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RESEARCH

Different parts of pequi (*Caryocar brasiliense*) alter physical and biochemical parameters differently in Wistar rats and their offspring

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Abstract

The aim of this study was to evaluate the effects of consuming pequi pulp and nuts (*Caryocar brasiliense*) by rats during pregnancy and lactation on the physical and biochemical parameters of both the mothers and their adolescent offspring. Three groups were formed: Control group, treated with distilled water, and the Pequi Pulp and Pequi Nuts groups, both treated with 2000 mg/kg of their respective substrates. Body weight, body length, thoracic and abdominal circumference, Lee index, glucose, triglycerides, total cholesterol and HDL-cholesterol levels were measured in both mothers and offspring. Body fat was removed and weighed, and the liver was analyzed to determine the fatty acid profile and malondialdehyde (MDA) levels. The results indicated a reduction in body weight, BMI, and Lee index in both mothers and offspring in the Pulp and Nuts groups. Blood glucose, triglycerides and body fat were lower in the mothers from the nuts group, while HDL and total cholesterol levels were higher compared to the other groups. The Pulp group showed increased body fat, blood glucose, triglycerides, total cholesterol, and HDL levels in the offspring, indicating an overall unfavorable metabolic profile despite the elevation in HDL. In the livers of the Nuts and Pulp groups, PUFA were elevated in the mothers but reduced in the offspring. MUFA showed increase in the offspring's liver and decrease in the mothers. Furthermore, maternal and offspring malondialdehyde (MDA) levels were elevated in both the Nuts and Pulp groups. In conclusion, maternal consumption of pequi nuts improved physical and biochemical parameters in both mothers and offspring, while pequi pulp had increased blood glucose, triglycerides and body fat. This way, different parts of the pequi fruit have different impacts on the maternal organism and its profile when offered during pregnancy and lactation.

Highlights

- Mothers who consumed nuts and pequi pulp, and their offspring, had reduced BMI and Lee index;
- Pequi nuts had a beneficial impact on the mothers' blood glucose, triglycerides, body fat and HDL-c;
- Pequi pulp had a negative impact on the offspring's physical and biochemical parameters;
- As there was an increase in PUFAs in the liver of mothers, there was a reduction in the offspring;
- Nuts and pequi pulp have different impacts on the mother's body and its profile when offered during pregnancy and lactation.

Keywords Fatty acids · Physical development · Pregnancy · Brazilian fruit

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Introduction

Pregnancy and lactation are critical periods that require specific attention and care, as they affect not only the mother's health but, more importantly, the development of her offspring [1]. Fetal programming occurs during early life in the intrauterine environment and can induce metabolic changes that persist into adulthood [2]. Research shows that maternal nutrition during pregnancy impacts both maternal health and the offspring's phenotype [3].

During both gestational and postnatal periods, maternal nutrition can modulate the offspring's health in the short and long term [4, 5]. Maternal nutrition is crucial for several vital functions, including growth, reproduction, and development [6]. Nutrients are provided to the fetus through the placenta and later via breast milk. An unbalanced maternal diet increases the risk of future chronic diseases for the offspring [7]. Intrauterine exposure to poor-quality diets, -whether due to undernutrition or overnutrition - can alter physical indicators in newborns, such as body mass index (BMI), with implications for metabolic syndrome [8].

Polyunsaturated fatty acids (PUFAs) play a key role in maternal nutrition because they influence fetal programming and epigenetic regulation [9, 10]. A study showed that maternal diets containing omega-3 or docosahexaenoic acid (DHA) improved the blood lipid profile of rat offspring [11]. Conversely, offspring of mothers fed a diet rich in saturated fatty acids exhibited increased body mass, visceral fat, adipocyte hypertrophy, and insulin resistance [12]. Additionally, such diets may decrease antioxidant defense mechanisms and contribute to cellular senescence in the liver of adult rats, increasing the risk of chronic liver disease [13].

Research on rats suggests that diets rich in omega-3 during pregnancy and lactation can modulate the expression of genes involved in lipid metabolism regulation and the inflammatory response, leading to reductions in adiposity and serum leptin levels [14], as well as a decreased risk of cardiovascular and metabolic diseases [15].

Several vegetables are sources of essential fatty acids, including pequi [16, 17]. Pequi, consumed in various forms such as jellies, creams, liqueurs, and primarily in natura, is notable for its lipid content, which ranges from 27% to 35%. Its pulp contains about 60% unsaturated fatty acids [18], while the nuts contains approximately 50% fat, primarily oleic, palmitic, and linoleic acids [19, 20].

Importantly, the pulp and nuts of pequi differ substantially in their nutritional and bioactive composition [21], which justifies their simultaneous investigation. The pulp presents a higher carbohydrate content, including simple sugars such as glucose and fructose [22], as well as a considerable proportion of saturated fatty acids [23], which may contribute to lipogenesis and metabolic alterations [24]. In contrast, the nuts are richer in proteins and lipids, particularly monounsaturated fatty acids such as oleic acid [25], which are associated with beneficial effects on lipid metabolism, including increased HDL levels [26].

Pequi is also a rich source of bioactive compounds such as carotenoids, phenolic compounds, and flavonoids [19, 27]. Studies have demonstrated pequi's anticancer effects [28] and anti-diabetic activity [29] in vitro. In rats, maternal consumption of pequi has been shown to reduce anxiety-like behavior in offspring [19], and research has indicated low toxicity with pequi pulp oil consumption [30].

Despite these findings, most studies have evaluated pequi as a whole fruit or focused only on its pulp, with limited attention to the nuts. Given the distinct nutritional profiles of these fractions, it is essential to investigate them separately to better understand their specific biological effects. This distinction is particularly relevant in the context of maternal nutrition, where different lipid sources can differentially influence fetal programming, metabolic regulation, and oxidative stress in offspring.

However, no studies have investigated the effects of maternal consumption of pequi pulp and nuts on the physical and biochemical outcomes of offspring. This way, we hypothesize that maternal consumption of pequi improves physical parameters, glycemic metabolism, lipid profile, and provides protection against oxidative liver damage in both mothers and offspring treated during gestation and lactation. Therefore, the aim of this study was to investigate the effects of consuming pequi pulp and nuts on the physical, biochemical, and hepatic oxidative parameters of lactating mothers and their adolescents offspring treated during early life.

Materials and methods

Raw material

Pequi fruits were purchased from a local market in Chapada do Araripe, Ceará, Brazil (-7.12732, -39.59378), under SISGEN registration number AE90D7F. The fruits were carefully packed in Low-Density Polyethylene (LDPE) vacuum-sealed plastic bags, then frozen at -18 °C. For transport, the fruits were placed in insulated thermal boxes with ice and transported in a dedicated vehicle to ensure their integrity. Upon arrival at the Bromatology Laboratory (LABROM) at the Education and Health Center/UFCG, the fruits were in good condition for processing to obtain both pulp and nuts.

The fruit selection process involved manually discarding any that showed physical damage, such as cuts or perforations in their shells. The remaining fruits were cleaned and

sanitized using a 2.5% sodium hypochlorite solution, with one tablespoon of hypochlorite per liter of water. After peeling the fruits manually with a stainless steel knife, the pulp was removed through a brief heat treatment (blanching). The pequi pulp was then manually separated from the seeds using a knife.

To obtain both the pulp and the nuts, the pulp was dried in a forced air circulation oven at 60 °C for 24 h, while the seeds were dried for 48 h to facilitate nuts extraction. Once dried, the pulp was allowed to cool at room temperature. Both the pulp and nuts were then crushed using a conventional blender (Mondial L-74 10v Class II), vacuum-packed, and stored in a freezer at -18 °C (±2 °C). Proper identification was made, and the samples were stored for a maximum period of two months before use in further research.

Biological tests

Animals and experimental diets

Eighteen primiparous female Wistar rats, aged 90 days or more and weighing 250 ± 50 g, were used to obtain lactating rats. Mating was conducted at a ratio of one male per female. After pregnancy was confirmed, the rats were housed individually in polypropylene maternity cages under standard laboratory conditions (temperature: 22 ± 1 °C, humidity: 65 ± 5%, and a 12/12-hour light/dark cycle, with artificial lighting from 6:00 a.m. to 6:00 p.m.). The dams were randomly divided into three groups ($n = 6$ per group), according to the treatment received: Control Group – administered distilled water; Pulp Group – administered 2000 mg/kg of body weight of pequi pulp; and Nuts Group – administered 2000 mg/kg of body weight of pequi nuts. All animals received standard commercial chow (Presence®) and water ad libitum, and litters were standardized to six pups per dam. After weaning, the offspring were allocated into three groups ($n = 10$ per group), corresponding to the maternal treatments: Control Group, Pulp Group, and Nuts Group. Only male offspring were included in the analyses. All animals were housed in collective cages with free access to standard commercial chow (Presence®) and water ad libitum.

The energy value and composition of pequi nuts and pequi pulp in commercial feed are described in Table S1 and Table S2. Total energy intake was calculated based on the macronutrient composition of the consumed diets, using Atwater conversion factors (4 kcal/g for proteins and carbohydrates, and 9 kcal/g for lipids). The contribution of each dietary component (standard diet, pequi pulp, and pequi nut) was considered according to its respective intake. Energy density (kcal/g) was determined by dividing the total energy intake by the total amount of food consumed over the same period.

The solutions were administered by gavage to the mothers during pregnancy and lactation. The experimental protocol followed the ethical guidelines set by the National Institutes of Health (Bethesda, USA) for animal care. The study protocol was approved by the Ethics Committee on Animal Use (CEUA) of the Center for Rural Health and Technology (CSTR/UFCG), under protocol number CEUA/CSTR Nº04/2020.

Murinometric assessment

On the final experimental day, body weight was measured using a Balmax® digital electronic scale (model ELP-25, max capacity: 500 g). Naso-anal length was measured with a tape measure fixed to a flat surface. Abdominal circumference (AC) and thoracic circumference (TC) were measured using a flexible tape. Body Mass Index (BMI) was calculated by dividing weight (g) by the square of height (cm^2) according to the method of [31]. The Lee index was calculated as the cube root of body weight divided by naso-anal length, following the methodology described by Bernardis et al. (1986). These measurements were taken for both lactating mothers and their offspring. The adiposity index (AI) was calculated using the formula: [body fat weight (epididymal + visceral + retroperitoneal)/body weight] x 100 [32].

Body fat

Immediately following euthanasia under analgesia, blood was collected via cardiac puncture, and visceral fats from the mesenteric and retroperitoneal regions (for both mothers and offspring) as well as epididymal fat (for offspring) were removed and weighed.

Biochemical analyses

Blood collected by cardiac puncture was centrifuged at 14,616 g for 15 min using a Centribio® centrifuge (New Technique NT810/RH4 × 50 A). The supernatant was used for biochemical analysis of total cholesterol, HDL cholesterol, triglycerides, and fasting blood glucose, utilizing enzymatic methods. These were analyzed with a commercial kit from Labtest (Minas Gerais, Brazil), with absorbance readings taken using a spectrophotometer. The Index of Insulin Resistance was calculated as the Ln[fasting triglycerides (mg/dL) x fasting glucose (mg/dL)/2]. The TyG index is expressed by a logarithmic scale [33].

Determination of malondialdehyde (MDA) in liver

For the determination of malondialdehyde (MDA) levels, liver tissue samples were weighed. The amount of Tris HCl buffer added to each sample was calculated using a 1:5 (w/v) ratio based on the weight. The liver tissue was cut for approximately 15 s and then homogenized in cold conditions using an Ultra Stirrer (Ultra 80) with added Tris HCl buffer. The homogenate was centrifuged at 2500 g for 10 min at 4 °C using a refrigerated bench centrifuge (SL 701, SOLAB, Piracicaba, São Paulo, Brazil). A 300 µL aliquot of the supernatant was collected and transferred to a 2 mL Eppendorf tube, to which 750 µL of chromogenic reagent and 225 µL of hydrochloric acid (HCl – 37%) were added.

The mixture was incubated in a thermostatic water bath (SL 150, SOLAB) with agitation at 45 °C for 40 min. It was then centrifuged again at 2500 g for 5 min at 4 °C. A 300 µL aliquot of the supernatant was placed in a 96-well microplate, in duplicate, and analyzed using a microplate reader (Polaris) at a wavelength of 586 nm. Malondialdehyde (MDA) content was determined by interpolation on a standard curve with 1,1,3,3-tetraethoxypropane, which hydrolyzes during the incubation step with HCl at 45 °C, producing MDA. The results were expressed in mol/g of tissue [34].

Determination of fatty acid profile of the liver

To determine the fatty acid profile of the liver, the lipid extract of the product was first obtained using the method of [35]. From this extract, methyl esters were obtained by esterification following the methodology of [36]. The identification and quantification of methyl esters were carried out in a Ciola & Gregori Ltda gas chromatograph (model CG-Master), with a flame ionization detector. The chromatographic analysis used a polyethylene glycol column (Carbowax 20 M), with fused silica, 30 m long, 0.53 mm in diameter, and 0.25 µm thick stationary phase film. The vaporizer and detector temperatures were 150 °C and 200 °C, respectively. The oven program was 80 °C for 30 min, with an increase of 10 °C/minute up to 180 °C. The mobile phase was hydrogen, with a flow rate of 5 mL/minute. A volume of 1 µL was injected, with a split ratio of 1:25. The characterization of fatty acids was carried out by comparing the mass spectrum obtained with standards also injected into GC-MS.

Statistical analysis

Data were analyzed using a one-way ANOVA test, followed by Tukey's post-hoc test. A significance level of $p<0.05$ was used to reject the null hypothesis.

Results

Physical parameters of mothers and offspring

In lactating mothers and their offspring, measurements of physical parameters showed no significant differences in abdominal and thoracic circumferences, or the ratio of these circumferences to body length, between the experimental pulp and nuts groups compared to the control group ($p>0.05$). However, both mothers and offspring in the nuts and pulp groups exhibited significantly lower weight, BMI, and Lee index compared to the control group ($p\leq0.05$) (Table 1).

In dams, the adiposity index was higher in the Pulp group compared to Control, while Nuts showed no difference; concurrently, insulin resistance was reduced in both treatments relative to Control, with a greater decrease in Pulp than in

Table 1 Murinometric parameters at the end of lactation of rats treated with pequi nuts or pulp during pregnancy and lactation and their offspring

	MOTHER			OFFSPRING		
	CONTROL	NUTS	PULP	CONTROL	NUTS	PULP
Final Body Weight	237.33±18.62	214.16±8.21*	214.57±5.77*	237.33±20.40	214.16±8.99*	214.57±6.24*
TC (cm)	13.56±0.60	13.17±0.57	13.41±0.93	13.56±0.67	13.11±0.66	13.53±0.90
AC (cm)	15.72±0.17	15.52±0.72	15.91±0.60	15.65±0.12	15.44±0.77	15.94±0.61
AC/TC	1.16±0.04	1.15±0.06	1.18±0.08	1.16±0.04	1.19±0.08	1.17±0.08
Body Length (cm)	21.16±0.62	20.81±0.27	20.71±0.99	21.00±0.71	20.66±0.40	20.77±1.22
BMI (g cm^{-2})	0.56±0.03	0.49±0.01*	0.51±0.05*	0.56±0.02	0.48±0.01*	0.47±0.03*
Lee Index	3.98±0.18	3.43±0.11*	3.54±0.23*	3.92±0.18	3.43±0.12*	3.40±0.22*
Adiposity Index	2.09±0.17	2.00±0.46	2.63±0.18*#	2.88±0.26	1.64±0.25*	3.15±0.31
Index of Insulin Resistance	17.69±4.57	12.27±3.39*	6.53±3.07*#	2.18±0.70	6.59±2.46*	15.31±5.58*#

CT Thoracic circumference, *AC* Abdominal circumference, *BMI* Body mass index

Data are expressed as mean±standard deviation ($n=6$ per group for dams; $n=10$ per group for offspring). *Indicates a significant difference versus the control group ($p<0.05$), and # indicates a significant difference versus the Nuts group ($p<0.05$). Data were analyzed using a one-way ANOVA followed by Tukey's post hoc test

Nuts. In the offspring, the adiposity index was significantly reduced in the Nuts group compared to Control, whereas Pulp showed higher values; in parallel, insulin resistance increased in Nuts and was markedly higher in Pulp compared to Control.

Body fat

In the mothers, total and mesenteric fat were significantly increased in the pulp group compared to both the Nuts and control groups ($p \leq 0.05$). The Nuts group also showed an increase in these fats when compared to the control ($p \leq 0.05$) (Fig. 1A and C). Retroperitoneal fat showed no significant difference between the experimental groups ($p > 0.05$) (Fig. 1E).

In the offspring, all fat types analyzed were significantly reduced in the Nuts group compared to the other groups ($p \leq 0.05$) (Fig. 1B, D and F, and 1G). The pulp group exhibited higher levels of total, mesenteric, and epididymal fat compared to the control group ($p < 0.05$) (Fig. 1F and G).

Biochemical parameters

In the lactating mothers, plasma glucose and triglycerides were significantly lower in the Nuts group compared to the pulp group (Fig. 2A and C). Total cholesterol levels were higher in the Nuts group compared to the control (Fig. 2E), and HDL levels were elevated in the Nuts group compared to both the control and pulp groups (Fig. 2G). The pulp group also had higher HDL levels than the control group ($p < 0.05$).

In the offspring, maternal consumption of pequi pulp led to an increase in plasma glucose levels compared to the other groups (Fig. 2B). Triglyceride levels were higher in the pulp group compared to all groups, and the Nuts group showed higher levels compared to the control (Fig. 2D). Total cholesterol levels were elevated in the Nuts group compared to all groups, and the pulp group also had higher cholesterol compared to the control (Fig. 2F). HDL levels were similar between both pequi-treated groups but were significantly higher than the control group (Fig. 2H) ($p < 0.05$).

Liver fatty acids

In the maternal liver, myristic fatty acid levels were significantly lower in both the nut and pulp groups, while in offspring, myristic acid was reduced only in the pulp group. Palmitic acid was significantly higher in the offspring of the pulp group compared to all other groups. Stearic acid levels were elevated in the maternal liver of both the nut and pulp groups compared to the control group, while offspring from the pulp group showed reduced stearic acid levels compared to all other groups.

For MUFAs, palmitoleic acid levels in the maternal liver were lower in both experimental groups compared to the control. Margaric acid levels were decreased in the pulp group compared to the other groups. In offspring, palmitoleic acid was higher in the nut group, while margaric acid was lower compared to both the control and pulp groups.

For PUFAs, the maternal liver showed increased levels of arachidonic, linoleic, and docosahexaenoic acids in the pulp group compared to the other groups. Docosatetraenoic acid was lower in the nut group compared to the control and in the pulp group compared to all other groups. In the offspring, arachidonic and docosahexaenoic acids were decreased in both pequi-treated groups, while docosatetraenoic acid was increased in both the nut and pulp groups compared to the control (Table 2).

Hepatic malondialdehyde (MDA)

Hepatic malondialdehyde (MDA) levels indicated increased lipid peroxidation in mothers treated with both Nuts and pequi pulp compared to the control group (Fig. 3A, $p \leq 0.05$). In the offspring, the Nuts group presented higher malondialdehyde (MDA) levels compared to both the pulp and control groups, while the pulp group exhibited higher levels than the control group ($p \leq 0.05$) (Fig. 3B).

Discussion

Maternal diet has a direct influence on the health of both the mother and her offspring, as nutrient demands increase to support fetal growth and development [37]. The quality of the diet during pregnancy and lactation, particularly the types of fatty acids consumed, significantly impacts the behavioral and metabolic responses of the offspring. These effects are mediated through the placenta during pregnancy and through breast milk during lactation [38]. In this study, we investigated how the consumption of different parts of pequi (pulp and nuts) during pregnancy and lactation affects the metabolism of both mothers and their offspring in rats.

Our findings demonstrate that the consumption of pequi pulp led to increased plasma glucose, triglycerides, and body fat deposition in rats. These effects were either less pronounced or opposite in animals treated with pequi nuts. However, in both pequi-treated groups, oxidative stress was elevated in the liver, and the deposition of PUFAs was reduced in the offspring's liver.

Importantly, these differential effects between pulp and nuts may be explained by their distinct lipid compositions. Pequi pulp is richer in saturated fatty acids, particularly palmitic acid (the fatty acid profile of the pulp and seed can be found in Supplementary Table 1) [19], which is known

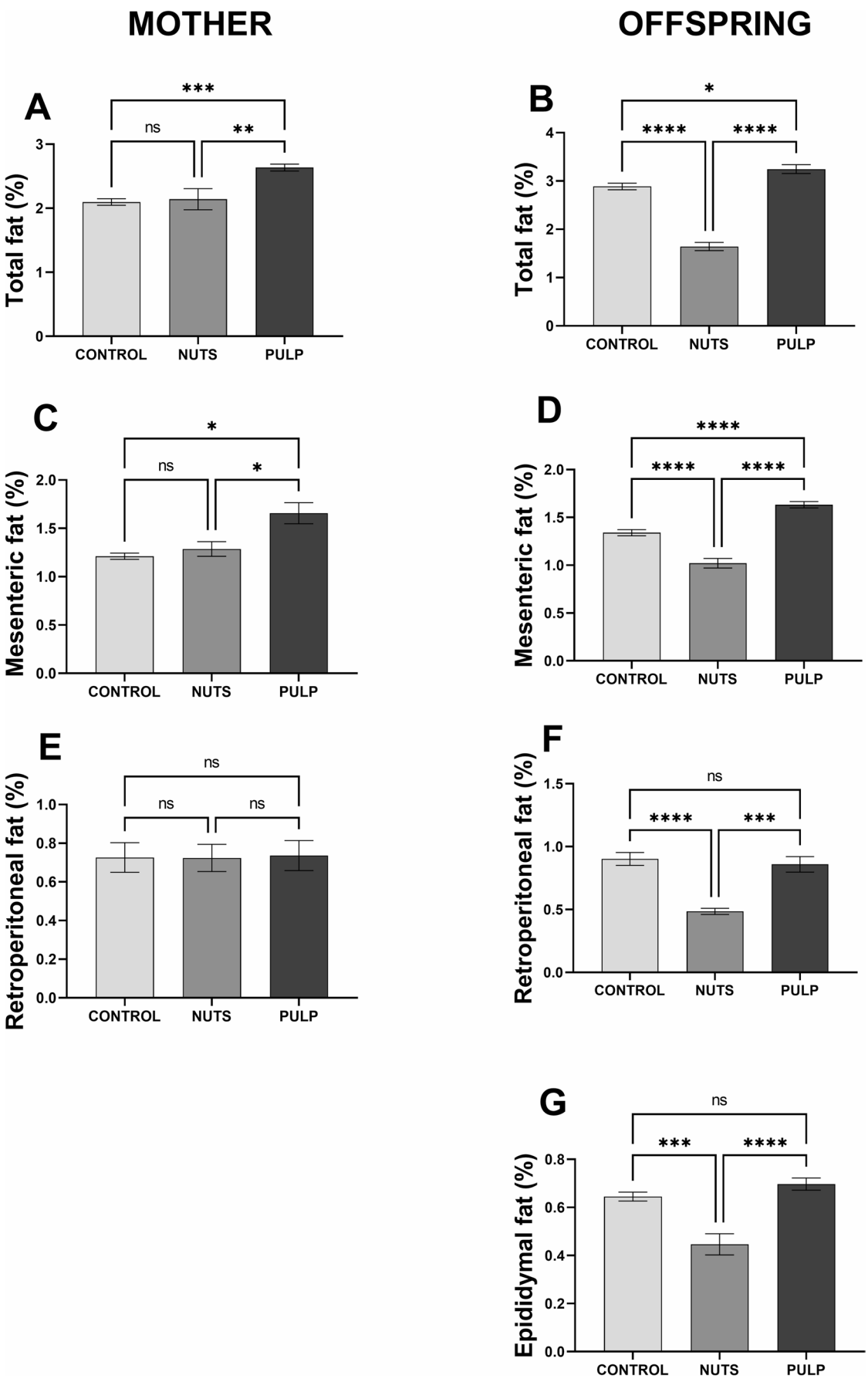

MOTHER
OFFSPRING
A
Total fat (%)
***
ns
**
CONTROL
NUTS
PULP
B
Total fat (%)
*
****
****
CONTROL
NUTS
PULP
C
Mesenteric fat (%)
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CONTROL
NUTS
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Mesenteric fat (%)
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CONTROL
NUTS
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Retroperitoneal fat (%)
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CONTROL
NUTS
PULP
G
Epididymal fat (%)
ns
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CONTROL
NUTS
PULP

Fig. 1 Body Fats at the end of lactation of rats treated with pequi nuts or pulp during pregnancy and lactation and their offspring. **A**, **B**: Total fat (%); **C**, **D**: Mesenteric fat (%); **E**, **F**: Retroperitoneal fat (%); **G**: Epididymal fat (%). Data are expressed as mean ± standard error ($n = 6$ per group for dams; $n = 10$ per group for offspring). *=$p < 0.05$, **=$p < 0.01$, ***=$p < 0.001$, and ****=$p < 0.0001$. Data were analyzed using a one-way ANOVA followed by Tukey's post hoc test

to promote hepatic lipogenesis, impair insulin signaling, and increase VLDL production [39, 40]. These mechanisms likely underlie the observed increases in glycemia, triglycerides, and adiposity, especially in offspring, indicating a more deleterious metabolic profile associated with pulp consumption.

A decrease in body weight was observed in mothers at the end of lactation and in offspring during adolescence, consistent with findings from previous studies where maternal consumption of avocado pulp [15] and cashew nuts [6] during pregnancy and lactation produced similar results. Both avocado and cashew, like pequi, are rich in unsaturated fatty acids, and cashew nuts are also high in protein and fiber, similar to pequi nuts. Foods high in protein (such as pequi nuts) and fatty acids (pequi pulp and nuts) may enhance satiety [41], facilitating weight loss. However, these changes in body weight should be correlated with other physical and biochemical parameters to fully understand their health implications.

In this study, no significant differences were observed in murinometric measurements, but body fat deposition was higher in both mothers and offspring in the pulp group, whereas this deposition was lower in the Nuts group. offspring. This difference might be due to the nutritional composition of pequi, as pequi pulp contains more carbohydrates (11%) and less protein (3%) and fat (33%) compared to Nuts, which contain approximately 8% carbohydrates, 25% protein, and 51% fat [19]. Additionally, the higher carbohydrate content of the pulp, including fructose and glucose, combined with its saturated fatty acid profile, may further exacerbate lipogenesis and fat accumulation, particularly in visceral depots, as observed in both mothers and offspring.

Pequi pulp is also a source of fructose and glucose [19]. Previous studies have shown that fructose consumption increases total body fat, particularly in the abdominal region [42], and in this study, mesenteric fat was increased in the group that consumed pequi pulp in both mothers and offspring. High fructose consumption has been associated with hypertriglyceridemia [43], which was also observed in animals that consumed pequi pulp in this study.

Excessive fruit consumption has been linked to an increased risk of gestational diabetes [44]. Our data also showed elevated plasma glucose levels in both mothers and offspring in the pulp group, similar to results reported in animals fed a fructose-rich diet during pregnancy and lactation [45].

High fructose intake during lactation has been shown to decrease hypothalamic leptin sensitivity in offspring, increasing leptin expression in retroperitoneal adipose tissue and causing hyperinsulinemia [46]. This occurs because fructose metabolism bypasses the liver's regulation and leads to increased uric acid production and lipogenesis in hepatocytes, as well as the activation of inflammatory pathways. These metabolic disruptions can create a fetal environment that predisposes offspring to long-term health risks, as seen in the pulp group of this study.

Although plasma insulin levels were not measured in this study, the insulin resistance index revealed important differences among the groups, indicating that the offspring from the pulp group exhibited relevant metabolic alterations. Specifically, a significant increase in this index was observed in the pulp group (15.31 ± 5.58) compared to the control group (2.18 ± 0.70) and the nut-treated group (6.59 ± 2.46), suggesting impaired insulin sensitivity. However, pequi pulp is not only a source of carbohydrates but also contains saturated (31%), monounsaturated (57%), and polyunsaturated (9%) fatty acids (the fatty acid profile of the pulp and seed can be found in Supplementary Table 1) [19]. This composition has been associated with increased HDL levels, providing cardiovascular benefits. A similar increase in HDL was observed in the seed-treated group, although the effects on biochemical parameters and fat deposition were opposite.

Pequi nuts, which are richer in monounsaturated fatty acids such as oleic acid (the fatty acid profile of the pulp and seed can be found in Supplementary Table 1) [19], may contribute to the observed increase in HDL levels in both mothers and offspring. This effect is consistent with the known role of monounsaturated fats in enhancing reverse cholesterol transport [47, 48]. However, despite this beneficial effect, the high lipid content of walnuts can also contribute to increased total cholesterol and consequently increased oxidative stress [49].

Previous studies on pistachio consumption by rats showed no alterations in biochemical parameters in healthy rats and improvements in glycemia and insulin in diabetic rats [50]. Additionally, açaí consumption during pregnancy and lactation did not alter biochemical, hepatic, or oxidative stress parameters in healthy dams and their offspring, with changes observed only in animals fed a high-fat diet alongside açaí [51]. These animals exhibited reduced hepatic steatosis and oxidative stress in both mothers and offspring [51].

Although pequi does not contain anthocyanins like açaí, its pulp and nuts are rich in phenolics, flavonoids, and carotenoids, which provide antioxidant protection (the fatty acid profile of the pulp and seed can be found in Supplementary

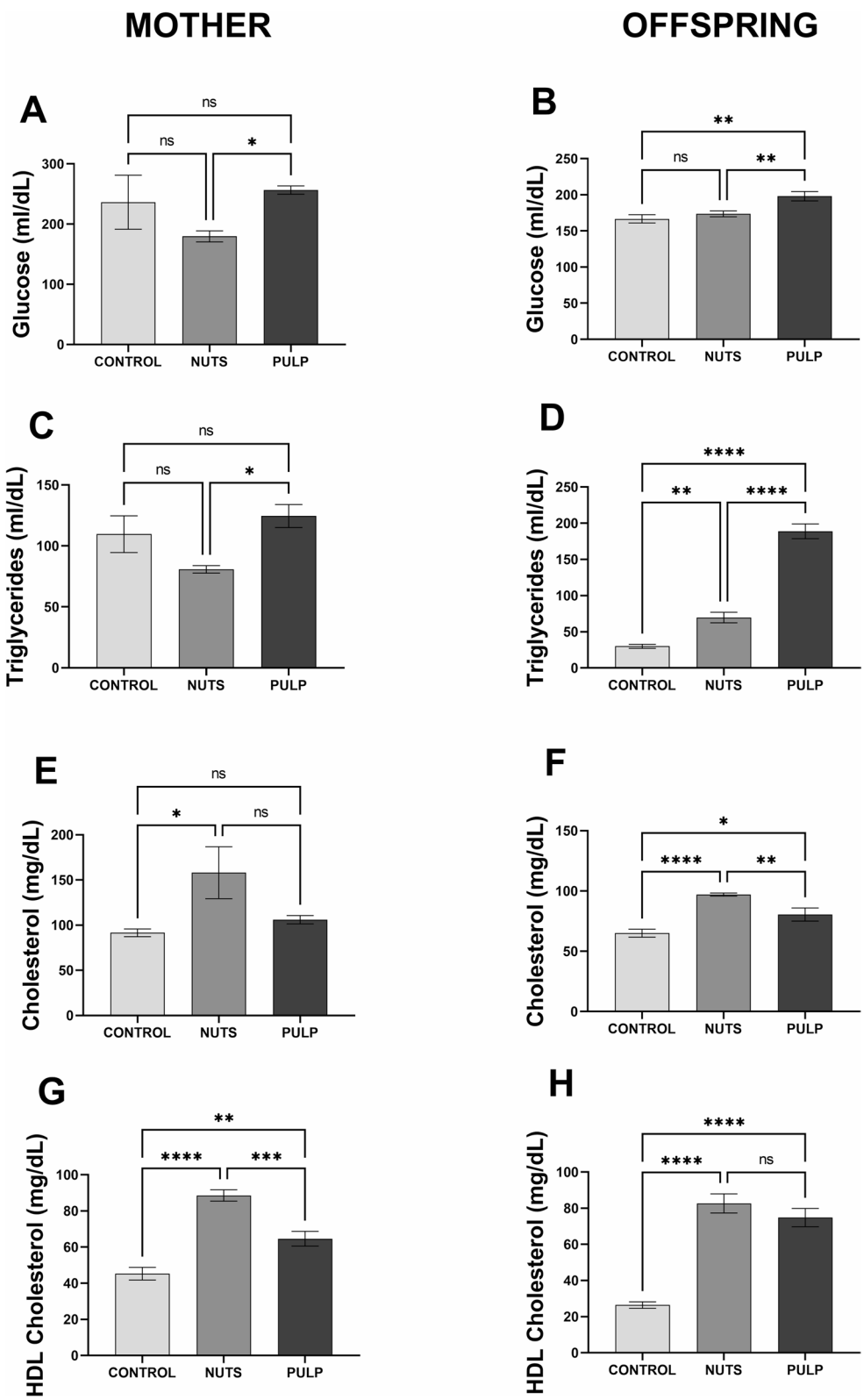


Fig. 2 Biochemical parameters at the end of lactation of rats treated with pequi nuts or pulp during pregnancy and lactation and their offspring. **A**, **B**: Glucose (ml/dL); **C**, **D**: Triglycerides (ml/dL); **E**, **F**: Cholesterol (mg/dL); **G**, **H**: HDL Cholesterol (mg/dL). Data are expressed as mean ± standard error ($n = 6$ per group for dams; $n = 10$ per group for offspring). *=$p < 0.05$, **=$p < 0.01$, and ****=$p < 0.0001$. Data were analyzed using a one-way ANOVA followed by Tukey's post hoc test

Table 1) [19]. However, these antioxidants were insufficient to prevent lipid peroxidation in the liver tissues of mothers and offspring in this study. This may be explained by the excessive availability of fatty acids, which can overwhelm mitochondrial β-oxidation capacity [52, 53], leading to increased electron leakage in the respiratory chain and enhanced production of reactive oxygen species (ROS) [54, 55]. Consequently, even lipid fractions considered

Table 2 Composition of fatty acids present in the liver at the end of lactation of rats treated with pequi nuts or pulp during pregnancy and lactation and their offspring

Fatty Acids (%)	Carbon						
		Dams Control	Dams Nuts	Dams Pulp	Offspring Control	Offspring Nuts	Offspring Pulp
SFA							
Myristic acid	C14:0	0.69 ± 0.03	0.30 ± 0.02*	0.27 ± 0.03*	0.20 ± 0.03	0.26 ± 0.02	0.08 ± 0.01*#
Palmitic acid	C16:0	19.44 ± 0.02	17.60 ± 0.01	18.63 ± 0.02	18.17 ± 0.03	18.50 ± 0.04	23.24 ± 0.02*#
Stearic acid	C18:0	17.77 ± 0.03	20.06 ± 0.02*	20.11 ± 0.02*	19.76 ± 0.02	20.27 ± 0.03*	17.40 ± 0.01*#
TOTAL		**37.9**	**37.96**	**39.01**	**38.13**	**39.03**	**40.72**
MUFA							
Palmitoleic acid	C16:1 ω7	2.88 ± 0.01	1.34 ± 0.02*	1.05 ± 0.01*	0.38 ± 0.03	1.08 ± 0.01*	0.37 ± 0.03#
Oleic acid	C18:1 ω9	18.4 ± 0.03	19.98 ± 0.01	18.74 ± 0.02	10.63 ± 0.03	14.37 ± 0.01*	18.38 ± 0.02*#
TOTAL		**21.28**	**21.32**	**19.79**	**11.01**	**15.45**	**19.21**
PUFA							
Linoleic acid	C18:2 ω6	12.88 ± 0.01	13.51 ± 0.01	16.41 ± 0.01*#	17.52 ± 0.02	17.21 ± 0.03	16.51 ± 0.01
Arachidonic acid	20:4 ω6	13.95 ± 0.01	13.39 ± 0.02	15.54 ± 0.03*#	20.14 ± 0.03	15.77 ± 0.01*	12.88 ± 0.02*#
Docosatetraenoic acid	C22:4 ω6	0.53 ± 0.02	0.43 ± 0.03*	0.34 ± 0.01*	0.44 ± 0.01	0.68 ± 0.02*	0.73 ± 0.03*
Docosahexaenoic acid	C22:6 ω3	2.74 ± 0.01	3.11 ± 0.02	4.04 ± 0.01*#	3.53 ± 0.02	2.11 ± 0.01*	2.53 ± 0.01*
TOTAL		**30.1**	**30.44**	**36.33**	**41.63**	**35.77**	**32.65**
SUMS							
Σ ω6		27.36	27.33	32.29	38.10	33.66	30.12
Σ ω7		2.88	1.34	1.05	0.38	1.08	0.37
Σ ω9		18.40	19.98	18.74	10.63	14.37	18.38

SFA Saturated fatty acids, *PUFA* Polyunsaturated fatty acids, *ω* Omega

Data are expressed as mean ± standard deviation ($n = 6$ per group for dams; $n = 10$ per group for offspring). *Indicates a significant difference versus the control group ($p < 0.05$), and # indicates a significant difference versus the Nuts group ($p < 0.05$). Data were analyzed using a one-way ANOVA followed by Tukey's post hoc test

metabolically beneficial may contribute to oxidative damage when consumed in excess.

As illustrated in Fig. 3, maternal malondialdehyde (MDA) levels were elevated in the pulp group compared to both the nuts and control groups. In contrast, offspring from the pulp group exhibited lower MDA levels than those in the nuts group. These results indicate a differential susceptibility to oxidative stress between mothers and their offspring. Such effects may be explained by developmental programming, whereby early exposure to distinct lipid profiles during gestation and lactation can modulate metabolic pathways and influence antioxidant capacity in the offspring [34, 56, 57].

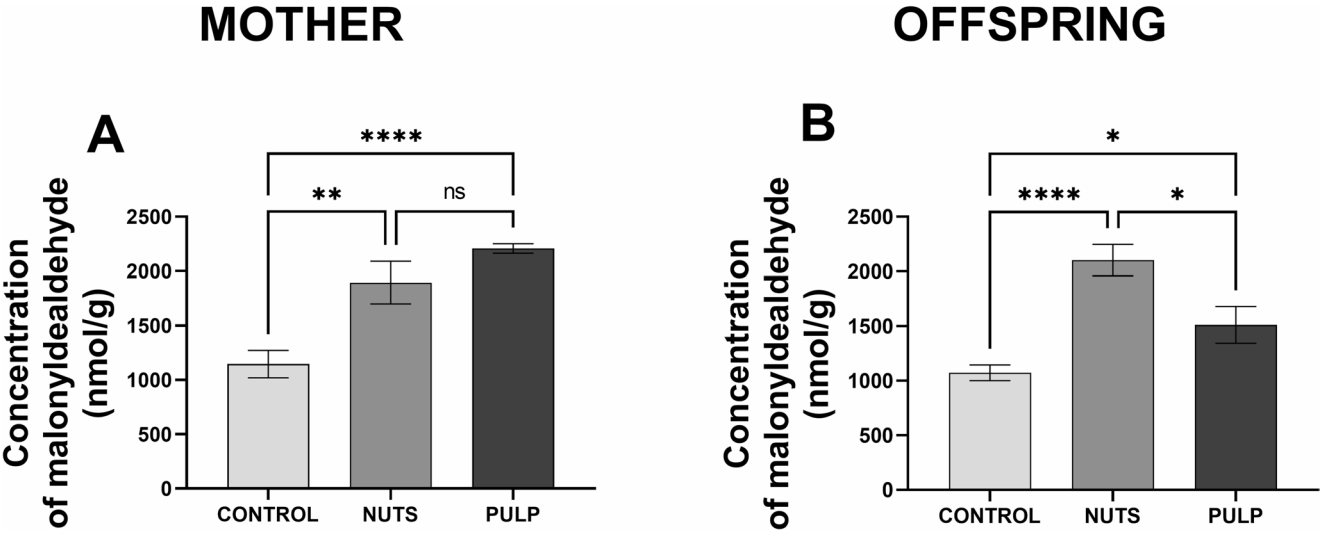


Fig. 3 Hepatic malondialdehyde levels at the end of lactation of rats treated with pequi nuts or pulp during pregnancy and lactation and their offspring. Data are expressed as mean ± standard error ($n = 6$ per group for dams; $n = 10$ per group for offspring). *=$p < 0.05$, **=$p < 0.01$, and ****=$p < 0.0001$. Data were analyzed using a one-way ANOVA followed by Tukey's post hoc test

Overall, pequi pulp appears to promote a more adverse metabolic phenotype, characterized by increased glycemia, triglycerides, adiposity, and oxidative stress, whereas pequi nuts induce a mixed response, with both beneficial effects (increased HDL) and detrimental outcomes (increased cholesterol and oxidative stress).

However, some limitations of this study should be considered, including the lack of data on glycemic curves, insulin levels in the offspring, the absence of HOMA index assessment, and the lack of measurement of important antioxidant enzymes such as superoxide dismutase (SOD), catalase, and reduced glutathione (GSH).

It is important to note that, according to [58], the 2,000 mg/kg dose of pequi pulp and pequi nut used in our rodent study is equivalent to approximately 340 mg/kg in humans. This equivalence is crucial to ensure the safety and efficacy of dosages in future clinical studies.

To mitigate this limitation, the TyG index was included as an indirect marker of insulin resistance, which has been described in the literature as a viable alternative to HOMA in population-based studies [33]. Future studies should investigate these parameters more comprehensively.

Conclusion

Maternal consumption of different parts of the pequi fruit during pregnancy and lactation produced distinct effects on physical, biochemical, and hepatic oxidative parameters in both lactating mothers and their offspring. Intake of pequi pulp was associated with increased blood glucose, triglycerides, and body fat, whereas consumption of pequi nuts resulted in improved metabolic profiles, including reduced lipid and glucose levels and increased HDL concentrations.

Regarding hepatic parameters, maternal pequi intake reduced MUFAs in mothers but increased their deposition in the offspring, while PUFAs were decreased in the offspring of both treated groups, especially in the pulp group. Additionally, both treatments were associated with increased hepatic oxidative stress.

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Authors' contributions **Suedna da Costa Silva Kindelan** : Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation. **Michelly Pires Queiroz:** Methodology. **Maria Elizângela Ferreira Alves:** Writing – review & editing, Visualization, Formal analysis. **Larissa Maria Gomes Dutra** : Methodology. **Juliano Carlo Rufino Freiras:** Methodology. **Vanessa Bordin Viera:** Methodology. **Marta Suely Madruga** : Conceptualization. **Juliana Késsia Barbosa Soares** : Writing – review & editing, Validation, Supervision, Conceptualization.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publishing Not applicable.

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