addition to their nutritional importance, the inclusion of carotenoid-rich sources in the diet can optimize their absorption and bioavailability. Studies show that the consumption of either 150g of avocado or 24g of avocado oil can significantly increase the absorption of lutein (up to fivefold) and beta-carotene (up to fifteenfold) from a meal.[51] This food synergy reinforces the potential of avocado oil as an efficient vehicle for the absorption of dietary carotenoids. A practical example of this effect is adding avocado oil to salads, which improves the bioavailability of the carotenoids present in tomatoes. Tomatoes, besides being a rich source of carotenoids, contain lysine (1.34%), vitamin C (0.76 µmol/g), and organic acids, compounds that play an important role in calcium absorption.[52–55]

Calcium absorption occurs through two main mechanisms: active (saturable) transcellular transport and passive (non-saturable) paracellular transport, both located in the duodenum. Vitamin D is a critical factor in this process, as it positively regulates the expression of vitamin D receptors (VDR), promoting the transcellular transport of calcium across the brush-border membrane of enterocytes. Therefore, carotenoids such as beta-carotene may also influence calcium absorption by stimulating the synthesis of retinoic acid, which in turn activates retinoid X receptors (RXR). The activation of RXR is essential for the dimerization of

VDR, a fundamental process for the transcription of the TRPV6 gene, which encodes calcium transporter proteins.[32,56]

Furthermore, the regulation of vitamin D levels may be compromised in chronic inflammatory states. Mangin et al.[57] suggest that chronic inflammation can reduce serum levels of 25(OH)D, compromising its function and, consequently, calcium absorption. In this sense, the carotenoids lutein and beta-carotene may play a relevant role, as they demonstrate the ability to suppress the generation of pro-inflammatory cytokines.[58,59] This anti-inflammatory effect may contribute to the improvement of vitamin D bioavailability and, indirectly, to calcium homeostasis.

Vitamin A

Given that vitamins A and Dare fat-soluble, it is plausible that there is competition in their absorption, and an excess of both can impact metabolic balance. However, adequate serum levels of these vitamins play an essential role in maintaining the integrity of the intestinal microbiome. Evidence suggests that a deficiency in vitamin A, 1,25$(OH)_2$D, or vitamin D receptors (VDR) can result in dysbiosis, increasing susceptibility to intestinal injury.[60,61]

As previously discussed, calcium absorption occurs predominantly in the duodenum through two mechanisms: active transcellular transport and passive paracellular transport. Both vitamin A and vitamin D influence this process by regulating the expression of tight junction proteins, including zonula occludens-1 (ZO-1), occludin, and claudins. These proteins play a fundamental role in maintaining the intestinal barrier, preventing imbalances in the microbiota that could indirectly compromise calcium absorption.[62–64]

Intestinal dysbiosis has been widely associated with a range of metabolic disorders, including obesity.[65] In this scenario, Wei et al.[66] analysed the vitamin A status in school-aged children and identified prevalences of overweight, obesity, and metabolic syndrome of 10.1%, 6.7%, and 3.5%, respectively. The study revealed statistically significant associations between vitamin A levels and anthropometric and metabolic markers, including BMI, waist circumference, HDL cholesterol, and blood glucose ($p<0.05$). Furthermore, 14.2% of the children evaluated presented marginal vitamin A deficiency, while 2.8% were classified as having severe deficiency. These findings reinforce the importance of the balance between the intake and metabolism of fat-soluble vitamins, not only for calcium homeostasis and intestinal health but also for the regulation of metabolic parameters and the risk of obesity-related disorders.

Vitamin E

Stenzel et al.[67] investigated serum antioxidant levels in adolescents with a mean age of 17.31 ± 1.34 years and identified a negative correlation between vitamin E levels and waist circumference. In addition to its well-known antioxidant property, Wong et al.[68] associated vitamin E, particularly the tocotrienol form, with body weight control, the regulation of inflammation and blood pressure, as well as the maintenance of blood glucose and cholesterol levels. These findings suggest that vitamin E might be a potential adjuvant in the treatment of clinical conditions associated with obesity and its metabolic complications.

Beyond its antioxidant functions, vitamin E components can act as phytoestrogens, contributing to the regulation of estrogen levels. Estrogen, in turn, plays a fundamental role in duodenal calcium absorption by modulating nuclear transcription factor receptors, such as estrogen receptors α (ERα) and β (ERβ). These

receptors influence the expression of TRPV6 and PMCA1b proteins, both essential for calcium transport in duodenal epithelial cells.[69]

Adequate calcium absorption depends not only on estrogen but also on the availability of active vitamin D. Chronic liver diseases, such as cirrhosis, can compromise its activation due to 25-hydroxylase dysfunction, which is aggravated by oxidative stress.[34] Thus, vitamin E can act as an ally in liver health, thanks to its antioxidant and anti-inflammatory properties, thereby favoring vitamin D metabolism.[70–73]

In addition to its participation in calcium and vitamin D homeostasis, vitamin E also appears to influence bone metabolism. Studies indicate that a deficiency of this vitamin, especially in the form of tocotrienol, may be associated with reduced bone calcification, whereas its supplementation has been shown to improve calcium content in bones.[74] Similar results were observed in research conducted by Smith et al.,[75] who reported that a vitamin E-deficient diet led to hypokalemia, secondary hyperparathyroidism, and vertebral bone loss in Sprague-Dawley rats. These findings reinforce the relevance of vitamin E in maintaining bone health, in addition to its metabolic and antioxidant roles.

Fatty acids: palmitic, oleic and linoleic

The intake of monounsaturated fatty acids (MUFA) has been widely associated with metabolic benefits in individuals with obesity, including improved lipid profile, reduced blood pressure, favorable modulation of insulin sensitivity, and a cardioprotective effect.[76] Among the main dietary sources of MUFA, olive oil (73%) and canola oil (58%) stand out, but the highest concentration of these fatty acids is found in avocado oil, which contains approximately 74% MUFA.[77]

The presence of fats in a meal, such as those found in vegetable oils, can enhance the absorption of vitamin D3 (cholecalciferol), promoting a significant increase in its serum levels.[78] Studies suggest that fatty acids modulate the transport of cholecalciferol at the basolateral membrane of enterocytes, influencing its bioavailability. In particular, oleic acid has been shown to increase cholecalciferol secretion in *in vitro* studies with Caco-2 cells, in addition to stimulating the synthesis of chylomicrons, the main transporters of vitamin D in post-absorption circulation.[79,80] Thus, the intestinal absorption of cholecalciferol can be optimized according to the composition of the fatty acids present in the diet.

As previously mentioned, vitamin D has an inverse relationship with BMI and inflammatory markers, such as interleukin-6 (IL-6) and C-reactive protein (CRP).[81,82] Although studies in animal models present more robust evidence, several clinical trials suggest that linoleic acid supplementation might contribute to improvements in BMI. Furthermore, this fatty acid has been associated with a reduction in serum levels of tumor necrosis factor-α (TNF-α), interleukins, and CRP, indicating a possible beneficial anti-inflammatory effect.[83–87]

Another relevant aspect is the influence of linoleic acid on calcium absorption. Studies demonstrate that this fatty acid can increase paracellular permeability in Caco-2 cells, possibly due to changes in the distribution of occludin, a protein essential for the integrity of tight junctions.[88] Unlike active transcellular transport, which is regulated by vitamin D, paracellular calcium transport occurs passively through tight junctions along the entire small intestine.[89] In the study by Kelly et al.[90], linoleic acid supplementation for eight weeks resulted in a significant increase ($P < 0.05$) in calcium absorption in Wistar rats compared to the control group, suggesting a possible mechanism for regulating mineral homeostasis.

Fatty acids can enhance calcium absorption by regulating the expression of proteins involved in this process. Diets rich in MUFA are associated with increased intestinal calbindin and Cyp2r1, the enzyme

responsible for vitamin D activation.[91] Furthermore, there is a positive correlation between serum estradiol levels and calcium absorption, with dietary fat potentially influencing its circulation. These findings highlight the role of fatty acids in regulating calcium and vitamin D metabolism, contributing to bone health and inflammatory modulation.[92,93]

ß-sitosterol

Gumede et al.[94] investigated the protective effect of beta-sitosterol against metabolicdys function in Sprague-Dawley rats fed a high-fructose diet, simulating early exposure to obesogenic diets. ß-sitosterol showed a significant preventive effect on visceral obesity, raising plasma adiponectin levels and reducing insulin concentrations, there by aiding in the prevention of metabolic dysfunction.

In vitro studies indicate that beta-sitosterol exerts immunomodulatory effects, reducing the production of TNF-α and IL-6, possibly through increased calcium uptake by neutrophils.[95–97] When combined with vitamin D3, its effect was potentiated, suggesting a complementary action on the same signaling pathways.[98] Furthermore, Kuhn et al.[99] observed that rats supplemented with vitamin D3 (25 µg/kg) and beta-sitosterol presented significantly higher plasma, hepatic, and cutaneous levels of vitamin D3 compared to the control group, highlighting the impact of this interaction on the vitamin's bioavailability.

Similar to vitamin A, ß-sitosterol strengthens the intestinal barrier by increasing the expression of tight junction proteins (claudin, occludin, and ZO-1). Ma et al.[100] observed that its supplementation increased the presence of *Lactobacillus* in the intestine, reducing the incidence of food allergies and improving absorptive capacity. This effect may contribute to attenuating the symptoms of cow's milk allergy, an important source of dietary calcium.[101,102]

Although a statistical difference in serum calcium levels was observed, this variation lacks significant clinical relevance, since calcemia is rigidly controlled by hormonal mechanisms and poorly reflects dietary intake. Furthermore, it is acknowledged that the use of a convenience sample and the evaluation of calcemia in isolation represent limitations of the present study. Even so, these results provide a foundation for future research with larger samples, allowing for a more robust analysis of the impacts of this supplementation on calcium and vitamin D absorption.

CONCLUSION

Supplementation with 1 g/day of avocado oil promoted a significant increase in serum calcium levels in adolescents with obesity, with no changes in vitamin D or the dietary intake of these nutrients. Although the observed effect was modest and non-linear in relation to the dose, the results suggest that bioactive compounds present in the oil, i.e., carotenoids, vitamin E, ß-sitosterol, and mono- and polyunsaturated fatty acids, might exert a positive influence on mineral metabolism.

Considering the multifactorial regulation of calcium and vitamin D, as well as the limitations regarding sample size and intervention duration, further controlled studies with greater statistical power and longer follow-up are necessary to elucidate the mechanisms of action and the clinical potential of avocado oil as an adjuvant in modulating bone and mineral metabolism in adolescents with obesity.

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Contributors

Kobal PS participated in the conception, design, analysis, and interpretation of the data, as well as the revision and final approval of the article; Castro AGP, Freiberg CK, Masquio DCL, da Silva SMC, and Ganen AP participated in the conception, design, and final approval of the article; Mello Filho CP collaborated through data analysis and interpretation, writing, and final approval.

Conflict of Interest: The authors declare a potential conflict of interest, as the study received financial support from Flor do Abacate Comércio e Indústria LTDA, the manufacturer of the tested product. However, the company had no influence on the data collection, analysis, or interpretation.

Received: March 21, 2025
Accepted: March 7, 2026