Food and Chemical Toxicology 217 (2026) 116305

Contents lists available at ScienceDirect

Food and Chemical Toxicology

journal homepage: www.elsevier.com/locate/foodchemtox

Perinatal exposure to polystyrene microplastics: biometric, hormonal and behavioral parameters of male and female Wistar rats at weaning, puberty and adulthood

Nathália Medeiros Nehme [a], Nelyana Oliveira Serpa [b], Mayara da Silva Almeida [a], Beatriz Souza da Silva [a], Luana Lopes de Souza [a], Rosiane Aparecida Miranda [a], Vitor Hugo Santos Duarte Pinheiro [a,c], Alex Christian Manhães [c], Egberto Gaspar de Moura [a], Iala Milene Bertasso [a], Patrícia Cristina Lisboa [a,*]

[a] Laboratory of Endocrine Physiology, Biology Institute, State University of Rio de Janeiro, RJ, Brazil
[b] Laboratory of Endocrine Physiology Doris Rosenthal, Institute of Biophysics, Federal University of Rio de Janeiro, Brazil
[c] Laboratory of Neurophysiology, Biology Institute, State University of Rio de Janeiro, RJ, Brazil

ARTICLE INFO

Handling Editor: Professor Matthew Wright

Keywords:
Microplastics
Perinatal exposure
Endocrine disruption
Metabolism
Behavior

ABSTRACT

Microplastics (MPs) are widespread in environment, being detected in human tissues, as placenta and breast milk. Given their potential endocrine and neurobehavioral effects, we studied whether perinatal exposure to MPs causes dysfunctions in dams and offspring. From gestational day 7 (G7) until weaning, Wistar rat dams received water (control group; n = 9) or 10 μm polystyrene microparticles (25 μg/kg body mass, MP group; n = 8). Biometric and biochemical parameters of dams and offspring were evaluated at weaning (21 days-old), puberty (45 days-old) and adulthood (120 days-old). Behavioral tests were performed at puberty and adulthood. MP dams showed lower body mass from the G10 until delivery but returned to control levels during lactation; also exhibited lower plasma cholesterol and T4 levels at weaning. MP offspring showed age- and sex-dependent alterations in lipid and endocrine homeostasis, including changes in cholesterol, triglycerides, corticosterone, thyroid hormones, leptin and FSH levels. Adult offspring also showed sex-specific behavioral alterations. MP males showed increased anxiety-like behavior during puberty and adulthood, reduced caloric intake and preference for the high-fat diet whereas adult females exhibited increased caloric intake. Thus, perinatal exposure to a single dose of 10-μm polystyrene microplastics was associated with behavior, lipid and endocrine disturbances in both dams and offspring.

1. Introduction

Since the 1950s, the global market has seen an increase in the production and consumption of plastic. The advantages of this material to preserve and transport food and water compared to other materials are undeniable, such as low cost, easy handling and manufacturing, high resistance, good rigidity and malleability (Nayanathara Thathsarani Pilapitiya and Ratnayake, 2024). Due to these advantages, annual plastic production has increased from 234 million in 2000 to 460 million tons in 2019 ("Global Plastics Outlook economic drivers, environmental impacts and policy options," 2022), and is projected to reach 1 billion in the next 25 years, if regulatory policies remain unchanged (Ritchie et al., 2023). The consequence of the excessive production and consumption of plastics is the generation of waste that may accumulate for centuries in the environment due to the improper disposal and handling of these materials (Geyer et al., 2017; Nayanathara Thathsarani Pilapitiya and Ratnayake, 2024). Plastics are degraded into smaller particles (microplastics, MPs) by the action of microorganisms, ultraviolet radiation, high temperatures, mechanical action and chemical degradation. MPs also accumulate and amplify the biological and environmental effects of plastics, being an emerging pollutant (Liu et al., 2022).

MPs are particles with a diameter of less than 5 mm that appear as foam, fiber, fragments or microspheres, and are classified according to their origin as primary or secondary. Primary MPs are those

* Corresponding author. Universidade do Estado do Rio de Janeiro - Instituto de Biologia, Departamento de Ciências Fisiológicas, 5º andar, Av. 28 de Setembro, 87-Rio de Janeiro, RJ, 20551-031, Brazil.
E-mail address: pclisboa@uerj.br (P.C. Lisboa).

https://doi.org/10.1016/j.fct.2026.116305
Received 21 April 2026; Received in revised form 28 July 2026; Accepted 29 July 2026
Available online 29 July 2026

intentionally produced in small dimensions for direct use in industry, being part of the composition of exfoliating cosmetics, glitter and synthetic fabrics. Secondary MPs are those originated from the environmental degradation of macroplastics such as bottles, bags and nets (Salvador Cesa et al., 2017; Ullah et al., 2023). It is estimated that, annually, an individual is exposed through inhalation, ingestion, or dermal contact to between 74,000 and 121,000 plastic particles present in atmospheric air, food and beverages. Although these values may vary depending on exposure scenarios and the methodological approaches used for particle detection, identification and quantification, they provide a useful estimate of human exposure to microplastics (Barceló et al., 2023; Ziani et al., 2023; Zurub et al., 2023).

In 2021, MPs (5–10 μm), including polypropylene-containing particles, were detected for the first time in human placentas (Ragusa et al., 2021). Since then, MPs have been observed in breast milk samples, where particles ranging from 2 to 12 μm were mainly composed of polyethylene, polyvinyl chloride, and polypropylene (Ragusa et al., 2022). In blood, particles ≥0.7 μm including polyethylene terephthalate (PET), polystyrene (PS), and polyethylene (PE), were detected (Leslie et al., 2022). In the lungs, MPs ranging from approximately 12 to 2475 μm were predominantly composed of polypropylene and PET (Jenner et al., 2022). In cardiac tissues, MPs ranging from approximately 20 to 469 μm were identified, including PET, polyurethane (PU) and poly(methyl methacrylate) (PMMA) (Yang et al., 2023). MPs ranging from approximately 21.8 to 286.7 μm were also identified in human testicular tissue and semen, with polystyrene predominating in the testis and polyethylene and polyvinyl chloride being the major polymers detected in semen (Zhao et al., 2023). More recently, micro- and nanoplastics, predominantly polyethylene and mainly in the nanoscale range (approximately 100–200 nm), were detected in human brain tissue (Campen et al., 2024).

The studies described above have reported different sizes and polymer types of plastic particles. These findings have raised several questions regarding the consequences of exposure to plastic particles on human health, and a considerable number of experimental studies have been conducted to investigate the mechanisms underlying these effects. Cell cultures and animal models have shown that MPs can affect digestive, respiratory, endocrine, reproductive, and immune systems (Lee et al., 2023). In experimental rodent models, the ingestion of MPs causes bioaccumulation, inflammation, and oxidative stress in the liver (Deng et al., 2017), lungs (Lim et al., 2021), intestine (Li et al., 2020), brain (Estrela et al., 2021), gonads (Jin et al., 2021), and placenta (Fournier et al., 2020), in addition to altering the immune response and lipid metabolism of offspring (Luo et al., 2019a). The presence of MPs in both human placenta and breast milk, and in the fetal tissues of experimental rodents, confirms their ability to contaminate offspring. The plasticity of the perinatal period makes individuals highly sensitive to physiological changes and, therefore, insults during this phase can cause important metabolic changes during adult life (Lisboa et al., 2021). Therefore, thorough investigations are needed to identify health-related consequences of early MP exposure and elucidate associated mechanisms.

In the literature, there are some studies using rodent models to evaluate the short- and long-term effects of MP exposure exclusively during pregnancy and lactation (Cheng et al., 2025; Lu et al., 2024; Luo et al., 2019a, 2019b; Zhang et al., 2023). In mice, Luo et al. (2019a) administered the 5 μm polystyrene MPs solution (100 and 1000 μg/L) via drinking water and showed metabolic disorders associated with gut microbiota dysbiosis, liver transcription disorders, and serum metabolites (such as cholesterol and triglycerides) in F1 and F2 generations. As one of the few experimental studies to evaluate microplastic exposure during pregnancy and lactation, this work demonstrated measurable biological effects at relatively low exposure levels. Consequently, its findings guided the selection of the particle size and the exposure dose adopted in the present study. The rationale was that if biological effects could be detected at such a small particle size and low exposure dose, these findings could have important implications for the establishment of public policies regarding population exposure to microplastics.

Based on this previous report, in rats, we designed a similar model of maternal MP exposure during perinatal period to investigate, for the first time, biometric, lipid and hormonal parameters of dams and male and female offspring at the end of exposure (weaning). The offspring were also studied during puberty and adulthood, during which periods we evaluated anxiety-like and eating behaviors. The hypothesis of the present study is that maternal exposure to polystyrene microparticles during gestation and lactation may induce short- and long-term alterations in metabolic homeostasis, lipid metabolism, endocrine regulation of major physiological axes such as the hypothalamic-pituitary-adrenal (HPA) and hypothalamic-pituitary-thyroid (HPT) axes, as well as anxiety-like and feeding behaviors in the offspring.

2. Materials and methods

2.1. ARRIVE statement

The experimental design was approved by the Animal Care and Use Committee of the Biology Institute of UERJ (CEUA 033/2022), which based its analysis on the principles adopted and promulgated by the Brazilian Law (no. 11.794/2008). All animal procedures were conducted in accordance with the ARRIVE guidelines and the NIH Guide for the Care and Use of Laboratory Animals (National Research Council, US) and all experiments and data analyses were performed in a blinded manner. Wistar rats were housed in a temperature-controlled vivarium (23 ± 1°C) with an artificial light/dark cycle (lights on from 7:00 a.m. to 7:00 p.m.), free access to water and standard diet for rodents (Nuvilab, São Paulo, Brazil). For 24 h, 3-months-old nulliparous female rats in estrous were mated with males at a proportion of two females:one male. The successful copulation was confirmed by examination of a vaginal smear for the presence of sperm, vaginal plug detection, estrous cycle monitoring and body mass evaluation.

2.2. Experimental design of perinatal exposure to microplastic

As depicted in Fig. 1, on 7th gestational day (G7), pregnant rat dams were assigned alternatively to one of two groups: MP (Microplastic group, n = 8) or CON (Control group, n = 9). However, there was no randomization, which represents a limitation of the study design.

The MP group received 25 μg/kg body mass/day of 10 μm polystyrene microparticles (72986 - Sigma Aldrich, São Paulo, Brazil) diluted in filtered water while the CON group received filtered water. From G7 until weaning (Postnatal day 21 - PND21), dams received the treatment by intragastric gavage. On the day after birth, all litters were adjusted to six pups per dam (3 males and 3 females) to maximize lactation performance and to ensure standardized nutrition until weaning (Passos et al., 2000). One male and female offspring per dam were euthanized at weaning (PND21), puberty (PND45) and adulthood (PND120), ensuring that the litter was considered the experimental unit.

2.3. Biometric parameters

During gestation and lactation, the dams' body masses (BM) and food intake were recorded daily. The pups' body masses were monitored every day from birth until PND21. At the 9th lactational day, pups milk intake was evaluated. For this, they were separated from their dams for 2 h, then they were weighed and placed with their dams for 1 h. After this period of ad libitum feeding, all pups were weighed again. From weaning onward, male and female offspring were housed in same-sex groups and received standard rodent chow. Chow consumption was measured per cage and expressed as the mean consumption per animal. Body mass and food intake were monitored two days per week until PN120.

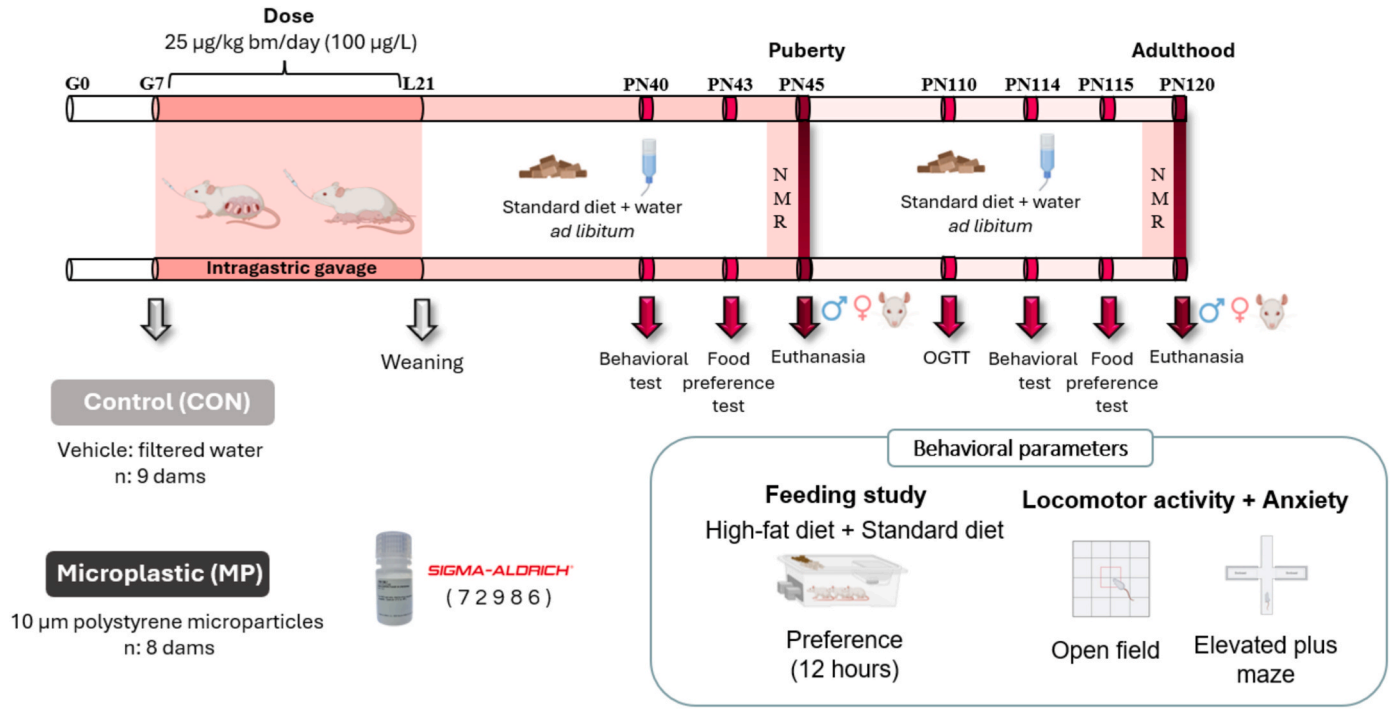

Fig. 1. Experimental model of perinatal exposure to microplastics. CON, Control group; MP, Microplastic group; G0, gestational day 0; G7, gestational day 7; L21, lactation day 21; PN40, postnatal day 40; PN43, postnatal day 43; PN45, postnatal day 45; PN114, postnatal day 114; PN115, postnatal day 115; PN120, postnatal day 120; NMR, nuclear magnetic resonance; BM, body mass.

2.4. Milk collection and analysis

At PND10 and PND18, dams were separated from the pups for 2 h and milk samples were collected. To induce milk secretion, synthetic oxytocin (Oxiton® 5U.I./mL, SP, Brazil) was administered (i.p.) and 10 min later, dams were lightly anesthetized with thiopental (Thiopentax® 50 µg/mL i.p.). Milk was extracted by gently stripping the thoracic and abdominal teats, being collected in a microtube and used for the quantification of carbohydrates, total protein and total fat (Rodrigues et al., 2018).

Carbohydrate content was measured by a colorimetric method using picric acid (Vetec Química fina LTDA, RJ, Brazil) (Khramov et al., 2008), commercial lactose being used as a standard (Sigma-Aldrich Co, St. Louis, MO, USA). Total protein content was estimated by the colorimetric method described by Peterson (1977) (Peterson, 1977), using bovine serum albumin (Sigma, St. Louis, MO, USA) as a standard. Total lipids content was determined by a colorimetric method using a commercial kit according to the manufacturer's instructions (Bioclin, Belo Horizonte, MG, Brazil).

All milk composition analyses were performed in duplicate using previously validated methodologies, and samples from all experimental groups were analyzed under identical analytical conditions.

2.5. Behavioral tests

2.5.1. Anxiety-like behavior and locomotion assessments

The elevated plus maze (EPM) and the open field (OF) tests were performed either on PND40 or on PND114; different animals were used at each age. The order of behavioral testing was not counterbalanced; all animals were evaluated first in the EPM and subsequently in the OF test 24 h later. However, the lack of counterbalancing may be a limitation of the study design. All behavioral tests were conducted in a sound-attenuated room. Animals were allowed a minimum of 10 min of habituation to the environment before the testing session began. Animals were tested under indirect light (40 lux at maze/arena level). After each test, animals were immediately returned to their home cage. The maze and the arena were cleaned with a 35% ethanol solution and dried between tests. All behavioral tests were video recorded. Behavior was assessed by a blind experimenter using the recorded images.

The EPM was performed to evaluate the animals' anxiety-like behavior. The EPM had 4 arms, 2 without protective walls (open arms – OA; 50 × 10 cm) and 2 with walls (closed arms – CA; 50 × 10 × 40 cm), arranged perpendicularly and 40 cm above the floor. Each animal was placed in the center of the maze and had 5 min to explore the maze. The total time spent and the number of entries into the open and closed arms, and the central area (CA) of the maze were recorded. The percentages of time spent in the open arms and entries into the open arms were used as measures of anxiety (Silva et al., 2019).

The OF was used to evaluate locomotor activity and anxiety-like behavior of the animals, being performed 24 h after the EPM. In this test, the enclosed arena (60 × 60 × 50 cm) had a floor divided by lines into 16 squares of the same size (12 external and 4 internal), defining central and peripheral areas. After being placed in the periphery of the arena, each animal was allowed to explore it for 5 min. Locomotor activity was quantified based on the number of rectangles crossed by the animals in the center (CN) and in the periphery (P). A crossing was considered valid when the animal crossed the line with all four paws (Silva et al., 2019).

2.5.2. Feeding behavior: preference test

On PND43 and PND115, animals did a food challenge test with a high-fat diet (HFD). Males and females were fasted from 7:00 a.m. to 7:00 p.m. Palatable food was offered during the active period of the rat, and animals were allowed to choose freely between the two diets: standard and HFD (PragSoluções Biociências, São Paulo, Brazil - Table S1). In each cage, the food compartment was divided into two sides, with each of the diets being offered on one of the sides. After a 12-h fasting period, the diets were offered continuously for 12 h. The diet consumption was considered as the difference between the initial and final diet present in each cage (Soares et al., 2022).

2.6. Oral glucose tolerance test (OGTT)

After fasting (12 h), a blood sample was collected from the tail of 120-day-age female and male offspring to determine basal glycemia (Time 0) using a glucometer (OneTouch Ultra®, Johnson & Johnson, São Paulo, Brazil). Then, glucose (50%) was administered in sterile saline (0.9% NaCl) via an oral probe at 2 g/kg of BM. The level of glucose was evaluated 15, 30, 60 and 120 min after the administration (Pietrobon et al., 2020). No animals were excluded from the OGTT analysis.

2.7. In vivo body composition evaluation – nuclear magnetic resonance (NMR)

At the day before the euthanasia, the total fat and lean mass of the offspring were evaluated using an NMR equipment for small animals (Minispec LF90 TD-NMR, Bruker, Rheinstetten, Germany). A quality control check of internal voltages, temperature, magnets, and parameters was performed using a standard provided by the manufacturer. The instrument was routinely calibrated and subjected to quality control according to the manufacturer's recommendations using the supplied reference standard. Non-anesthetized rats were placed in a clear plastic cylinder and kept immobile by insertion of a tight-fitting plunger into the cylinder. Then, the tube was inserted in the chamber of the NMR for approximately 2 min (duration of the scan). Results are shown as percentage (%) of fat mass and of lean mass.

2.8. Euthanasia

At weaning (PND21), one pup from each sex and litter was euthanized after a 2-h fast and the dams after a 12-h fast. At puberty (PND45) and adulthood (PND120), one offspring from each sex and litter was euthanized after 12-h fast. All rats were euthanized by quick decapitation. At PND90, the estrous cycle of all female offspring was evaluated every day (8:00 a.m.) by vaginal smears and they were euthanized during diestrus. To minimize physiological variability associated with the estrous cycle, all hormonal and tissue analyses in adult females were performed using samples collected during diestrus.

The total blood was collected in heparinized tubes and centrifuged (1500 ×g/20 min, 4°C) to obtain plasma, which was kept frozen (−20°C) until assaying. The visceral fat depots (retroperitoneal, gonadal and mesenteric), thyroid, adrenal gland, pancreas and gonads (testicles and ovaries - only in adulthood) were dissected out, weighed and immediately frozen (−80°C).

2.9. Plasma analysis

Before euthanasia, the dam's and offspring's fasting glycemia was measured from the tail tip using a handheld glucometer (OneTouch Ultra®, Johnson & Johnson, São Paulo, Brazil). Plasma cholesterol (CHOL) and triglycerides (TG) concentrations were determined using Biosystem® commercial test kits (Bioclin, Belo Horizonte, MG, Brazil), following the manufacturer's instructions. Plasma insulin, leptin, thyroid hormones, thyrotropin (TSH), corticosterone, estradiol, testosterone, follicle stimulating hormone (FSH) and luteinizing hormone (LH) levels were determined using commercial kits, as depicted in Table S2. In the hormone assays, some data points were excluded because they fell outside the assay's standard curve range and/or were identified as outliers by Prism software. The number of samples was never lower than five per group.

2.10. Statistical analyses

Results were expressed as mean ± standard error of the mean (SEM) and analyzed through the statistical program GraphPad Prism 8.0 (San Diego, CA, USA). Data were tested for normality using the Kolmogorov–Smirnov test and were analyzed by Student's *t*-test, considering $p < 0.05$ as significant. Since sex was not considered a factor, only the programming effect (MP *vs* CON) was included in the analyses. For offspring analyses, the litter was considered the experimental unit. Therefore, only one male and one female offspring from each litter were included at each age evaluated, with each animal representing its respective litter.

3. Results

3.1. Dam's biometric, plasma and milk measurements at weaning

From the 3rd MP exposure day (G10) until delivery (G21), MP dams showed lower BM (Fig. 2A), which was associated with a 16% reduction in BM gain ($p = 0.013$, Fig. 2B) and reduced food intake (−11%, $p = 0.025$, Fig. 2C). From delivery until weaning, the MP dam's BM and food intake were similar to control ones (Fig. 2A–D), as well as the mass of white adipose tissue compartments at PND21 (Fig. 2E).

The masses of thyroid, adrenal gland and pancreas of dams were similar between MP and control groups (Table S3).

Milk macronutrient content on the 3rd (PND10) and 11th (PND18) MP exposure day was similar between groups (Table S4). At weaning, MP dams showed 34% and 9% reductions in plasma cholesterol ($p = 0.0381$, Table S5), and T4 levels ($p = 0.0195$, Table S5), respectively, whereas fasting glucose, plasma triglyceride, insulin, leptin, TSH, T3, and corticosterone contents were unchanged (Table S5).

3.2. Offspring's biometric and plasma parameters at weaning and puberty

MP male pups had an 9% reduction in BM from PND9 until weaning (Fig. 3A), whereas total lean and fat mass were unchanged (Fig. 3C), but the retroperitoneal adipose compartment was reduced in 44% when compared to control (MP = 0.017 ± 0.002 g; CON = 0.031 ± 0.003 g, $p = 0.010$, Fig. 3D), while gonadal and mesenteric compartments were unchanged. MP males did not show any differences between the masses of thyroid, adrenal gland and pancreas when compared to controls (Table S6). Regarding plasma parameters at weaning, male pups showed higher TG (+93%, $p = 0.0457$, Table S7) and lower corticosterone levels (−65%, $p < 0.001$, Table S7). Fasting glucose, CHOL, insulin, leptin, TSH, T3, and T4 plasma concentrations were similar to those of controls (Table S7).

In the first 4 days after weaning, MP male pups had increased BM (+21%, $p = 0.008$, Fig. 3A), which can be associated with the increased food intake at same period (+8%, $p = 0.007$, Fig. 3B). From PND25 until PND45, MP male BM and food intake were similar to the control group (Fig. 3A and B). At puberty, body composition and adipose tissue compartments were unchanged (Fig. 3E and F). MP's male adrenal gland was 12% smaller than control group ($p = 0.026$, Table S8), whereas thyroid and pancreas did not show any differences between groups. At this same age, the MP male CHOL, TG and T3 plasma levels were 27% ($p = 0.0167$), 39% ($p = 0.0094$) and 43% ($p = 0.0159$) lower than controls, respectively (Table 1). Fasting glucose, insulin, leptin, TSH, T4, and corticosterone were unchanged (Table 1).

MP female pups had lower BM from PND15 until weaning (−9%, Fig. 3G), while total lean and fat mass were unchanged (Fig. 3I), but the mesenteric adipose compartment was 47% less than the control ones (MP = 0.087 ± 0.014 g; CON = 0.165 ± 0.023 g, $p = 0.016$, Fig. 3J), whereas retroperitoneal and gonadal compartments were unchanged. MP females did not show any differences between groups regarding the masses of thyroid, adrenal gland and pancreas (Table S6). At weaning, MP females had 40% and 2-fold higher CHOL ($p = 0.0107$) and TG ($p = 0.0490$) plasma levels, respectively (Table S7). Fasting glucose, insulin, leptin, TSH, T3, T4, and corticosterone were similar between groups (Table S7).

From weaning to puberty, BM and food intake in MP females were unchanged (Fig. 3G and H). At PND45, MP female total lean and fat

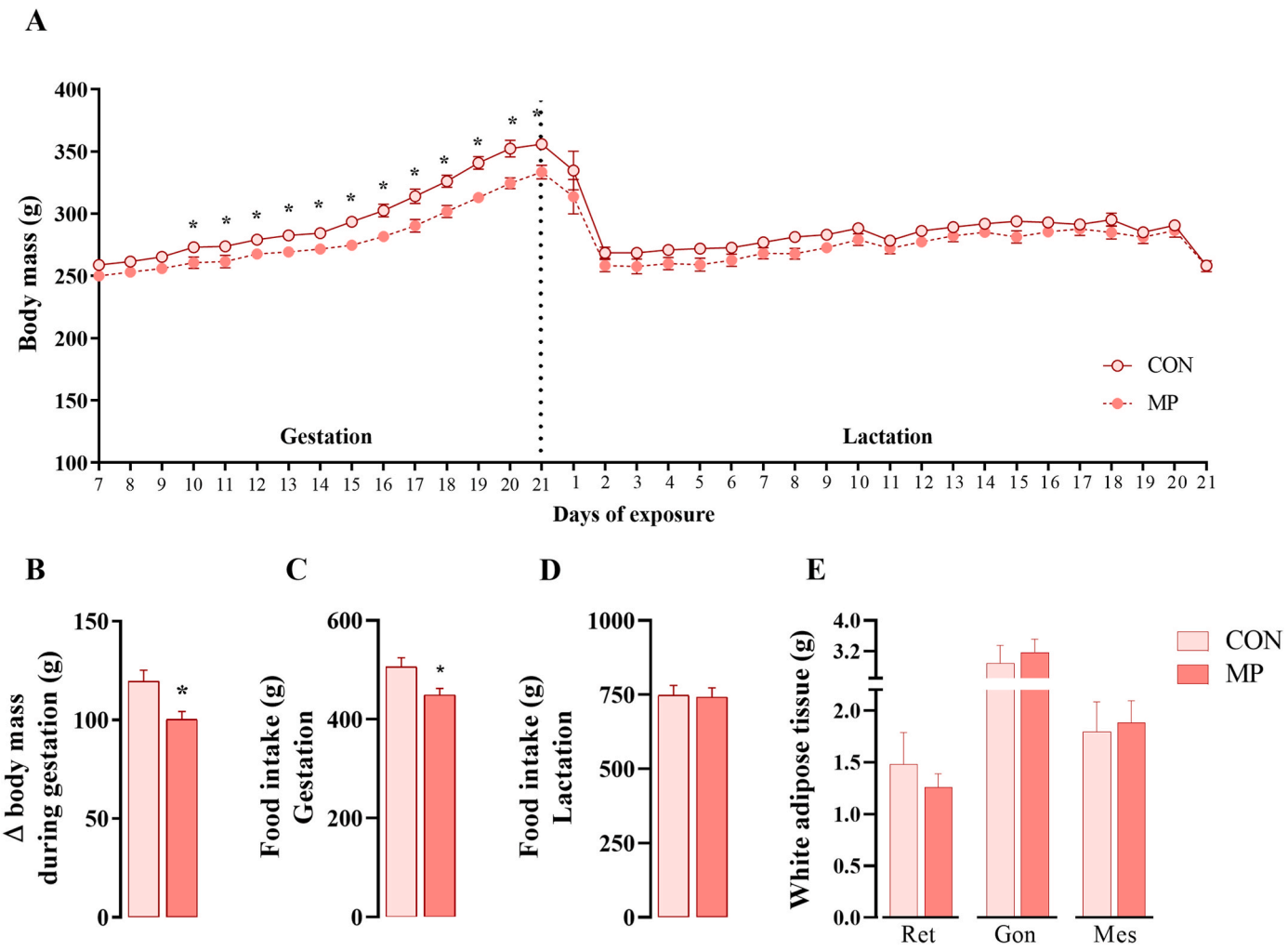

Fig. 2. Effects of microplastics administration during gestation and lactation on maternal biometric parameters. Body mass evolution during gestation and lactation (A). Body mass gain during gestation (B). Cumulative food intake during gestation (C). Cumulative food intake during lactation (D). Mass of white adipose tissue compartments (E). Ret, retroperitoneal compartment; Gon, gonadal compartment; Mes, mesenteric compartment. Values are mean ± SEM. CON n = 9, MP n = 8. Student's unpaired *t*-test. *$p < 0.05$.

masses were similar to control ones (Fig. 3K), whereas retroperitoneal fat depots were 40% lighter than those of the control group (MP = 0.176 ± 0.026 g; CON = 0.293 ± 0.015 g, $p = 0.001$, Fig. 3L). MP showed similar masses of thyroid, adrenal gland and pancreas when compared to controls (Table S8). Plasma lipids and hormones were unchanged in the female MP group (Table 1).

3.3. Offspring's biometric and plasma parameters at adulthood

From puberty until adulthood, MP male had was similar to control ones (Fig. 4A), despite showing 4% less food intake during this period ($p = 0.003$, Fig. 4B). At PND120, total lean mass, total fat mass and compartments were unchanged in MP males (Fig. 4C and D). MP male pancreas mass was 6.5% smaller than in the control group ($p = 0.03$, Table S9), whereas thyroid, adrenal gland and testicles did not show any differences. Adult MP male fasting glucose and plasma lipids were similar to control ones (Table 2), whereas plasma leptin level was 42% lower ($p = 0.0419$) and FSH was 53% higher ($p = 0.0115$) than control ones (Table 2). Plasma insulin, TSH, T3, T4, Corticosterone, LH and sexual steroids were unchanged in adult MP males (Table 2).

Concerning females, both BM and food intake were similar between groups from puberty until adulthood (Fig. 4E and F). The body composition at PND120, as well as the adipose tissue compartments were also similar between groups (Fig. 4G and H). MP females showed no differences in thyroid, adrenal gland, pancreas and ovaries when compared to controls (Table S9). At this age, MP female fasting glucose, insulin, leptin, T4, gonadotrophins, sexual steroids levels, and plasma lipids were unchanged, whereas corticosterone was 58% lower ($p = 0.0138$) than in the control group and TSH, and T3 were 53% ($p = 0.0275$) and 150% ($p = 0.0106$) higher in the controls, respectively (Table 2).

3.4. Offspring's behavioral tests

Regarding behavior traits, MP males showed anxious behavior in open field test with lower percentage of entrances in center both in puberty (−70%, $p = 0.014$, Fig. 5B) and adulthood (−69%, $p = 0.02$, Fig. 5D), whereas MP females did not show any differences in anxious behavior (Fig. 5E and G) and locomotor activity (Fig. 5F and H), regardless of age.

At puberty, both MP males and females showed feeding behavior similar to control animals (Fig. 6A–D). At adulthood, MP males showed energy intake 9% lower than controls ($p = 0.014$, Fig. 6E), which can be associated with a 10% lower preference for HFD observed in these animals ($p = 0.013$, Fig. 6F). On the other hand, MP females showed total energy intake 5% higher than control ones ($p = 0.04$, Fig. 6G), however, the SD and HFD intake was similar between groups (Fig. 6H).

In adulthood, MP males and females showed similar blood glucose

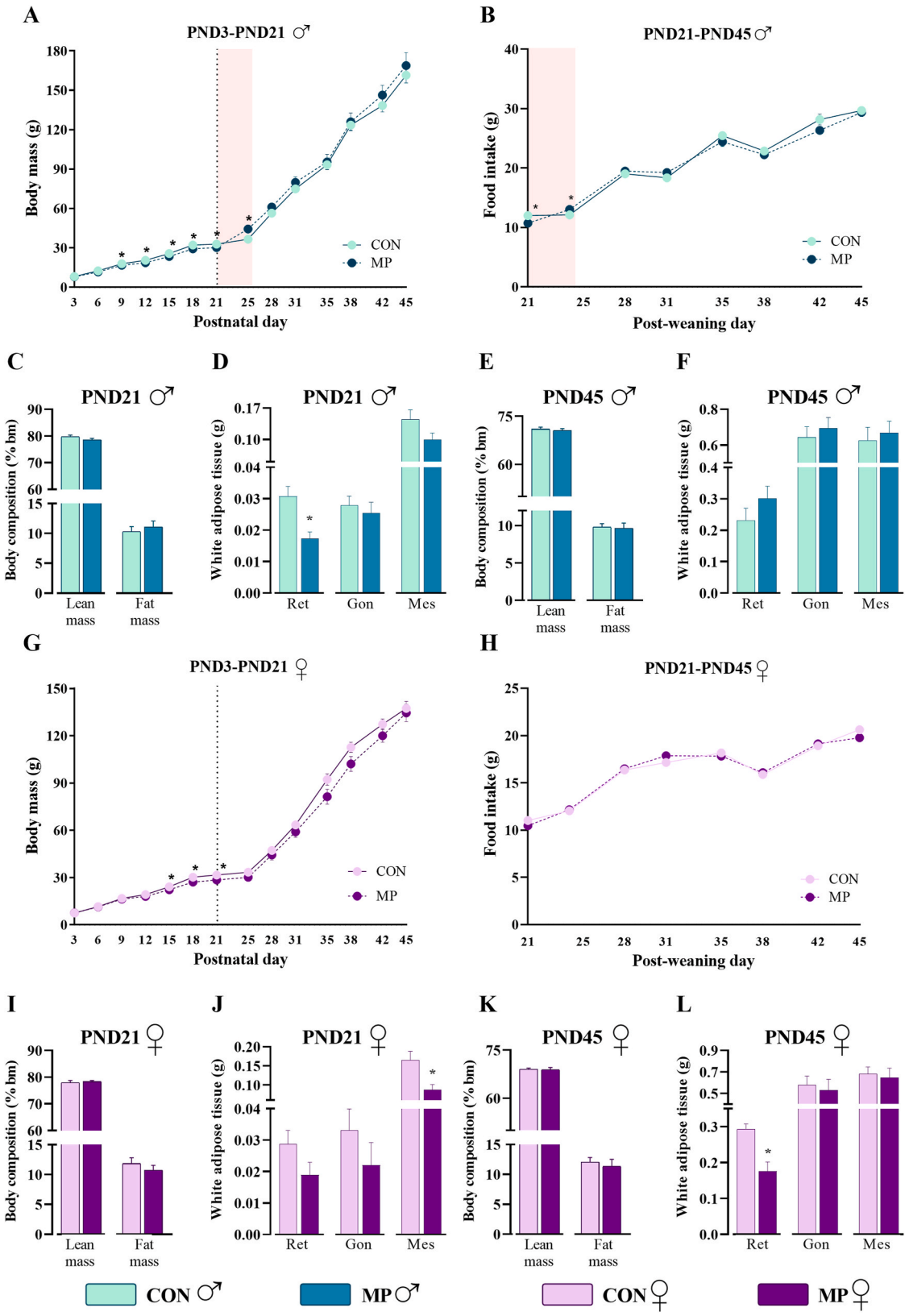

Fig. 3. Effects of microplastics administration during gestation and lactation on biometric parameters of offspring at weaning and puberty. Body mass evolution of male offspring (A). Cumulative food intake of male offspring (B). Body composition at weaning of male offspring (C). Mass of white adipose tissue compartments at weaning of male offspring (D). Body composition at puberty of male offspring (E). Mass of white adipose tissue compartments at puberty of male offspring (F). Body mass evolution of female offspring (G). Cumulative food intake of female offspring (H). Body composition at weaning of female offspring (I). Mass of white adipose tissue compartments at weaning of female offspring (J). Body composition at puberty of female offspring (K). Mass of white adipose tissue compartments at puberty of female offspring (L). BM, body mass; Ret, retroperitoneal compartment; Gon, gonadal compartment; Mes, mesenteric compartment. Values are mean ± SEM. CON n = 9, MP n = 8. Student's unpaired *t*-test. $^{*}p < 0.05$.

Table 1
Plasma parameters of pubescent offspring exposed to MP during the perinatal period.

	CON	MP	*p*
MALE			
Glucose (mg/dL)	100.90 ± 4.96	97.71 ± 4.35	0.6443
CHOL (mg/dL)	71.73 ± 5.70	52.57 ± 3.62	0.0167*
TG (mg/dL)	30.19 ± 3.06	18.37 ± 2.05	0.0094*
Insulin (ng/mL)	0.16 ± 0.039	0.35 ± 0.14	0.2473
Leptin (ng/mL)	0.24 ± 0.04	0.26 ± 0.10	0.8979
TSH (ng/mL)	1.75 ± 0.29	1.92 ± 0.30	0.6915
T3 (ng/mL)	1.88 ± 0.22	1.07 ± 0.19	0.0159*
T4 (ng/mL)	434.00 ± 20.95	372.00 ± 25.05	0.0766
Corticosterone (ng/mL)	91.75 ± 15.89	55.99 ± 14.39	0.1339
FEMALE			
Glucose (mg/dL)	99.25 ± 3.46	90.43 ± 4.91	0.1580
CHOL (mg/dL)	57.92 ± 3.24	51.01 ± 2.80	0.1418
TG (mg/dL)	18.73 ± 1.28	16.52 ± 3.72	0.5637
Insulin (ng/mL)	0.14 ± 0.08	0.16 ± 0.05	0.8705
Leptin (ng/mL)	0.13 ± 0.04	0.14 ± 0.04	0.9053
TSH (ng/mL)	1.07 ± 0.10	0.98 ± 0.11	0.5520
T3 (ng/mL)	0.91 ± 0.09	0.65 ± 0.09	0.0657
T4 (ng/mL)	362.00 ± 30.81	313.30 ± 22.48	0.2469
Corticosterone (ng/mL)	48.67 ± 6.74	67.23 ± 14.98	0.2267

CHOL, Cholesterol; TG, Triglycerides; TSH, Thyroid stimulating hormone; T3, Triiodothyronine; T4, Thyroxine. Groups: CON - dams that were exposed to filtered water during gestation and lactation; MP - dams that were exposed to 10 μm polystyrene microparticles during the same period. Values are mean ± SEM of 1/sex/litter of CON (n = 5-9) and MP dams (n = 5-8). Student's unpaired *t*-test. *$p < 0.05$ - MP *vs* CON.

levels during the oral glucose tolerance test (OGTT) at all evaluated time points (males: $p(t15) = 0.4487$; $p(t30) = 0.6469$; $p(t60) = 0.6725$; $p(t120) = 0.8839$; females: $p(t15) = 0.9460$; $p(t30) = 0.2610$; $p(t60) = 0.6023$; $p(t120) = 0.9226$). Furthermore, the area under the curve (AUC) did not differ between groups in either sex (males: $p = 0.9892$; females: $p = 0.5867$, Figs. S1 and S2).

Fig. 7 provides an integrated summary of the main biometric, metabolic, endocrine, and behavioral alterations observed in dams and offspring following perinatal MP exposure, highlighting age- and sex-dependent responses.

4. Discussion

The increase in plastic generation worldwide has worsened the dispersion of microplastics in the environment. Thus, we humans are more exposed to these particles. Several plasticizers are already known to cause serious hormonal and metabolic alterations, known as chemical endocrine disruptors (Braun, 2017; Haverinen et al., 2021; Silva et al., 2019). Microplastics still lack a clear mechanism of action, but it is known that they are not inert particles, as previously thought, as they have been demonstrated in the literature as possible causes of oxidative stress, inflammation, and metabolic alterations (Ali et al., 2024).

In this study, we evaluated the effects of maternal exposure to MPs on male and female offspring at different ages, including weaning (PND21), puberty (PND45), and adulthood (PND120). We observed biometric changes, with both body mass loss as well as gain, depending on age. Regarding hormonal parameters, we observed changes in TSH, T3, T4, corticosterone, leptin, and FSH. Changes in lipid metabolism were also observed, both in plasma triglyceride and cholesterol concentrations. Regarding the behavior of these animals, we observed changes in feeding behavior in both sexes and anxiety only in males.

The transient increase in body mass observed in male offspring immediately after weaning was accompanied by increased food intake during the same period and occurred after the reductions in body mass and retroperitoneal adipose tissue observed at weaning. Taken together, these findings suggest a compensatory adaptation to restore growth and energy reserves, a phenomenon commonly described following developmental insults during critical windows of development (Barker, 2004). Since these differences were no longer present at puberty, the effect appears to be transient rather than indicative of a persistent alteration in body weight regulation.

Luo et al. (2019a) provided the basis for defining the dose to be followed in this study. The dose they administered in mice during pregnancy and lactation, of 100 μg/L of 5 μm particles, via drinking water, is equivalent to the dose of 25 μg/kg of body mass that we used in rats after correcting for the animal's contact surface. Luo et al. (2019a) is one of the few groups, to date, that has worked with a model of MP exposure during critical periods of offspring development.

In our study, MP dams had lower plasma cholesterol concentrations; Luo et al. (2019a) found an increase in this parameter. Regarding puberty, we found changes in lipid metabolism only in MP males, with a reduction in both cholesterol and triglycerides. Luo et al. (2019a) also observed this reduction in triglycerides, but an increase in cholesterol. Furthermore, they also observed changes in females, with a decrease in both parameters (Luo et al., 2019a). Thus, these differences can be explained by specie-specific effects.

In another study, Luo et al. (2019b) exposed female mice only during gestation to MP particles at the same dose as ours (100 μg/L), with a size of 5 μm, and evaluated the offspring at puberty (PND42). They also measured serum cholesterol and triglycerides in both males and females. They observed an increase in cholesterol in MP males and a decrease in triglycerides in both MP males and females. When compared with our results during puberty, we observed a similarity only in the reduction in triglyceride content in MP males, while cholesterol in our model was also reduced and females showed no change (Luo et al., 2019b).

These transient changes in lipid metabolism, which differed between male and female offspring, may indicate the programming of metabolic pathways during critical developmental windows, when regulatory mechanisms involved in lipid homeostasis, including hepatic lipid metabolism, are not yet fully mature (Wesolowski et al., 2016). Early-life disturbances in lipid homeostasis may be particularly sensitive to sex-specific endocrine pathways, which modulate lipid handling across development and could contribute to the divergent patterns observed between males and females at weaning and puberty (Palmisano et al., 2018). Although we did not measure sex steroid hormone levels or signaling at weaning, MP exposure may could have affected these pathways, potentially contributing to the alterations in lipid homeostasis observed in the offspring.

MP male offspring at adulthood had higher plasma FSH concentrations. Jin et al. (2022), also working with MP direct exposure of adult male mice, via drinking water, at a dose of 100 μg/L and with 10 μm particles, similarly showed increased plasma FSH concentrations (Jin et al., 2022). This group also found lower LH and testosterone concentrations, which was not observed in our research group. Increased FSH concentrations may be indicative of infertility, as this hormone is associated with gametogenesis. Xu et al. (2023), administering polystyrene nanoplastic particles to adult mice, observed decreased male fertility by inducing oxidative stress in the testes and influencing the expression of genes related to apoptosis and inflammation. Furthermore, there was a decrease in sperm count and quality (Xu et al., 2023).

Jin et al. (2021) exposed male mice to MP of different sizes (0.5 μm, 4 μm, and 10 μm) and demonstrated the occurrence of impaired spermatogenesis, testicular inflammation, and damage to the blood-testicular barrier (Jin et al., 2021). FSH is known to act on Sertoli cells, stimulating sperm development and maturation. Thus, any changes in these cells could be reflected in FSH concentrations, especially if there is decreased synthesis of inhibin, the hormone responsible for FSH negative feedback.

Grillo et al. (2024) studied cultured mouse Sertoli cells (TM4) and exposed them to 5 μm microplastic particles at two concentrations (10 μg/mL and 50 μg/mL). They observed antiproliferative and cytotoxic effects, inducing oxidative stress, autophagy, apoptosis, and

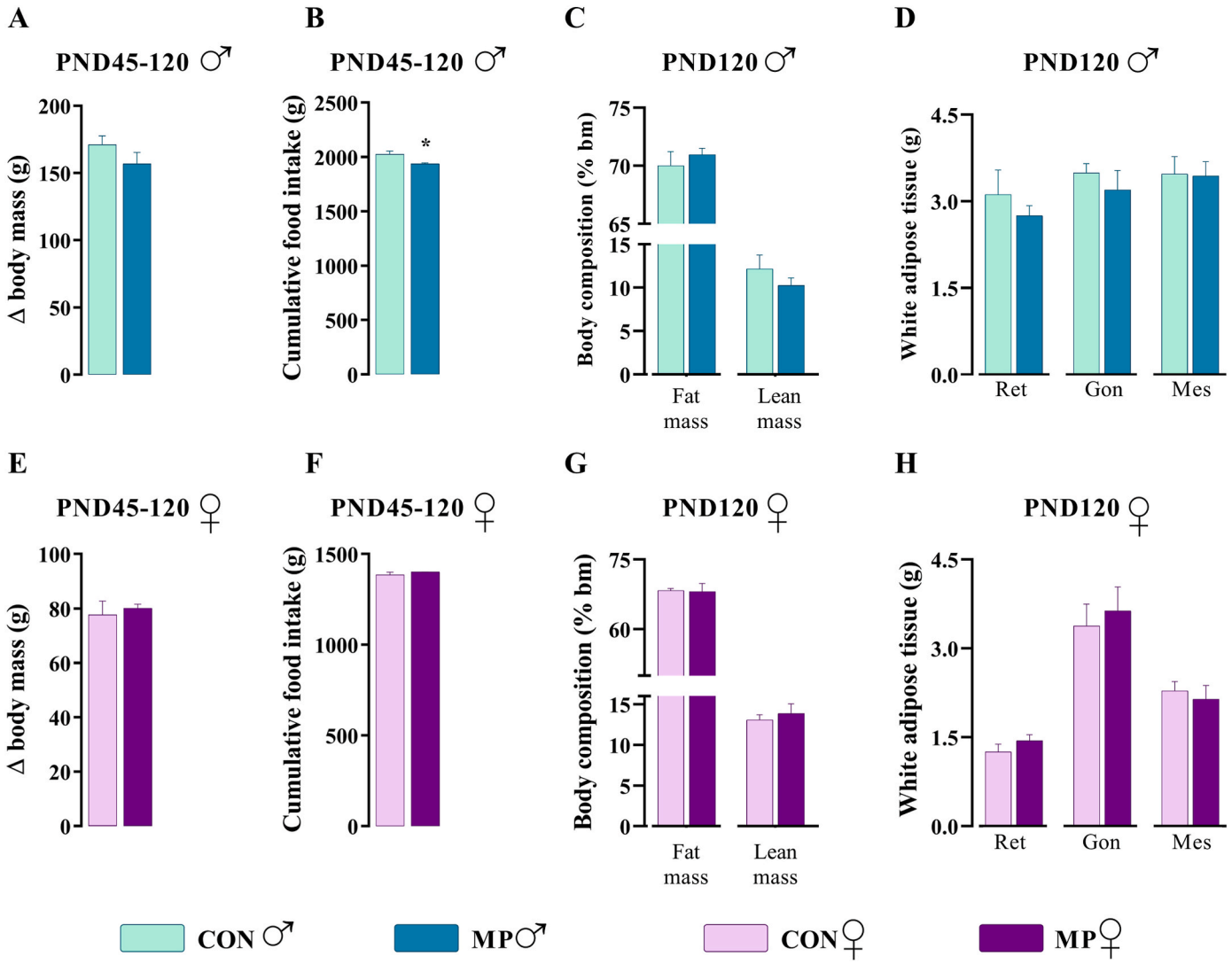

Fig. 4. Effects of microplastic administration during gestation and lactation on biometric parameters of offspring at adulthood. Body mass gain from puberty to adulthood of male offspring (A). Cumulative food intake from puberty to adulthood of male offspring (B). Body composition at adulthood of male offspring (C). Mass of white adipose tissue compartments at adulthood of male offspring (D). Body mass gain from puberty to adulthood of female offspring (E). Cumulative food intake from puberty to adulthood of female offspring (F). Body composition at adulthood of female offspring (G). Mass of white adipose tissue compartments at adulthood of female offspring (H). BM, body mass; Ret, retroperitoneal compartment; Gon, gonadal compartment; Mes, mesenteric compartment. Values are mean ± SEM. CON n = 9, MP n = 8. Student's unpaired *t*-test. *$p < 0.05$.

Table 2
Plasma parameters of adult offspring exposed to MP during the perinatal period.

	Male			Female		
	CON	MP	*P*	CON	MP	*P*
Glucose (mg/dL)	88.38 ± 3.36	89.50 ± 4.09	0.8348	104.00 ± 6.03	99.50 ± 3.22	0.5211
CHOL (mg/dL)	38.33 ± 2.91	37.34 ± 5.08	0.8682	41.43 ± 3.10	48.26 ± 2.74	0.1806
TG (mg/dL)	18.00 ± 2.68	15.21 ± 3.21	0.5155	20.60 ± 2.52	22.21 ± 1.89	0.6192
Insulin (ng/mL)	0.20 ± 0.04	0.14 ± 0.05	0.2730	0.11 ± 0.01	0.07 ± 0.02	0.0828
Leptin (ng/mL)	1.71 ± 0.25	0.98 ± 0.18	0.0419*	1.08 ± 0.21	1.12 ± 0.13	0.8750
TSH (ng/mL)	4.62 ± 0.73	4.23 ± 0.38	0.6649	1.01 ± 0.12	1.55 ± 0.18	0.0275*
T3 (ng/mL)	1.10 ± 0.12	1.40 ± 0.26	0.3367	0.52 ± 0.08	1.30 ± 0.23	0.0106*
T4 (ng/mL)	434.90 ± 25.03	390.80 ± 32.97	0.3013	298.10 ± 16.49	341.30 ± 13.84	0.0703
Corticosterone (ng/mL)	18.92 ± 4.96	19.32 ± 4.10	0.9509	33.22 ± 5.56	13.83 ± 3.78	0.0138*
FSH (mIU/mL)	16.40 ± 2.23	25.13 ± 2.01	0.0115*	40.34 ± 5.77	28.80 ± 4.05	0.1240
LH (mIU/mL)	4.84 ± 0.41	6.32 ± 1.18	0.2568	7.45 ± 1.43	5.57 ± 0.87	0.2542
Testosterone (ng/mL)	36.51 ± 4.99	32.05 ± 5.54	0.5586	1.55 ± 0.29	1.56 ± 0.48	0.9964
Estradiol (ng/mL)	0.53 ± 0.04	0.52 ± 0.06	0.9006	0.51 ± 0.05	0.59 ± 0.06	0.5683

CHOL, Cholesterol; TG, Triglycerides; TSH, Thyroid stimulating hormone; T3, Triiodothyronine; T4, Thyroxine; FSH, Follicle stimulating hormone; LH, Luteinizing hormone. Groups: CON - dams that were exposed to filtered water during gestation and lactation; MP - dams that were exposed to 10 μm polystyrene microparticles during the same period. Values are mean ± SEM of 1/sex/litter of CON (n = 5-9) and MP dams (n = 5-8). Student's unpaired *t*-test. *$p < 0.05$ - MP *vs* CON.

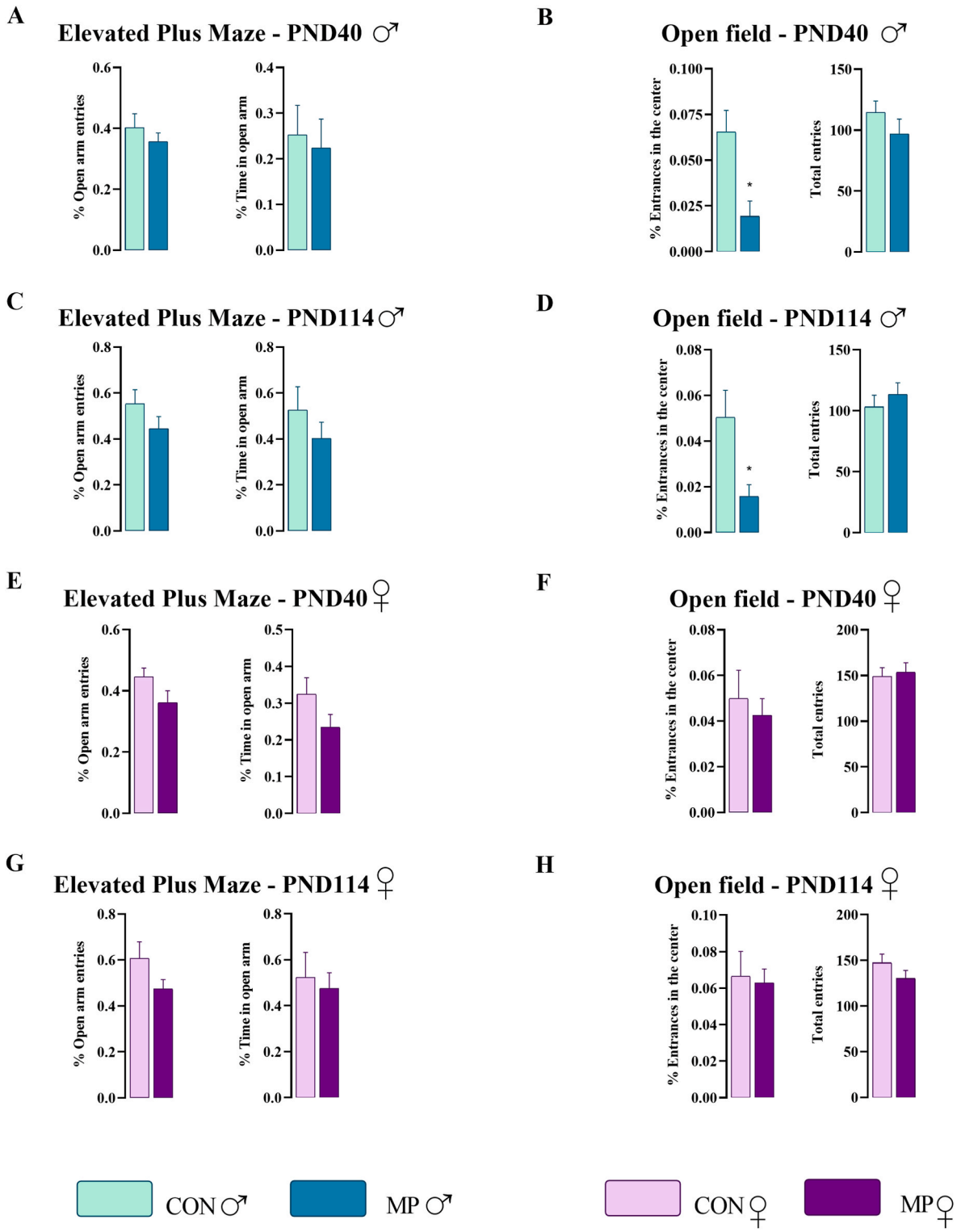

Fig. 5. Effects of microplastics (MP) administration during gestation and lactation on behavioral parameters of offspring at puberty and adulthood. Anxiety-like behavior assessed in Elevated Plus Maze of male offspring at puberty (A) and adulthood (C). Locomotor activity and anxiety-like behaviors assessed in Open Field Test of male offspring at puberty (B) and adulthood (D). Anxiety-like behavior assessed in Elevated Plus Maze of female offspring at puberty (E) and adulthood (G). Locomotor activity and anxiety-like behaviors assessed in Open Field Test of female offspring at puberty (F) and adulthood (H). Values are mean ± SEM. CON n = 9, MP n = 8. Student's unpaired *t*-test. $^{*}p < 0.05$.

mitochondrial dysfunction triggered by endoplasmic reticulum stress. These data suggest that these particles may influence male fertility by interfering with Sertoli cell homeostasis (Grillo et al., 2024).

Although increased FSH concentrations may suggest alterations in the regulation of the hypothalamic-pituitary-gonadal (HPG) axis, the present study did not directly evaluate reproductive function. Therefore, it is not possible to conclude whether the alterations observed in adult MP males translate into impaired fertility. Nevertheless, considering the evidence from previous studies demonstrating adverse effects of micro- and nanoplastics on spermatogenesis, Sertoli cell homeostasis, sperm

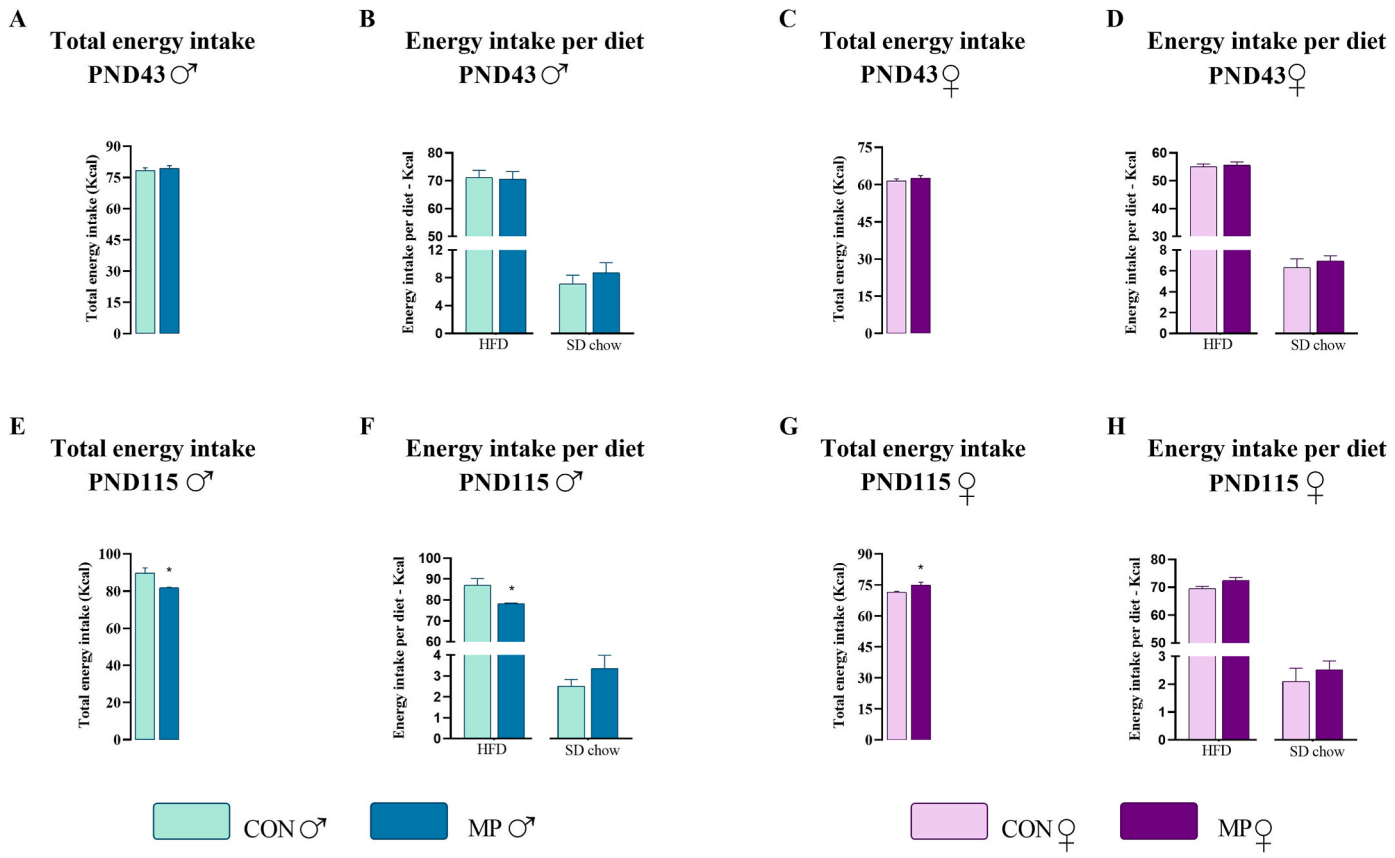

Fig. 6. Effects of microplastics (MP) administration during gestation and lactation on feeding behavioral parameters of offspring at puberty and adulthood. Total energy intake of male offspring at puberty (A) and adulthood (E). Energy intake per diet of male offspring at puberty (B) and adulthood (F). Total energy intake of female offspring at puberty (C) and adulthood (G). Energy intake per diet of female offspring at puberty (D) and adulthood (H). Values are mean ± SEM. CON n = 9, MP n = 8. Student's unpaired *t*-test. *$p < 0.05$.

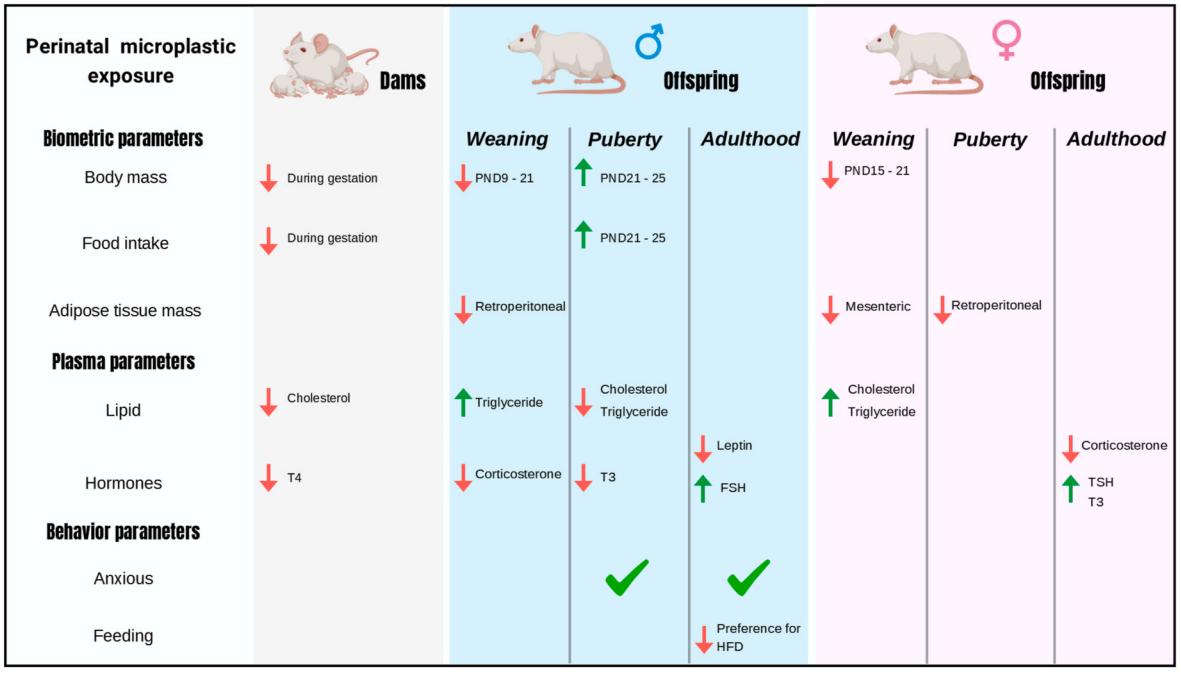

Fig. 7. Outcomes in rat dams and offspring of both sexes and different ages in the model of perinatal MP exposure.

quality and testicular integrity, the increase in FSH may indicate alterations in endocrine regulation that explain further investigation rather than direct evidence of reproductive dysfunction. Future studies evaluating sperm parameters, testicular histology, inhibin concentrations,

and fertility outcomes are necessary to clarify the functional significance of this hormonal alteration.

At adulthood, MP male offspring showed lower plasma leptin, with a slightly reduced food intake. Roh et al. (2024), working with oral MP direct exposure of adult male mice, at a dose of 100 μg/mL and particles with 0.5 μm of diameter, one time per day and 3 days per week (0.5 mL/day) for 9 weeks, showed increased leptin levels both in serum and adipose tissue, with no alteration in food intake (Roh et al., 2024). Moon et al. (2024) evaluated the impact of MP exposure (10 μg/mL for 14 days, 2.0 μm particle size) on adipose tissue in vivo and in vitro. Adult males showed MP accumulation in white adipose tissue (visceral and subcutaneous), as well as smaller adipocyte size with the presence of inflammatory markers (Moon et al., 2024). In stem cells derived from human adipose tissue, these authors observed dysfunction in adipocyte differentiation and a reduced capacity for the formation of functional adipose tissue (Moon et al., 2024). Thus, in our study, perinatal exposure to MP may have programmed white adipose tissue dysfunction, being associated with lower leptin synthesis in adult males.

Leptin acts both centrally and peripherally. The central response involves action on the hypothalamic arcuate nucleus with an anorexigenic effect. In a model of perinatal exposure to bisphenol A (BPA), MacKay et al. (2017) observed structural changes in the hypothalamic leptin circuit. The male offspring showed a reduction in POMC neurons, indicating that the hypothalamic architecture that responds to leptin was altered during an insult in a critical developmental window (MacKay et al., 2017). Therefore, it is possible that in our study this circuitry is altered by MP and, even with hypoleptinemia, its central sensitivity is increased, reducing food intake. Regarding the peripheral response of leptin, its action on the sympathetic nervous system (SNS) should be highlighted. In obesity, selective leptin resistance is observed, meaning that even with hypothalamic resistance, the SNS remains stimulated, leading to hypertension and modulation of vascular tone in obese individuals (Correia and Rahmouni, 2006). Thus, in our experimental model, an alteration in peripheral leptin sensitivity could affect the SNS and have cardiovascular consequences. As neither hypothalamic circuitry nor sympathetic nervous system activity was directly evaluated in the present study, the proposed mechanisms linking perinatal MP exposure to altered leptin signaling remain speculative and are based on previous experimental evidence. Thus, more studies are necessary to clarify the molecular mechanisms linking perinatal MP exposure and the regulation of leptin expression, secretion, and hypothalamic signaling.

Our results showed that both male MP offspring at weaning and female MP offspring in adulthood had lower plasma corticosterone levels. Xiong et al. (2025) demonstrated a reduction in this parameter in male mice. In this study, exposure was via gavage of 5 μm particles for 4 weeks, with three different doses: 0.25 mg/day, 0.5 mg/day, and 1 mg/day. MP exposure was observed to lead to mitochondrial damage caused by oxidative stress, thus impairing steroidogenesis through the inhibition of important pathways. Consequently, corticosterone levels were reduced (Xiong et al., 2025).

Farag et al. (2024) studied adult male Sprague-Dawley rats and exposed them to two doses (3.75 mg/kg and 15 mg/kg body mass) of polyethylene microplastic with an average size between 4.0 and 6.0 μm. These microparticles had a detrimental effect on the histological characteristics of the adrenal gland, as well as hormonal changes in both corticosterone and ACTH levels. At both doses, higher plasma ACTH concentrations were observed, while only the higher dose resulted in lower corticosterone levels. This adrenal gland dysfunction has been linked to oxidative stress and inflammation caused by MP (Farag et al., 2024).

Here, we observed different response patterns between male and female offspring when separately analyzed, which may reflect differential developmental programming induced by MP exposure. Some studies demonstrated that gestational and direct exposures to MPs and NPs can produce distinct physiological outcomes in male and female offspring, such as sexually dimorphic alterations in cardiovascular development and function, differences in oxidative stress, immune responses and body weight regulation, suggesting that susceptibility to MP exposure during critical developmental windows may differ between sexes (Cary et al., 2025; Lafram et al., 2026).

Early-life environmental insults may induce long-term changes in neuroendocrine regulation that emerge at different developmental stages in males and females, probably due to differences in the maturation of stress-responsive pathways and steroid hormone regulation (Burgess et al., 2019; Gehrand et al., 2018; Zambrano et al., 2023). In this study, corticosterone levels were reduced in males at weaning, whereas reductions in females were observed only during adulthood, suggesting distinct trajectories of HPA axis adaptation following perinatal MP exposure. Some studies observed that developmental programming of stress-related pathways differs between male and female offspring after early-life insults, with endocrine alterations becoming apparent at different ages in each sex (Burgess et al., 2019; Gehrand et al., 2018; Zambrano et al., 2023). Thus, the distinct timing of corticosterone alterations observed in this study may reflect differential adaptation of the HPA and HPG axes following developmental MP exposure. However, one limitation of our study was the lack of evaluation of the HPG axes on the puberty, although we detected increased FSH concentration in adult males. Based on previous experimental studies, alterations in adrenal morphology, oxidative stress markers, inflammatory pathways, and mitochondrial function are potential mechanisms that could explain our findings (Farag et al., 2024; Xiong et al., 2025). Future investigations evaluating adrenal gland histology and molecular pathways involved in steroidogenesis will be necessary to clarify how perinatal MP exposure leads to corticosterone alterations in male and female offspring. Also, although we did not detected changes in circulating sex steroid hormone concentrations, the action of these hormones on neurohormonal circuits related to behavior, could explain the changes in anxiety-like behavior.

In our results, we observed changes in the thyroid axis at certain ages. MP dams had lower T4 concentrations, MP males at puberty had lower T3 levels, while, in adulthood, MP females had higher concentrations of both TSH and T3. Zhang et al. (2024a) exposed adult Mus Musculos to two doses (5 and 50 mg/kg body mass) of 5 μm polystyrene microplastics and 50 nm polystyrene nanoplastics. In this study, changes in the thyroid axis were also observed. Animals treated with the lower dose of both particles showed higher thyroglobulin expression. Regarding hormone levels, TSH was lower in the group exposed to the lowest dose in both those exposed to MP and NP. T3 showed the same behavior, while T4 was higher (Zhang et al., 2024), suggesting a lower peripheral conversion.

Adult MP female exhibited increased TSH and T3 concentrations, but not T4 concentrations. Although the mechanisms underlying this response remain unclear, the simultaneous elevation of these hormones suggests a disruption of the normal feedback regulation of the hypothalamic-pituitary-thyroid axis (Mullur et al., 2014). Developmental MP exposure may have induced long-term alterations in thyroid hormone homeostasis, leading to compensatory activation of the axis to maintain adequate thyroid hormone signaling in peripheral tissues. Alternatively, changes in peripheral thyroid hormone metabolism may have contributed to the increased T3 concentrations observed in adulthood, as MP exposure has previously been associated with alterations in TH metabolism (Zhang et al., 2024). Since thyroid hormone sensitivity, including cellular uptake, deiodinase activity, and thyroid receptor signaling were not evaluated, further investigations are needed to clarify the mechanisms underlying these alterations.

In a direct exposure study using the open field test, Chen et al. (2023) demonstrated increased anxious behavior in adult male mice after 60 days of treatment with a dose of 0.5 mg/day and 1.0 μm of size particles with reduced time spent in the central region of the open field. This result was similar to that demonstrated in our study. Interestingly, it should be noted that the period of exposure in this previous study (Chen

et al., 2023) is out of the critical period of gestation and lactation. In addition, MP dose and particle size was also different.

Here, we showed for the first time that perinatal MP exposure alters food preference in an age-dependent manner, with different response patterns observed between male and female offspring, with lower HFD preference observed only in adult males. Similar differences by age and between males and females have already been reported in other perinatal exposure models: BPA exposure reduced HFD preference only in adult females (Silva et al., 2019); caffeine exposure increased HFD preference in puberty males and decreased in adult females (de Souza et al., 2024). Given the central role of the dopaminergic system in food reward and regulation of HFD intake (Joshi et al., 2021; Jovanoski et al., 2023), and evidence that early MP exposure impairs dopaminergic neuron development in zebrafish (Cai et al., 2025), our current findings raise the possibility that perinatal MP exposure disrupts brain dopaminergic reward pathways. Further investigation of dopamine-related biomarkers, including enzymes, receptors, and transporters, is needed to clarify the mechanisms underlying these hedonic alterations.

As neurotransmitter concentrations, dopamine-related receptors, transporters, and signaling pathways were not evaluated in the present study, the proposed involvement of dopaminergic circuits remains hypothetical and is based on previous experimental evidence (Cai et al., 2025).

Adult MP males consumed fewer calories and exhibited a reduced preference for a HFD, whereas adult MP females showed a slight increase in caloric intake. Our findings suggest that perinatal MP exposure may affect neural and endocrine pathways involved in the regulation of feeding behavior. The different patterns observed when male and female offspring were analyzed separately indicate that developmental MP exposure may influence food-related behaviors differently in each sex later in life.

The mechanism of action of MPs has not yet been clarified, but what is known is that they can promote inflammation, oxidative stress, and metabolic alterations. In vitro studies demonstrate that several characteristics of MPs are related to their mechanism of action, such that an irregularly shaped MP with sharper edges, when in contact with cell membranes, can damage them (Choi et al., 2021). Furthermore, their shape is capable of influencing particle movement and its interaction with both other MPs and membranes and biological barriers, causing various cellular damage (Danopoulos et al., 2022; Liu et al., 2020).

MPs have been detected in human placentas (Ragusa et al., 2021), indicating that plastic particles can interact directly with placental cells and potentially cross the maternal-fetal interface through energy-dependent cellular processes (Aengenheister et al., 2018; Grafmueller et al., 2015). In addition, MPs have been identified in human breast milk (Ragusa et al., 2022), supporting the possibility of postnatal exposure during lactation. Recent evidence has demonstrated the accumulation of polystyrene MPs in mammary tissue and suggested that MP-induced disruption of the gut-mammary axis and blood-milk barrier may facilitate their transfer to nursing offspring (Wang et al., 2025). Although the mechanisms by which 10-μm polystyrene MPs are transferred from dams to offspring remain unclear, both gestational and lactational exposure pathways appear biologically plausible, supporting the hypothesis that these routes may contribute to offspring exposure and to the alterations observed in the present study.

There are scant studies in the literature that have exposed pregnant and/or lactating rats to MPs. Our current data show that exposure to these particles during critical developmental windows can lead to biometric, lipid metabolism, hormonal, dietary, and behavioral changes. This was observed both in dams, who received direct exposure, and in the offspring in the short and long term. This research is the first to follow animals from intrauterine life to adulthood after perinatal exposure to microplastics. Given that rodent physiology is similar to humans, current findings allow us to relate the potential consequences of human exposure to this pollutant, which is part of our daily routine.

A limitation of this study is that maternal behavior was not evaluated. Although litter size was standardized to minimize variability in postnatal nutrition, litter culling may have influenced maternal care and offspring stress responsiveness. Therefore, the effects of this procedure on neuroendocrine and behavioral outcomes cannot be completely excluded. Furthermore, milk collection required the administration of oxytocin and light anesthesia at PND10 and PND18. These procedures were applied equally to all experimental groups and followed an established protocol with repeated milk collections performed several days apart to minimize stress and alterations in milk composition (Rodrigues et al., 2018). Nevertheless, potential effects on maternal physiology and milk composition cannot be completely excluded.

Another limitation is that intra- and inter-assay coefficients of variation were not determined for the milk composition evaluation. Although milk triglycerides and cholesterol were evaluated using commercially enzymatic kits, and protein and lactose were determined using previously methodologies used in our laboratory, the lack of analytical reproducibility parameters limits the assessment of assay reproducibility. The relatively small sample size may have reduced the statistical power to detect small differences in milk composition, increasing the possibility of a type II error.

There is a gap in understanding how MPs act on offspring: do the microparticles accumulate in offspring after passing through the placenta and breast milk, or are the alterations due to epigenetic changes caused by exposure during a critical phase of development? In the environment, MP is not alone, it is adsorbed with other substances (toxic or not), and here we only show the isolated effect of the microparticle.

Funding

This study was financed by The Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), The Fundação Carlos Chagas Filho de Amparo à Pesquisa do Estado do Estado do Rio de Janeiro (FAPERJ), The Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) Finance Code 001 and The INCT-Desreguladores Endócrinos e Repercussões Endócrino-Metabólicas, 400815/2024-9/CNPq/FNDCT/CAPES/FAPERJ).

CRediT authorship contribution statement

Nathália Medeiros Nehme: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. **Nelyana Oliveira Serpa:** Formal analysis, Investigation, Visualization. **Mayara da Silva Almeida:** Formal analysis, Investigation, Visualization. **Beatriz Souza da Silva:** Formal analysis, Investigation, Visualization. **Luana Lopes de Souza:** Formal analysis, Investigation, Visualization. **Rosiane Aparecida Miranda:** Formal analysis, Investigation, Visualization. **Vitor Hugo Santos Duarte Pinheiro:** Formal analysis, Investigation, Methodology, Visualization. **Alex Christian Manhães:** Formal analysis, Investigation, Methodology, Visualization, Writing – review & editing. **Egberto Gaspar de Moura:** Project administration, Resources, Visualization, Writing – review & editing. **Iala Milene Bertasso:** Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – review & editing. **Patrícia Cristina Lisboa:** Conceptualization, Data curation, Funding acquisition, Project administration, Resources, Supervision, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors are grateful to Mr. Ulisses Risso and Mrs. Fabiana Gallaulckydio for technical assistance.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fct.2026.116305.

Data availability

Data will be made available on request.

References

Aengenheister, L., Keevend, K., Muoth, C., Schönenberger, R., Diener, L., Wick, P., Buerki-Thurnherr, T., 2018. An advanced human in vitro co-culture model for translocation studies across the placental barrier. Sci. Rep. 8, 5388. https://doi.org/10.1038/S41598-018-23410-6.

Ali, N., Katsouli, J., Marczylo, E.L., Gant, T.W., Wright, S., Bernardino de la Serna, J., 2024. The potential impacts of micro-and-nano plastics on various organ systems in humans. EBioMedicine 99, 104901. https://doi.org/10.1016/j.ebiom.2023.104901.

Barceló, D., Picó, Y., Alfarhan, A.H., 2023. Microplastics: detection in human samples, cell line studies, and health impacts. Environ. Toxicol. Pharmacol. 101. https://doi.org/10.1016/j.etap.2023.104204.

Barker, D.J.P., 2004. The developmental origins of well-being. Phil. Trans. Biol. Sci. 359, 1359. https://doi.org/10.1098/RSTB.2004.1518.

Braun, J.M., 2017. Early-life exposure to EDCs: role in childhood obesity and neurodevelopment. Nat. Rev. Endocrinol. 13, 161–173. https://doi.org/10.1038/nrendo.2016.186.

Burgess, D.J., Dorey, E.S., Gardebjer, E.M., Bielefeldt-Ohmann, H., Moritz, K.M., Cuffe, J. S.M., 2019. Periconceptional ethanol exposure alters the stress axis in adult female but not male rat offspring. Stress 22, 347–357. https://doi.org/10.1080/10253890.2018.1563068.

Cai, X., Yang, Q., Chen, J., Lu, Xiaojuan, Peng, S., Lu, Xuan, Chen, G., Lai, B., Jin, Y., Xing, L., 2025. Early-life microplastic exposure elicits ADHD-like behaviors by disrupting dopaminergic neurodevelopment in zebrafish. J. Hazard Mater. 496, 139466. https://doi.org/10.1016/j.jhazmat.2025.139466.

Campen, M., Nihart, A., Garcia, M., Liu, R., Olewine, M., Castillo, E., Bleske, B., Scott, J., Howard, T., Gonzalez-Estrella, J., Adolphi, N., Gallego, D., Hayek, E. El, 2024. Bioaccumulation of microplastics in decedent human brains assessed by pyrolysis gas chromatography-mass spectrometry. Res. Sq. https://doi.org/10.21203/rs.3.rs-4345687/v1.

Cary, C.M., Adams, S., Moreno, G.M., Seymore, T.N., Polunas, M., Goedken, M.J., Wang, X., Yurkow, E.J., Stapleton, P.A., 2025. Gestational exposure to micro and nanoplastics differentially impacts cardiac development and function in male and female rats throughout the lifespan. Toxicol. Appl. Pharmacol. 504, 117507. https://doi.org/10.1016/J.TAAP.2025.117507.

Chen, X., Xu, L., Chen, Q., Su, S., Zhuang, J., Qiao, D., 2023. Polystyrene micro- and nanoparticles exposure induced anxiety-like behaviors, gut microbiota dysbiosis and metabolism disorder in adult mice. Ecotoxicol. Environ. Saf. 259. https://doi.org/10.1016/j.ecoenv.2023.115000.

Cheng, Y.C., Chen, W.L., Yu, H.R., Tsai, C.Y., Sheen, J.M., Tiao, M.M., Hsu, C.N., Tain, Y. L., 2025. Microplastic-induced hypertension in rats: a two-hit model exploring oxidative stress and gut microbiota. NanoImpact 39. https://doi.org/10.1016/j.impact.2025.100586.

Choi, D., Hwang, J., Bang, J., Han, S., Kim, T., Oh, Y., Hwang, Y., Choi, J., Hong, J., 2021. In vitro toxicity from a physical perspective of polyethylene microplastics based on statistical curvature change analysis. Sci. Total Environ. 752, 142242. https://doi.org/10.1016/j.scitotenv.2020.142242.

Correia, M.L.G., Rahmouni, K., 2006. Role of leptin in the cardiovascular and endocrine complications of metabolic syndrome. Diabetes Obes. Metabol. 8, 603–610. https://doi.org/10.1111/j.1463-1326.2005.00562.x.

Danopoulos, E., Twiddy, M., West, R., Rotchell, J.M., 2022. A rapid review and meta-regression analyses of the toxicological impacts of microplastic exposure in human cells. J. Hazard Mater. 427, 127861. https://doi.org/10.1016/j.jhazmat.2021.127861.

de Souza, L.L., Meyer, L.G., Rossetti, C.L., Miranda, R.A., Bertasso, I.M., Lima, D.G.V., da Silva, B.S., Pinheiro, V.H.S.D., Claudio-Neto, S., Manhães, A.C., Moura, E.G., Lisboa, P.C., 2024. Maternal low-dose caffeine intake during the perinatal period promotes short- and long-term sex-dependent hormonal and behavior changes in the offspring. Life Sci. 354. https://doi.org/10.1016/j.lfs.2024.122971.

Deng, Y., Zhang, Y., Lemos, B., Ren, H., 2017. Tissue accumulation of microplastics in mice and biomarker responses suggest widespread health risks of exposure OPEN. Sci. Rep. 7, 46687. https://doi.org/10.1038/srep46687.

Estrela, F.N., Guimarães, A.T.B., Araújo, A.P. da C., Silva, F.G., Luz, T.M. da, Silva, A.M., Pereira, P.S., Malafaia, G., 2021. Toxicity of polystyrene nanoplastics and zinc oxide to mice. Chemosphere 271, 129476. https://doi.org/10.1016/j.chemosphere.2020.129476.

Farag, A.A., Bayoumi, H., Radwaan, S.E., El Gazzar, W.B., Youssef, H.S., Nasr, H.E., Badr, A.M., Mansour, H.M., Elalfy, A., Sayed, A.E.D.H., Kharboush, T.G., Aboelkomsan, E.A.F., Sliem, R.E., 2024. Melatonin counteracts polyethylene microplastics induced adreno-cortical damage in male albino rats. Ecotoxicol. Environ. Saf. 279. https://doi.org/10.1016/j.ecoenv.2024.116499.

Fournier, S.B., D'Errico, J.N., Adler, D.S., Kollontzi, S., Goedken, M.J., Fabris, L., Yurkow, E.J., Stapleton, P.A., 2020. Nanopolystyrene translocation and fetal deposition after acute lung exposure during late-stage pregnancy. Part. Fibre Toxicol. 17. https://doi.org/10.1186/s12989-020-00385-9.

Gehrand, A.L., Hoeynck, B., Jablonski, M., Leonovicz, C., Cullinan, W.E., Raff, H., 2018. Programming of the adult HPA axis after neonatal separation and environmental stress in Male and female rats. Endocrinology 159, 2777–2789. https://doi.org/10.1210/EN.2018-00370.

Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made. Sci. Adv. 3. https://doi.org/10.1126/sciadv.1700782.

Global Plastics Outlook ECONOMIC DRIVERS, 2022. ENVIRONMENTAL IMPACTS AND POLICY OPTIONS. https://doi.org/10.1787/de747aef-en.

Grafmueller, S., Manser, P., Diener, L., Diener, P.A., Maeder-Althaus, X., Maurizi, L., Jochum, W., Krug, H.F., Buerki-Thurnherr, T., von Mandach, U., Wick, P., 2015. Bidirectional transfer Study of polystyrene nanoparticles across the placental barrier in an ex vivo human placental perfusion model. Environ. Health Perspect. 123, 1280–1286. https://doi.org/10.1289/EHP.1409271.

Grillo, G., Falvo, S., Latino, D., Chieffi Baccari, G., Venditti, M., Di Fiore, M.M., Minucci, S., Santillo, A., 2024. Polystyrene microplastics impair the functions of cultured mouse leydig (TM3) and sertoli (TM4) cells by inducing mitochondrial-endoplasmic reticulum damage. Ecotoxicol. Environ. Saf. 274, 116202. https://doi.org/10.1016/j.ecoenv.2024.116202.

Haverinen, E., Fernandez, M.F., Mustieles, V., Tolonen, H., 2021. Metabolic syndrome and endocrine disrupting chemicals: an overview of exposure and health effects. Int. J. Environ. Res. Publ. Health 18. https://doi.org/10.3390/ijerph182413047.

Jenner, L.C., Rotchell, J.M., Bennett, R.T., Cowen, M., Tentzeris, V., Sadofsky, L.R., 2022. Detection of microplastics in human lung tissue using μFTIR spectroscopy. Sci. Total Environ. 831, 154907. https://doi.org/10.1016/j.scitotenv.2022.154907.

Jin, H., Ma, T., Sha, X., Liu, Z., Zhou, Y., Meng, X., Chen, Y., Han, X., Ding, J., 2021. Polystyrene microplastics induced Male reproductive toxicity in mice. J. Hazard Mater. 401. https://doi.org/10.1016/j.jhazmat.2020.123430.

Jin, H., Yan, M., Pan, C., Liu, Z., Sha, X., Jiang, C., Li, L., Pan, M., Li, D., Han, X., Ding, J., 2022. Chronic exposure to polystyrene microplastics induced male reproductive toxicity and decreased testosterone levels via the LH-mediated LHR/cAMP/PKA/StAR pathway. Part. Fibre Toxicol. 19 (1 19), 13. https://doi.org/10.1186/s12989-022-00453-2, 2022.

Joshi, A., Faivre, F., la Fleur, S.E., Barrot, M., 2021. Midbrain and lateral nucleus accumbens dopamine depletion affects free-choice high-fat high-sugar diet preference in Male rats. Neuroscience 467, 171–184. https://doi.org/10.1016/j.neuroscience.2021.05.022.

Jovanoski, K.D., Duquenoy, L., Mitchell, J., Kapoor, I., Treiber, C.D., Croset, V., Dempsey, G., Parepalli, S., Cognigni, P., Otto, N., Felsenberg, J., Waddell, S., 2023. Dopaminergic systems create reward seeking despite adverse consequences. Nature 623 (7986 623), 356–365. https://doi.org/10.1038/s41586-023-06671-8, 2023.

Khramov, V.A., Kolomeĭtseva, A.S., Papichev, N.V., 2008. Jaffe color test-based microtechnique for determination of milk lactose. Gig. Sanit. 3, 86–87.

Lafram, A., Laadraoui, J., Al Naggar, Y., Sabri, S., Roky, R., 2026. Sex-based differences in toxicity after exposure to microplastics or nanoplastics in aquatic and terrestrial organisms: a systematic review. Environ. Pollut. 393, 127709. https://doi.org/10.1016/J.ENVPOL.2026.127709.

Lee, Y., Cho, J., Sohn, J., Kim, C., 2023. Health effects of microplastic exposures: current issues and perspectives in South Korea. Yonsei Med. J. 64, 301. https://doi.org/10.3349/ymj.2023.0048.

Leslie, H.A., van Velzen, M.J.M., Brandsma, S.H., Vethaak, A.D., Garcia-Vallejo, J.J., Lamoree, M.H., 2022. Discovery and quantification of plastic particle pollution in human blood. Environ. Int. 163, 107199. https://doi.org/10.1016/j.envint.2022.107199.

Li, B., Ding, Y., Cheng, X., Sheng, D., Xu, Z., Rong, Q., Wu, Y., Zhao, H., Ji, X., Zhang, Y., 2020. Polyethylene microplastics affect the distribution of gut microbiota and inflammation development in mice. Chemosphere 244, 125492. https://doi.org/10.1016/j.chemosphere.2019.125492.

Lim, D., Jeong, J., Song, K.S., Sung, J.H., Oh, S.M., Choi, J., 2021. Inhalation toxicity of polystyrene micro(nano)plastics using modified OECD TG 412. Chemosphere 262, 128330. https://doi.org/10.1016/j.chemosphere.2020.128330.

Lisboa, P.C., Miranda, R.A., Souza, L.L., Moura, E.G., 2021. Can breastfeeding affect the rest of our life? Neuropharmacology 200. https://doi.org/10.1016/j.neuropharm.2021.108821.

Liu, L., Xu, M., Ye, Y., Zhang, B., 2022. On the degradation of (micro)plastics: degradation methods, influencing factors, environmental impacts. Sci. Total Environ. 806, 151312. https://doi.org/10.1016/j.scitotenv.2021.151312.

Liu, S., Wu, X., Gu, W., Yu, J., Wu, B., 2020. Influence of the digestive process on intestinal toxicity of polystyrene microplastics as determined by in vitro Caco-2 models. Chemosphere 256. https://doi.org/10.1016/j.chemosphere.2020.127204.

Lu, H., Xu, P., Sun, G., Chen, B., Zheng, Y., Zhang, J., Wang, G., 2024. Early-life exposure to polystyrene micro- and nanoplastics disrupts metabolic homeostasis and gut microbiota in juvenile mice with a size-dependent manner. Sci. Total Environ. 955. https://doi.org/10.1016/j.scitotenv.2024.176802.

Luo, T., Wang, C., Pan, Z., Jin, C., Fu, Z., Jin, Y., 2019a. Maternal polystyrene microplastic exposure during gestation and lactation altered metabolic homeostasis in the dams and their F1 and F2 offspring. Environ. Sci. Technol. 53, 10978–10992. https://doi.org/10.1021/acs.est.9b03191.

Luo, T., Zhang, Y., Wang, C., Wang, X., Zhou, J., Shen, M., Zhao, Y., Fu, Z., Jin, Y., 2019b. Maternal exposure to different sizes of polystyrene microplastics during gestation causes metabolic disorders in their offspring. Environ. Pollut. 255. https://doi.org/10.1016/j.envpol.2019.113122.

MacKay, H., Patterson, Z.R., Abizaid, A., 2017. Perinatal exposure to low-dose Bisphenol-A disrupts the structural and functional development of the hypothalamic feeding circuitry. Endocrinology 158, 768–777. https://doi.org/10.1210/en.2016-1718.

Moon, H., Jeong, D., Choi, J.W., Jeong, S., Kim, H., Song, B.W., Lim, S., Kim, I.K., Lee, S., Kim, S.W., 2024. Microplastic exposure linked to accelerated aging and impaired adipogenesis in fat cells. Sci. Rep. 14 (1 14), 23920. https://doi.org/10.1038/s41598-024-74892-6, 2024.

Mullur, R., Liu, Y.Y., Brent, G.A., 2014. Thyroid hormone regulation of metabolism. Physiol. Rev. 94, 355. https://doi.org/10.1152/PHYSREV.00030.2013.

Nayanathara Thathsarani Pilapitiya, P.G.C., Ratnayake, A.S., 2024. The world of plastic waste: a review. Clean. Mater. 11, 100220. https://doi.org/10.1016/j.clema.2024.100220.

Palmisano, B.T., Zhu, L., Eckel, R.H., Stafford, J.M., 2018. Sex differences in lipid and lipoprotein metabolism. Mol. Metabol. 15, 45. https://doi.org/10.1016/J.MOLMET.2018.05.008.

Passos, M.C.F., Ramos, C.F., Moura, E.G., 2000. Short and long term effects of malnutrition in rats during lactation on the body weight of offspring, 20, 1603–1612. https://doi.org/10.1016/S0271-5317(00)00246-3.

Peterson, G.L., 1977. A simplification of the protein assay method of Lowry et al. which is more generally applicable. Anal. Biochem. 83, 346–356. https://doi.org/10.1016/0003-2697(77)90043-4.

Pietrobon, C.B., Miranda, R.A., Bertasso, I.M., Mathias, P.C. de F., Bonfleur, M.L., Balbo, S.L., Reis, M.A. de B., Latorraca, M.Q., Arantes, V.C., de Oliveira, E., Lisboa, P. C., de Moura, E.G., 2020. Early weaning induces short- and long-term effects on pancreatic islets in Wistar rats of both sexes. J. Physiol. 598, 489–502. https://doi.org/10.1113/JP278833.

Ragusa, A., Notarstefano, V., Svelato, A., Belloni, A., Gioacchini, G., Blondeel, C., Zucchelli, E., De Luca, C., D'avino, S., Gulotta, A., Carnevali, O., Giorgini, E., 2022. Raman microspectroscopy detection and characterisation of microplastics in human breastmilk. Polymers (Basel) 14. https://doi.org/10.3390/polym14132700.

Ragusa, A., Svelato, A., Santacroce, C., Catalano, P., Notarstefano, V., Carnevali, O., Papa, F., Rongioletti, M.C.A., Baiocco, F., Draghi, S., D'Amore, E., Rinaldo, D., Matta, M., Giorgini, E., 2021. Plasticenta: first evidence of microplastics in human placenta. Environ. Int. 146. https://doi.org/10.1016/j.envint.2020.106274.

Ritchie, H., Samborska, V., Roser, M., 2023. Plastic pollution. Our world in data. https://doi.org/10.1787/de747aef-en.

Rodrigues, V.S.T., Moura, E.G., Bernardino, D.N., Carvalho, J.C., Soares, P.N., Peixoto, T. C., Peixoto-Silva, N., Oliveira, E., Lisboa, P.C., 2018. Supplementation of suckling rats with cow's milk induces hyperphagia and higher visceral adiposity in females at adulthood, but not in males. JNB (J. Nutr. Biochem.) 55, 89–103. https://doi.org/10.1016/j.jnutbio.2017.12.001.

Roh, Y., Kim, J., Song, H., Seol, A., Kim, T., Park, E., Park, K., Lim, S., Wang, S., Jung, Y., Kim, H., Lim, Y., Hwang, D., 2024. Impact of the oral administration of polystyrene microplastics on hepatic lipid, glucose, and amino acid metabolism in C57BL/6Korl and C57BL/6-Lepem1hwl/Korl mice. Int. J. Mol. Sci. 25, 4964. https://doi.org/10.3390/ijms25094964.

Salvador Cesa, F., Turra, A., Baruque-Ramos, J., 2017. Synthetic fibers as microplastics in the marine environment: a review from textile perspective with a focus on domestic washings. Sci. Total Environ. 598, 1116–1129. https://doi.org/10.1016/j.scitotenv.2017.04.172.

Silva, B.S., Bertasso, I.M., Pietrobon, C.B., Lopes, B.P., Santos, T.R., Peixoto-Silva, N., Carvalho, J.C., Claudio-Neto, S., Manhães, A.C., Cabral, S.S., Kluck, G.E.G., Atella, G. C., Oliveira, E., Moura, E.G., Lisboa, P.C., 2019. Effects of maternal bisphenol A on behavior, sex steroid and thyroid hormones levels in the adult rat offspring. Life Sci. 218, 253–264. https://doi.org/10.1016/j.lfs.2018.12.039.

Soares, P.N., Miranda, R.A., Bertasso, I.M., Pietrobon, C.B., Rodrigues, V.S.T., de Oliveira, E., Manhães, A.C., de Moura, E.G., Lisboa, P.C., 2022. Late effects of early weaning on food preference and the dopaminergic and endocannabinoid systems in male and female rats. J. Dev. Orig. Health Dis. 13, 90–100. https://doi.org/10.1017/S2040174421000039.

Ullah, Sana, Ahmad, S., Guo, X., Ullah, Saleem, Ullah, Sana, Nabi, G., Wanghe, K., 2023. A review of the endocrine disrupting effects of micro and nano plastic and their associated chemicals in mammals. Front. Endocrinol. 13. https://doi.org/10.3389/fendo.2022.1084236.

Wang, Z., Wang, S., Liu, S., Wang, Z., Li, F., Bu, Q., An, X., 2025. Polystyrene microplastics induce potential toxicity through the gut-mammary axis. npj Science of Food 9 (1), 139. https://doi.org/10.1038/s41538-025-00517-5. (Accessed 14 July 2025).

Wesolowski, S.R., Kasmi, K.C.E., Jonscher, K.R., Friedman, J.E., 2016. Developmental origins of NAFLD: a womb with a clue. Nat. Rev. Gastroenterol. Hepatol. 14, 81. https://doi.org/10.1038/NRGASTRO.2016.160.

Xiong, Y., Chen, Z., Xiang, H., Liu, Y., Wang, Y., 2025. Polystyrene microplastics disrupt adrenal steroid synthesis in male mice via mitochondrial dysfunction. Ecotoxicol. Environ. Saf. 290. https://doi.org/10.1016/j.ecoenv.2024.117528.

Xu, W., Yuan, Yangyang, Tian, Y., Cheng, C., Chen, Y., Zeng, L., Yuan, Yuan, Li, D., Zheng, L., Luo, T., 2023. Oral exposure to polystyrene nanoplastics reduced male fertility and even caused male infertility by inducing testicular and sperm toxicities in mice. J. Hazard Mater. 454, 131470. https://doi.org/10.1016/j.jhazmat.2023.131470.

Yang, Y., Xie, E., Du, Z., Peng, Z., Han, Z., Li, L., Zhao, R., Qin, Y., Xue, M., Li, F., Hua, K., Yang, X., 2023. Detection of various microplastics in patients undergoing cardiac surgery. Environ. Sci. Technol. 57, 10911–10918. https://doi.org/10.1021/acs.est.2c07179.

Zambrano, E., Reyes-Castro, L.A., Rodríguez-González, G.L., Chavira, R., Lomas-Soria, C., Gerow, K.G., Nathanielsz, P.W., 2023. Developmental programming-aging interactions have sex-specific and developmental stage of exposure outcomes on life course circulating corticosterone and dehydroepiandrosterone (DHEA) concentrations in rats exposed to maternal protein-restricted diets. Nutrients 15, 1239. https://doi.org/10.3390/NU15051239.

Zhang, J., Liu, L., Dai, X., Li, B., Zhang, S., Yu, Y., 2024. Thyroid and parathyroid function disorders induced by short-term exposure of microplastics and nanoplastics: exploration of toxic mechanisms and early warning biomarkers. J. Hazard Mater. 476. https://doi.org/10.1016/j.jhazmat.2024.134960.

Zhang, Y., Wang, X., Zhao, Y., Zhao, J., Yu, T., Yao, Y., Zhao, R., Yu, R., Liu, J., Su, J., 2023. Reproductive toxicity of microplastics in female mice and their offspring from induction of oxidative stress. Environ. Pollut. 327. https://doi.org/10.1016/j.envpol.2023.121482.

Zhao, Q., Zhu, L., Weng, J., Jin, Z., Cao, Y., Jiang, H., Zhang, Z., 2023. Detection and characterization of microplastics in the human testis and semen. Sci. Total Environ. 877. https://doi.org/10.1016/j.scitotenv.2023.162713.

Ziani, K., Ioniță-Mîndrican, C.B., Mititelu, M., Neacşu, S.M., Negrei, C., Moroşan, E., Drăgănescu, D., Preda, O.T., 2023. Microplastics: a real global threat for environment and food safety: a State of the art review. Nutrients 15, 2023. https://doi.org/10.3390/nu15030617. Page 617 15, 617.

Zurub, R.E., Cariaco, Y., Wade, M.G., Bainbridge, S.A., 2023. Microplastics exposure: implications for human fertility, pregnancy and child health. Front. Endocrinol. (Lausanne). 14, 1330396. https://doi.org/10.3389/fendo.2023.1330396.