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Effects of repeated intravenous polystyrene microplastic exposure in sheep: changes in body weight and haematological parameters

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ABSTRACT. The widespread occurrence of microplastics has raised increasing concerns regarding their potential impact on animal health, yet data on the systemic effects of intravenous polystyrene microplastics (PS-MPs) in large-animal models remain limited. This study evaluated the effects of repeated intravenous exposure to PS-MPs on body weight and haematological parameters in sheep. Eighteen sheep were randomly assigned to a control group and two groups receiving low (LD) or high (HD) doses of spherical PS-MPs (2 µm in diameter) over 34 days. Body weight was monitored weekly, while white blood cell (WBC), lymphocyte (LYM), red blood cell (RBC), and platelet (PLT) counts and haemoglobin (HGB) concentrations were measured at 12 sampling time points. Scanning electron microscopy (SEM) confirmed the presence of PS-MPs in blood samples. Repeated PS-MP exposure was associated with changes in body weight and haematological parameters that varied with dose and exposure duration. Body weight was significantly reduced in the HD group at the end of the experiment ($P < 0.05$). WBC and PLT counts were elevated during the later stages of exposure ($P < 0.05$), while LYM counts increased transiently in the LD group on day 10 ($P < 0.05$). RBC and HGB values were significantly higher in the LD group during the early phase of exposure ($P < 0.05$–0.01), but returned to comparable levels at later phases in all groups. These findings indicate that repeated intravenous PS-MP exposure is associated with dose- and time-dependent changes in body weight and selected haematological parameters in sheep, potentially reflecting inflammatory, immune, haemostatic, and erythropoietic responses, without clear evidence of overt haematological pathology.

Introduction

In recent decades, global plastic production has exceeded several hundred million tonnes annually, contributing to the accumulation of plastic waste in the environment. The durability, low cost and versatility of plastics have made them essential materials in modern society, but their resistance to degradation causes that plastic waste persist for decades or even centuries. Physical, chemical and biological processes gradually fragment larger plastic materials into smaller particles, including microplastics, defined as plastic particles less than 5 mm in size. These particles are widespread in water, soil and air and have been detected in organisms at all trophic levels (Bajt, 2021; Alva and Thomas, 2025).

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Numerous studies have demonstrated that microplastics can be taken up by a wide range of organisms, such as aquatic invertebrates, fish, birds and mammals, including humans (Wu et al., 2022). They have been detected in various tissues and organs, among others the liver, muscles and reproductive organs, demonstrating their ability to reach different parts of the body (Dzierżyński et al., 2024). A growing body of evidence suggests that these particles may cross biological barriers, including the intestinal and alveolar-capillary barriers, enter the bloodstream and affect various tissues and cells (Zhu et al., 2023, Leonard et al., 2024). Experimental studies have linked microplastic exposure to cellular dysfunction, oxidative stress, membrane damage and metabolic disorders (Remigante et al., 2024). Thus, the presence of microplastics in the bloodstream raises questions concerning their interactions with blood cells and other tissues and their potential systemic toxicity (Leonard et al., 2024, Schwaerzer, 2025).

Although the effects of microplastics on human health have been widely studied (Aardema et al., 2024; Lackner and Branka, 2024), their impact on farm animals is not yet fully understood. Livestock may be exposed to microplastics through feed, water and contact with contaminated soil. Sheep (*Ovis aries*) are frequently reared in extensive production systems, where they may be exposed to microplastics present in the soil or vegetation. Studying microplastic exposure in farm animals may therefore provide valuable information on their distribution within the food chain and potential transfer into animal-derived products (Chang et al., 2024, Yang et al., 2025).

Physiological and haematological measurements can help assess the effects of microplastic exposure on animal health. Blood parameters, including red blood cells (RBC) count, haemoglobin (HGB) concentration, and haematocrit, are commonly used to evaluate physiological status and responses to stressors or toxic substances (Turini et al., 2024). Microplastic exposure has been associated with metabolic disturbances, oxidative stress, and inflammatory responses, which may also affect haematological parameters (Prata et al., 2020).

Despite increasing research on microplastic exposure, information regarding its effects on physiological and haematological parameters in farm animals have been less extensively examined. This study therefore aimed to evaluate the effects of repeated intravenous administration of polystyrene microplastics (PS-MPs) on body weight and selected haematological parameters in sheep, with particular attention to changes associated with exposure dose and duration.

Material and methods

Animal management

All procedures involving animals were approved by the 2nd Local Ethics Committee for Animal Experiments at the Institute of Pharmacology, Polish Academy of Sciences, Kraków, Poland (approval No. 204/2024; 8 August 2024) and were conducted in accordance with Directive 2010/63/EU of the European Parliament and of the Council. Eighteen Romanowska sheep aged 9–10 months were used in the experiment. The Romanowska is an early-maturing, highly prolific breed with a prolonged breeding season. The animals were housed at the Sheep Breeding Centre of the Kielanowski Institute of Animal Physiology and Nutrition, Polish Academy of Sciences under natural lighting conditions (52° N, 21° E). They were fed a pelleted concentrate twice daily, with rations adjusted to their physiological requirements in accordance with the recommendations of the National Research Institute of Animal Production (Kraków-Balice, Poland) and the French National Institute for Agricultural Research (Strzetelski, 2014). Hay, water, and mineral licks were available *ad libitum*. During the experimental period, sheep were housed in pairs in pens allowing visual and olfactory contact with the rest of the flock.

Experimental design

The experiment was conducted during the sheep's first breeding season, from mid-October to December. Once the ewes had reached reproductive maturity, their oestrous cycles were synchronised using the Chronogest-CR protocol (Młotkowska et al., 2020). Subsequently, a catheter was inserted into the external jugular vein of each animal, and the sheep were randomly divided into three groups of six animals each. PS-MP (particle diameter: 2 μm; Cat. No. 78452, Merck KGaA, Darmstadt, Germany), were suspended in 250 ml of physiological saline and infused intravenously every three days over two oestrus cycles. The groups received (1) physiological saline alone (control), (2) PS-MPs at 0.015 mg/kg body weight (low-dose group, LD) or (3) PS-MPs at 0.15 mg/kg body weight (high-dose group, HD) (Młotkowska et al., 2026). The doses were selected based on published data on microplastic concentrations in human blood and toxicity in animal models (da Silva Brito et al., 2022, Leonard et al., 2024, Volsa et al., 2025). PS-MP administration was

conducted for 34 days and ended during the preovulatory phase of the second oestrous cycle. During each infusion (250 ml/120 min), the sheep were housed in experimental pens to which they had previously been acclimatised and in which they could lie down comfortably. Body weight was recorded weekly throughout the experiment. Blood samples (3 ml) were collected 24 h after each administration for haematological analysis. The following parameters were measured: white blood cells (WBC), lymphocytes (LYM), RBC, and platelet (PLT) counts, and HGB concentration.

Scanning electron microscopy (SEM)

The surface morphology of the blood samples was assessed using a Thermo Scientific Apreo 2 S scanning electron microscope (Thermo Fisher Scientific, Waltham, MA, USA). The samples were mounted on 12.7-mm-diameter aluminium stubs and examined directly in the microscope chamber. Imaging was performed using a low-vacuum secondary electron detector (LVD) at an accelerating voltage of 10 kV, with 5 kV used in selected cases to improve the visibility of specific structures. Magnifications of 5 000×, 10 000× and 20 000× were used to examine surface morphology and identify particles measuring several micrometres. Scale bars of 10, 5 and 3 µm were included in the images, depending on magnification.

Statistical analysis

Data were initially tested for normality using the Shapiro-Wilk test and then grouped into parametric and nonparametric variables. Differences in RBC, LYM, HGB and body weight between treatment groups were analysed using repeated-measures analysis of variance (ANOVA), followed by Fisher's least significant difference (LSD) post hoc test when significant effects were detected. Differences WBC and PLT levels between treatment groups were assessed using the Friedman test. All analyses were performed using STATISTICA (StatSoft, Tulsa, OK, USA). Relationships between selected haematological parameters were assessed using Spearman's rank correlation analysis. Data are presented as means ± standard error of the mean (SEM), and statistical significance was set $P < 0.05$.

Results

Scanning electron microscopy (SEM)

SEM examination at 10 000× magnification revealed individual spherical particles approximately 2 µm in diameter in freeze-dried sheep blood samples. These particles were clearly distinguishable from the surrounding biological material (Figure 1).

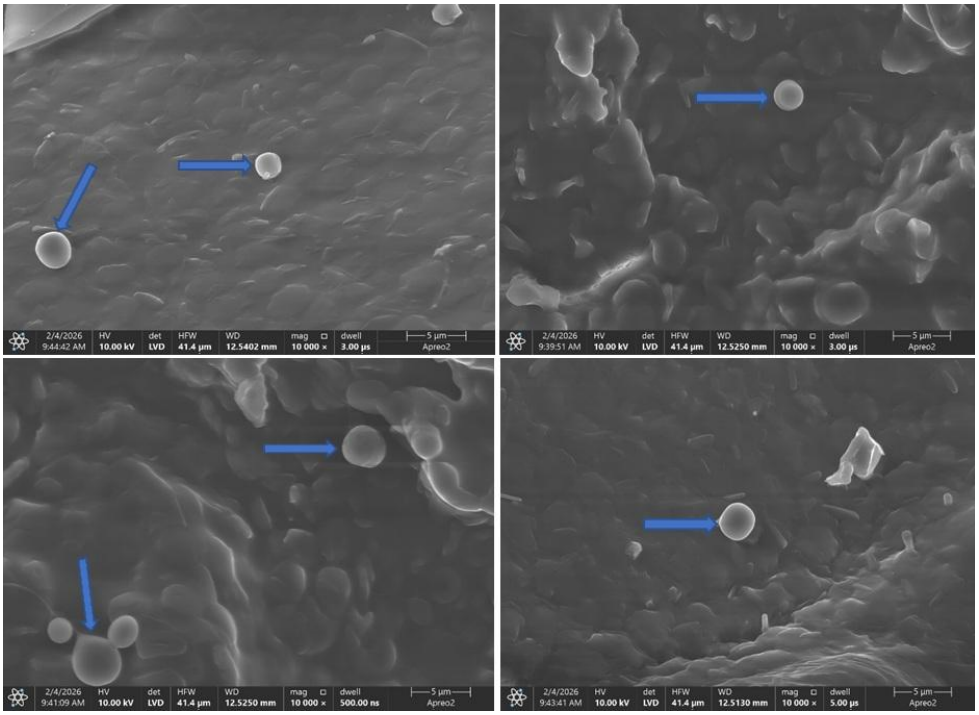


Figure 1. Representative scanning electron microscopy (SEM) images showing microplastic particles observed in freeze-dried blood samples. Blue arrows indicate the observed particles. Images were acquired at a magnification of 10 000×, using an accelerating voltage of 10 kV and a low-vacuum (LVD) detector. Scale bar: 5 µm

Body weight analysis

Body weight showed different patterns of changes among the experimental groups throughout the study (Figure 2, Table 1). In the control group (C), body weight decreased during the first week, followed by a gradual increase over the subsequent observation period. By the end of the experiment, mean body weight had returned to approximately its baseline value.

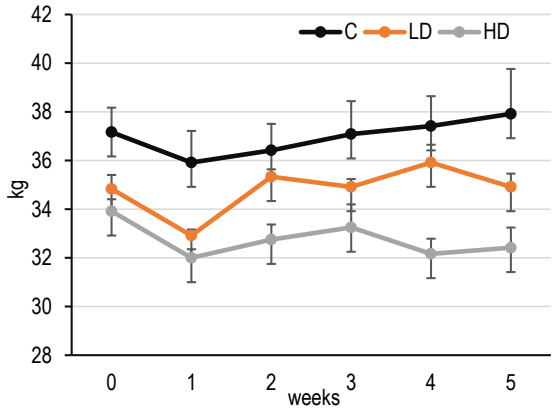


Figure 2. Changes in mean body weight (kg) of sheep during the 5-week experimental period in the vehicle control (C), low-dose microplastic (LD), and high-dose microplastic (HD) groups. Body weight was measured weekly

Table 1. Weekly changes in body weight (kg) in the control (C), low-dose microplastic (LD), and high-dose microplastic (HD) groups during the experiment

Week	C	LD	HD
1	−1.25	−1.91	−1.92
2	0.50	2.41	0.75
3	0.66	−0.41	0.50
4	0.34	1.00	−1.08
5	0.50	−1.00	0.25

In the LD group, body weight fluctuated more markedly than in the control group. Following an initial decrease, a significant increase was observed during the second week and subsequently showed alternating increases and decreases. The final mean body weight was similar to the baseline value, with no consistent upward or downward trend over the study period.

In the HD group, body weight decreased during the first week and fluctuated moderately thereafter. Although body weight increased transiently, this increase was not sustained, and the final mean body weight was below the baseline value. The change in body weight from baseline till the end of the experiment differed significantly between the HD and control groups ($P < 0.05$; Figure 3). Overall, the HD group showed the greatest reduction in body weight by the end of the experiment.

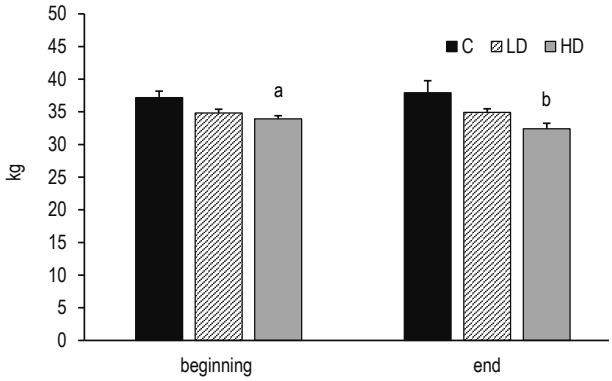


Figure 3. Mean body weight (kg) of sheep in the control (C), low-dose microplastic (LD), and high-dose microplastic (HD) groups at the beginning and end of the experiment

Data are presented as mean ± SEM (n = 6 per group). SEM – standard error of the mean; ab - means within a bar with different superscripts are significantly different at $P < 0.05$

Blood parameter analysis

White blood cells

White blood cells (WBC) counts varied with exposure duration and the administered PS-MP dose (Figure 4). The reference range for sheep was 5.00–14.00 × 10^3/µl, as indicated by the dotted lines in the figure. During the early phase of the experiment (blood samples 1–4; days 1, 4, 7 and 10), WBC counts were similar in all groups, with minor fluctuations and a slight upward trend in both PS-MP-exposed groups. In the control group (C), WBC counts remained within the reference range throughout the experiment. In the LD group, counts stayed within this range until day 28 (sample 10), but slightly exceeded its upper limit on days 31 and 34 (samples 11 and 12). In the HD group, WBC counts were within the reference range until day 19 (sample 7), exceeded the upper limit from day 22 to day 28 (samples 8–10) and returned to the reference range on days 31 and 34 (samples 11 and 12). A statistically significant increase in WBC counts was observed in the LD group on days 28, 31 and 34 ($P < 0.05$ for each comparison) and in the HD group on day 13 ($P < 0.05$). A further marked increase in WBC counts was observed in the HD group from day 19 onwards, which persisted until the end of the experiment. However, owing to individual variation in WBC counts, these later differences between the HD and control groups were not statistically significant ($P > 0.05$). Moreover, no significant differences were detected between the LD and HD groups throughout the experiment ($P > 0.05$).

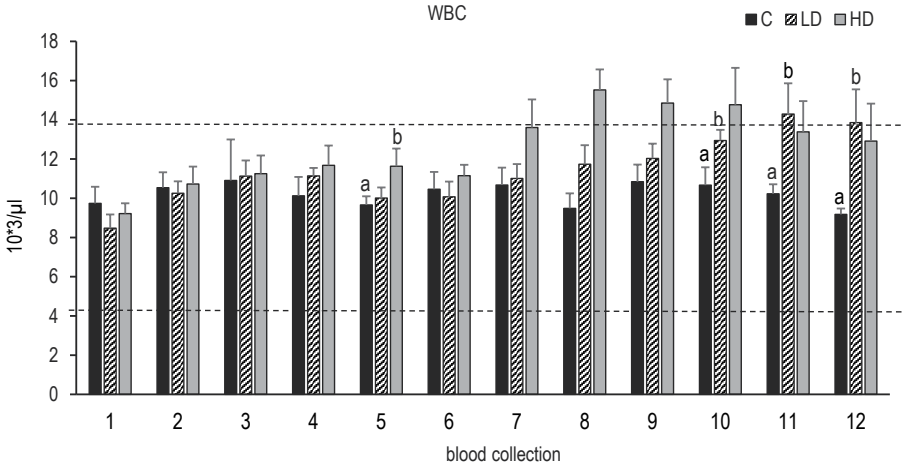


Figure 4. Changes in white blood cell (WBC) counts (×10³/µl) at 12 consecutive blood sampling time points in the control (C), low-dose microplastic (LD), and high-dose microplastic (HD) groups. The reference range for WBC counts (5.00–14.00 × 10³/µl) is indicated by the dotted lines. Data are presented as mean ± SEM (n = 6 per group)

SEM – standard error of the mean; ab – means within a bar with different superscripts are significantly different at $P < 0.05$; 1 – day 1, 2 – day 4, 3 – day 7, 4 – day 10, 5 – day 13, 6 – day 16, 7 – day 19, 8 – day 22, 9 – day 25, 10 – day 28, 11 – day 31, 12 – day 34

Lymphocytes

Lymphocytes (LYM) counts varied with exposure duration and the administered PS-MP dose (Figure 5). The reference range for sheep was 0.83–4.69 ×10³/µl (indicated by dotted lines on the graph). Throughout the study period, LYM values in all groups exceeded the upper reference limit. During the early phase of the experiment (blood samples 1–4; days 1, 4, 7 and 10), LYM counts were generally similar in all groups, although a more pronounced upward trend was observed in the LD group. Counts remained above the reference range throughout the experiment in all three groups, with the highest values generally observed in the LD group. On day 10 (sample 4), LYM counts were significantly higher in the LD group than in the control and HD groups ($P < 0.05$ for both comparisons), whereas the HD and control groups did not differ significantly ($P > 0.05$). At subsequent sampling points, LYM counts fluctuated only slightly, with no significant differences among groups ($P > 0.05$). During the second half of the experiment, LYM counts tended to be higher in the LD group and lower in the HD group, but these differences were not statistically significant ($P > 0.05$). No significant differences were detected between successive sampling points ($P > 0.05$).

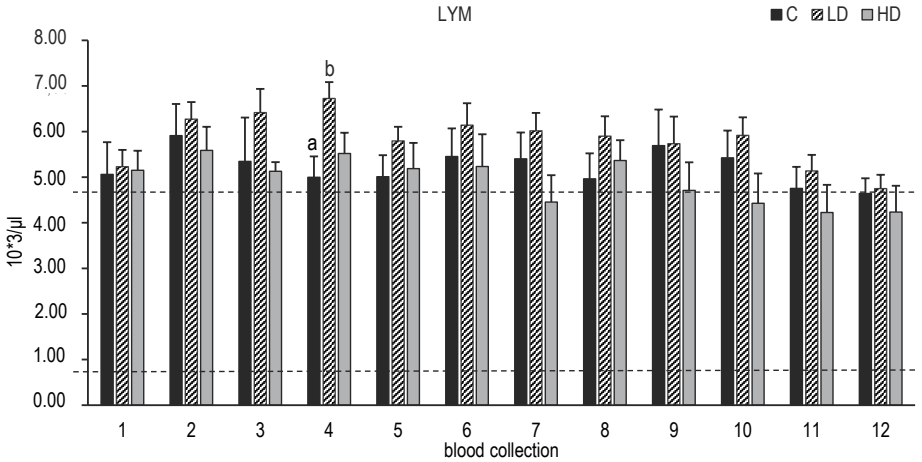


Figure 5. Changes in lymphocyte (LYM) counts (×10³/µl) at 12 consecutive blood sampling time points in the control (C), low-dose microplastic (LD), and high-dose microplastic (HD) groups. The reference range for LYM counts (0.83–4.69 × 10³/µl) is indicated by the dotted lines. Data are presented as mean ± SEM (n = 6 per group)

SEM – standard error of the mean; ab – means within a bar with different superscripts are significantly different at $P < 0.05$; 1 – day 1, 2 – day 4, 3 – day 7, 4 – day 10, 5 – day 13, 6 – day 16, 7 – day 19, 8 – day 22, 9 – day 25, 10 – day 28, 11 – day 31, 12 – day 34

Red blood cells

RBC counts varied with exposure duration and the administered PS-MP dose (Figure 6). The reference range for sheep was 7.80–13.80 × 10^6/µl (indicated by dashed lines in the figure). During the early phase of the experiment (blood draws 1–4; days 1, 4, 7, and 10), RBC counts were relatively high in all groups, with the highest values observed in the LD group. In the control group (C), RBC values slightly exceeded the upper reference limit on days 4 and 7 (samples 2 and 3), but remained within the reference range from day 10 (sample 4) onwards. In the LD group, RBC counts exceeded the upper reference limit from day 1 to day 25 (samples 1–9), before returning to the reference range on days 28–34 (samples 10–12). In the HD group, RBC counts exceeded the upper reference limit on days 1–10 (samples 1–4) and remained within the reference range from day 13 (sample 5) until the end of the experiment. Compared with the control group, RBC counts were significantly higher in the LD group on days 4 ($P < 0.01$), 7 ($P < 0.05$), 13 ($P < 0.01$) and 16 ($P < 0.01$). RBC counts were also significantly higher in the LD group than in the HD group on days 7 and 13 ($P < 0.01$ for both comparisons) and day 16 ($P < 0.05$). During the second half of the experiment, RBC counts gradually decreased in all groups. In the HD group, RBC counts were significantly lower than in the LD group on days 22 ($P < 0.01$) and 25 ($P < 0.05$). On day 25, RBC counts were also significantly lower in the HD group than in the control group ($P < 0.05$). No significant differences were detected between the groups during the final three sampling points (days 28–34; $P > 0.05$).

Haemoglobin

HGB concentration varied with exposure duration and the administered PS-MP dose (Figure 7). The reference range for sheep was 9.00–15.5 g/dl (marked by dashed lines in the figure). Throughout the experiment, HGB values in all groups remained within this range. In the initial phase of the study (blood samples 1–4; days 1, 4, 7, and 10), HGB concentration increased gradually in all groups, with the highest values observed in the LD group. From day 13 (sample 5) onwards, HGB concentration gradually decreased in all groups until the end of the experiment. HGB concentration was significantly higher in the LD group on days 7 ($P < 0.05$), 13 ($P < 0.01$) and 16 ($P < 0.05$) compared to the control group. HGB concentration was also significantly higher in the LD group than in the HD group on days 7, 13 and 16 ($P < 0.05$ for each comparison). On day 13, HGB concentration was additionally significantly higher in the HD group than in the control group ($P < 0.05$). During the second half of the experiment (samples 7–12; days 19–34), no significant differences in HGB concentration were detected among groups ($P > 0.05$), despite the gradual decrease observed in all groups.

Blood platelets

PLT counts varied with exposure duration and the administered PS-MP dose (Figure 8). The reference range was 180–400 × 10^3/µl, as indicated by the dotted lines in the figure. During the first four blood samplings (days 1, 4, 7, and 10), PLT counts remained at comparable levels in all experimental groups. In the control group (C), PLT values stayed within the reference range throughout the study.

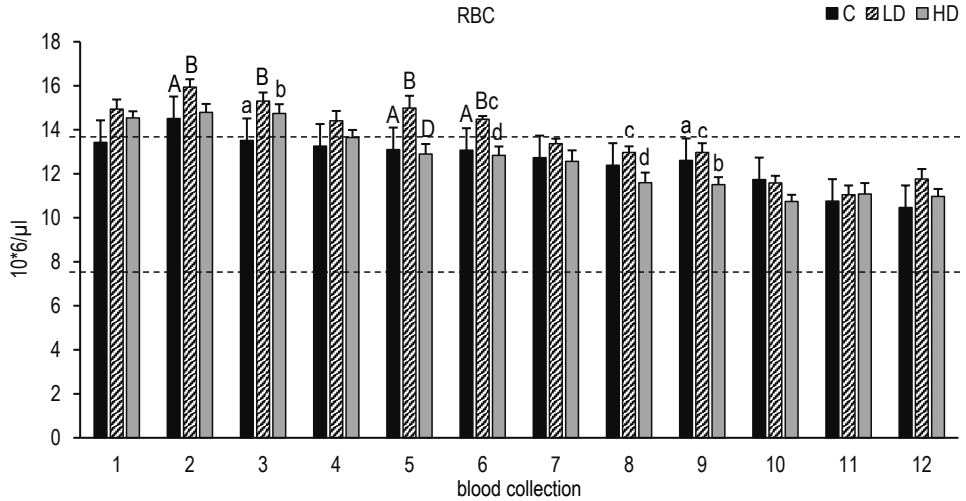


Figure 6. Changes in red blood cell (RBC) counts (×10^6/µl) at 12 consecutive blood sampling time points in the control (C), low-dose microplastic (LD), and high-dose microplastic (HD) groups. The reference range for RBC counts (7.80–13.80 × 10^6/µl) is indicated by the dotted lines. Data are presented as mean ± SEM (n = 6 per group)

SEM – standard error of the mean; ab, cd – means within a bar with different superscripts are significantly different at $P < 0.05$; AB,CD – means within a bar with different superscripts are significantly different at $P < 0.01$; 1 – day 1, 2 – day 4, 3 – day 7, 4 – day 10, 5 – day 13, 6 – day 16, 7 – day 19, 8 – day 22, 9 – day 25, 10 – day 28, 11 – day 31, 12 – day 34

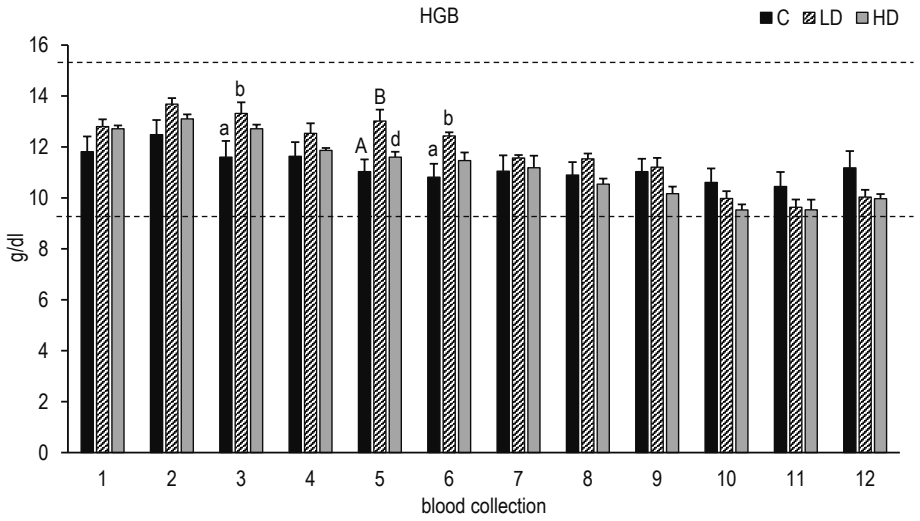


Figure 7. Changes in haemoglobin (HGB) concentration (g/dl) at 12 consecutive blood sampling time points in the control (C), low-dose microplastic (LD), and high-dose microplastic (HD) groups. The reference range for HGB concentration (9.00–15.50 g/dl) is indicated by the dotted lines. Data are presented as mean ± SEM (n = 6 per group)

SEM – standard error of the mean; ab, cd – means within a bar with different superscripts are significantly different at $P < 0.05$; AB - means within a bar with different superscripts are significantly different at $P < 0.01$; 1 – day 1, 2 – day 4, 3 – day 7, 4 – day 10, 5 – day 13, 6 – day 16, 7 – day 19, 8 – day 22, 9 – day 25, 10 – day 28, 11 – day 31, 12 – day 34

In the LD group, all values were within the reference range until day 28 (sample 10), but exceeded the upper reference limit on days 31 and 34 (samples 11 and 12). In the HD group, PLT counts were within the reference range until day 25 (sample 9), exceeded the upper reference limit on day 28 (sample 10) and returned to the reference range on days 31 and 34 (samples 11 and 12). On day 7 (sample 3), PLT counts were significantly higher in the control group than in the HD group ($P < 0.05$), with no significant differences between the C and LD groups or between the LD and HD groups ($P > 0.05$). Later in the experiment, PLT counts increased in both PS-MP-exposed groups, particularly in the HD group. On day 28 (sample 10), PLT counts were significantly higher in the HD group than in both the control and LD groups ($P < 0.05$ for both comparisons). On day 31 (sample 11), PLT counts were significantly higher in the LD group than in both the control and HD groups ($P < 0.05$ for both comparisons). At the final sampling (day 34), no statistically significant differences were detected between the groups ($P > 0.05$), although PLT counts showed an upward trend towards the end of the experiment in both PS-MP-exposed groups.

Correlation between white blood cells and lymphocytes

In the control group, a strong positive correlation_was observed between WBC and LYM counts ($r_s = 0.662$; $P < 0.001$) (Table 2), indicating that higher WBC counts were closely associated with higher LYM numbers. In the LD group, this correlation was weaker but remained statistically significant ($r_s = 0.424$; $P < 0.001$). In the HD group, the correlation was weak but still statistically significant ($r_s = 0.283$; $P = 0.016$).

Table 2. Correlation between white blood cell (WBC) and lymphocyte (LYM) counts in the control and polystyrene microplastic (PS-MP)-exposed groups

Group	r_s	*P*-value	Correlation
Control (C)	0.662	2.5×10^{-10}	strong positive
Low dose (LD)	0.424	0.00021	moderate positive
High dose (HD)	0.283	0.0159	weak positive

r_s – Spearman's rank correlation coefficient

Correlation between red blood cells and haemoglobin

Spearman's rank correlation analysis was used to assess the relationship between RBC count and HGB concentration in each experimental group. In the C group, a very strong positive correlation was demonstrated between these parameters ($r_s = 0.912$; $P < 0.001$; Table 3). Higher RBC counts were associated with higher HGB concentrations, consistent with the normal physiological relationship between these parameters. A similar relationship was

Table 3. Correlation between red blood cell (RBC) count and haemoglobin (HGB) concentration in the control and polystyrene microplastic (PS-MP)-exposed groups

Group	r_s	*P*-value	Correlation
Control (C)	0.912	<0.001	very strong positive
Low dose (LD)	-0.079	0.507	not significant
High dose (HD)	0.915	<0.001	very strong positive

r_s – Spearman's rank correlation coefficient

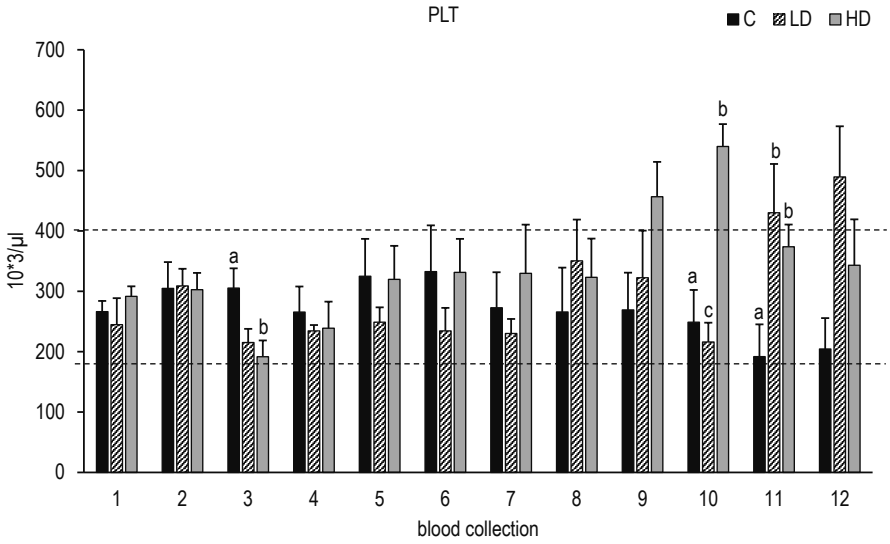


Figure 8. Changes in platelet (PLT) counts (×10³/µl) at 12 consecutive blood sampling time points in the control (C), low-dose microplastic (LD), and high-dose microplastic (HD) groups. The reference range for PLT counts (180–400 × 10³/µl) is indicated by the dotted lines. Data are presented as mean ± SEM (n = 6 per group)

SEM – standard error of the mean; ab, cd – means within a bar with different superscripts are significantly different at $P < 0.05$; 1 – day 1, 2 – day 4, 3 – day 7, 4 – day 10, 5 – day 13, 6 – day 16, 7 – day 19, 8 – day 22, 9 – day 25, 10 – day 28, 11 – day 31, 12 – day 34

observed in the HD group, with a very strong positive correlation ($r_s = 0.915$; $P < 0.001$). Its strength was comparable to that observed in the C group, suggesting that the relationship between RBC count and HGB concentration was maintained despite PS-MP exposure. In the LD group, however, no statistically significant correlation was found between RBC counts and HGB concentrations ($r_s = -0.079$; $P = 0.507$). The correlation coefficient was close to zero, indicating no evidence of a monotonic relationship between these parameters in this group.

Discussion

Appropriate doses of (PS-MPs for sheep were selected based on data on microplastic concentrations measured in human blood and effects reported in other animal models (Deng et al., 2017, Leonard et al., 2024). The lower dose was selected based on reported microplastic concentrations in human blood, ranging from 1.84 to 4.65 µg/ml, to ensure the biological relevance of the experimental model to human exposure (Leonard et al., 2024). The higher dose was determined experimentally as a multiple of the lower dose to investigate the effects of incrementing PS-MP exposure. The use of two exposure levels allowed to assess the effects of concentrations comparable to those reported in human blood, alongside additional changes associated with higher exposure, thereby increasing the toxicological and translational value of the findings. In the sheep model, both doses of PS-MPs induced changes in physiological and haematological parameters, indicating effects on haematopoietic and immune function, as well as overall metabolic status. These findings suggest a complex biological response potentially involving both adaptive and toxic mechanisms. They are consistent with previous reports that microplastics can exert systemic effects on living organisms, including mammals and humans (Leonard et al., 2024; Maitz et al., 2025).

In the present study, P spherical PS-MP particles (2 µm in diameter) were administered directly into the jugular vein. Their size is smaller than the diameter of many capillaries (5–8 µm), allowing them to pass through narrow blood vessels, and may also permit their passage across the blood-brain barrier and the blood-cerebrospinal fluid barrier (Gouin et al., 2024). Given the similar densities of polystyrene and blood (1.05 and 1.053 g/cm^3, respectively), the microplastics may remain suspended in circulating blood rather than settling under gravity. The risk of platelet aggregation and thrombus formation is therefore expected to be relatively low. Available literature indicates that adverse effects on blood components may be induced by polystyrene particles at the nanoscale (nanoplastics) or be associated with the presence of amino or carboxyl groups (Christodoulides et al., 2023). Non-functionalised polystyrene particles generally have little effect on blood coagulation dynamics, except for 50 nm particles at a relatively high concentration of 25 µg/ml. Nanoscale plastic

particles have a higher surface area-to-volume ratio than larger microplastic, which may increase their reactivity and potential toxicity (Lett et al., 2021).

Differences in body weight observed between the groups are important indicators of the animals' overall health and welfare. In sheep, weight gain depends on many factors, including nutrient utilisation efficiency, liver and muscle function, hormonal balance, energy expenditure, immune system activity and the extent of inflammation. Disruption of any of these processes can reduce weight gain, even when feed intake remains unchanged. In this study, the highest body weights were recorded in the control group, whereas weight gain was markedly lower in both PS-MP-exposed animals, particularly in the HD group. As PS-MPs were administered intravenously, the observed changes cannot be explained solely by gastrointestinal disturbances, which predominate in oral exposure models. A more likely explanation is a systemic effect of PS-MPs following their distribution through the bloodstream and accumulation in organs responsible for metabolism and detoxification, such as the liver, spleen, lungs and kidneys. Previous studies have demonstrated that PS-MPs can induce oxidative stress, trigger inflammatory responses and impair mitochondrial function and cellular energy metabolism, potentially increasing energy expenditure and reducing anabolic processes (Yong et al., 2020, Li et al., 2024). A growing body of evidence also suggests that microplastics can interfere with pathways regulating lipid, glucose and protein metabolism, thereby disrupting energy balance. In mice, exposure to PS-MPs has been associated with liver damage, impaired fatty acid β-oxidation and altered expression of genes involved in lipid metabolism and energy homeostasis (Lu et al., 2018; Deng et al., 2022). In Japanese quails, chronic microplastic exposure was associated with reduced body weight and altered lipid metabolism (de Souza et al., 2022). Similar effects have also been described in fish, where PS-MP exposure resulted in impaired growth, reduced feed utilisation and changes in energy metabolism (Rashid et al., 2025). Although most of these studies concerned oral exposure, their findings suggest a common mechanism involving disruption of metabolic homeostasis that may operate independently of the exposure route. The greater variability in body weight observed in the LD group may reflect a biphasic or adaptive response to PS-MP exposure, involving compensatory mechanisms activated at lower doses. This pattern could be consistent with hormesis, a biphasic dose–response phenomenon in which low levels of a stressor elicit adaptive responses, whereas higher levels exceed the capacity of these mechanisms. In contrast, the sustained reduction in body weight observed in the HD group could indicate that the animals were less able to adapt to higher PS-MP exposure, potentially leading to disturbances in metabolic homeostasis and changes in inflammatory status.

Analysis of haematological parameters showed increased WBC counts in the groups exposed to PS-MPs, particularly in the later stages of the experiment, potentially indicating immune system activation and an inflammatory response that became more pronounced with prolonged exposure. Although leukocyte counts remained outside the reference range for sheep ($5.00–14.00 \times 10^3/\mu l$), the upward trend observed in PS-MP-exposed animals suggested a subclinical immune response without overt leucocytosis. The absence of significant differences between groups early in the experiment and their subsequent emergence (days 28–34) indicated a delayed response to repeated intravenous PS-MP exposure. The absence of differences during the middle phase could also reflect transient immune adaptation, followed by reactivation of pro-inflammatory mechanisms due to the cumulative effect of long-term exposure. Similar effects have been described in animal studies, in which microplastic exposure induced leukocyte infiltration into tissues and increased the expression of inflammatory markers, including interleukin-6 (IL-6), tumour necrosis factor alpha (TNF-α) and nuclear factor kappa B (NF-κB), consistent with a chronic inflammatory response (Chen et al., 2024). Prolonged exposure to polystyrene nanoplastics has also been reported to impair haematopoiesis and reduce the number of blood-forming cells in the bone marrow. These effects have been linked to activation of the Kelch-like ECH-associated protein-1/phosphoglycerate mutase family member 5/apoptosis-inducing factor mitochondrial associated 1 (Keap1/PGAM5/AIFM1) and p53/p21 signalling pathways, associated with oxeiptosis and cellular senescence, respectively (Guo et al., 2023). *Ex vivo* studies using human blood have shown that nanoplastics can be internalised by leukocytes, leading to increased reactive oxygen species (ROS) production and the release of pro-inflammatory cytokines. Individual effects depend on particle properties, including size, surface charge and polymer type (Arribas Arranz et al., 2024). Monocytes and neutrophils are particularly sensitive to nanoplastics, suggesting that these phagocytic cells may be their primary targets of exposure and play a key role in the development of the inflammatory response.

Unlike WBC counts, changes in LYM numbers showed a different pattern over time. In the control group, LYM values remained stable, whereas in the LD group, they increased transiently, reaching a peak on day 10 – the only time point at which they were significantly higher than in the control and HD groups. This could indicate transient activation of the adaptive immune response during the early phase of PS-MP exposure. In the HD group, however, lymphocyte counts tended to decrease from the midpoint of the experiment, suggesting a dose-dependent reduction in the lymphocytic response during repeated exposure. Although LYM values, particularly at the baseline, exceeded the reference range for sheep ($0.83–4.69 \times 10^3$/µl), the differences between groups suggested that PS-MP exposure altered the pattern of lymphocyte responses at subsequent time points. A comparison of WBC and LYM counts showed that the increase in total WBC numbers in the HD group was not accompanied by a proportional increase in LYM counts, which could indicate a greater contribution of other leukocyte populations, such as granulocytes and monocytes, to the overall response. Correlation analysis revealed a gradual progressive weakening of the association between WBC and LYM counts across the experimental groups, from a strong correlation in the control group ($r_s = 0.662$; $P = 2.5 \times 10^{-10}$), through a moderate correlation in the LD group ($r_s = 0.424$; $P = 0.00021$), to a weak correlation in the HD group ($r_s = 0.283$; $P = 0.0159$). However, all three correlations were statistically significant. The observed pattern may reflect differences in the relative contributions of lymphocytes and other leukocyte populations to total WBC counts between the groups. Studies in fish have shown that microplastic exposure can alter lymphocyte counts and impair immune function, with increases associated with inflammatory responses and decreases related to immunosuppression following prolonged exposure. These changes have also been accompanied by increased expression of pro-inflammatory cytokines, suggesting chronic inflammation (Subaramaniyam et al., 2023). In mice exposed to polystyrene nanoplastics, reduced lymphocyte counts were accompanied by increased DNA fragmentation and impaired mitochondrial function in lymphocytes, suggesting cytotoxic effects on immune cells (Guo et al., 2023). *Ex vivo* studies using human whole blood have shown that nanoplastics can be internalised by leukocytes, including lymphocytes and monocytes, with the latter showing the highest uptake and the former increased ROS production. These findings indicate that nanoplastics can affect immune cells directly, although their implications for chronic inflammatory and autoimmune diseases are uncertain (Arribas Arranz et al., 2024).

Both RBC counts and HGB concentrations varied over time and between groups during repeated intravenous PS-MP exposure. RBC counts initially increased and subsequently declined. During the early phase of exposure, RBC counts were significantly higher in the LD group than in the control group, whereas a more pronounced decline was observed in the HD group during the second half of the experiment. Although RBC counts in both exposed groups transiently exceeded the upper reference limit for sheep ($7.80–13.80 \times 10^6$/µl), they returned to the reference range by the end of the study. These changes may reflect transient physiological responses, although it is unclear whether they resulted from haemoconcentration, altered erythropoiesis or other mechanisms. HGB concentrations followed a similar pattern, with the highest values recorded in the LD group during the early phase and smaller differences between groups later in the experiment. All HGB levels remained within the reference range (9.00–15.50 g/dl), and no persistent abnormalities in RBC or HGB parameters were evident at the final sampling.

Correlation analysis revealed a very strong positive association between RBC count and HGB concentrations in the control and HD groups, whereas no statistically significant correlation was detected in the LD group. This difference may reflect greater variability between erythrocyte number and HGB levels in the LD group. However, these correlations do not explain the mechanisms responsible for the recorded changes. Overall, the findings suggest that RBC and HGB responses differed between PS-MP exposure groups and over time, although these changes alone do not provide evidence of altered erythropoiesis.

Previous studies have linked microplastic exposure to changes in RBC counts, HGB concentrations, haematocrit (HCT), erythrocyte membrane function, and erythropoiesis in various species. Erythrocytes transport oxygen and carbon dioxide contribute to acid-base balance and antioxidant defence (Banerjee and Shelver, 2021, Kim et al., 2021). Oxidative stress has been proposed as a potential mechanism of microplastic-induced erythrocyte damage. Excessive ROS production can cause membrane lipid peroxidation, potentially reducing erythrocyte survival and impairing oxygen transport (Banerjee and Shelver, 2021).

Consistent with this hypothesis, studies in fish have reported changes in haematological parameters, including RBC counts and HGB concentrations, accompanied by histopathological

alterations in haematopoietic tissues and changes in oxidative stress biomarkers following exposure to PS-MPs (Rashid et al., 2025). Similarly, PS-MP exposure in mice was associated with reductions in RBC counts, HGB concentrations, and HCT, together with increased levels of oxidative stress biomarkers (Abdel-Zaher et al., 2023). *In vitro* studies have also demonstrated that polystyrene nanoplastics interact with erythrocyte membranes, potentially compromising membrane function and increasing susceptibility to haemolysis. The extent of these effects may depend on particle size, surface charge, and polymer composition (Płuciennik et al., 2023). Likewise, *ex vivo* studies using human whole blood have reported increased erythrocyte haemolysis following exposure to polystyrene nanoplastics, with particle-membrane interactions and oxidative stress suggested as possible contributing mechanisms (Arribas Arranz et al., 2024; Popa et al., 2025).

Taken together, previous findings suggest that oxidative stress and direct interactions between plastic particles and erythrocyte membranes may contribute to microplastic-associated haematological changes. In the present study, alterations in RBC counts and HGB concentrations over time, together with differences in their correlations, suggest that erythrocyte-related responses varied between experimental groups. However, as oxidative stress, haemolysis and erythropoietic activity were not directly measured, their involvement in these alterations is not uncertain.

PLT counts varied over time and between dose groups during repeated PS-MP exposure. While PLT values remained within the physiological range in the control group (180–400 × 10^3/µl), both exposed groups showed an overall increase, which was more pronounced in the HD group. In the LD group, PLT values remained within the reference range for most of the experiment, exceeding the upper limit only during the final phase. In the HD group, however, they exceeded this limit earlier and were significantly higher during the second half of the experiment. The LD group initially showed a transient decline in PLT counts, followed by a gradual increase, while the number of these cells in the HD group rose sharply from approximately day 22 and reached the highest values on day 28. The progressive increase in PLT counts, particularly in the HD group, may reflect inflammatory responses to repeated PSMP exposure. Beyond their role in haemostasis, platelets actively participate in immune regulation by interacting with leukocytes and endothelial cells, and releasing pro-inflammatory mediators. Thus, thrombocytosis may also be associated with a systemic inflammatory response to PS-MP exposure. The distinct response patterns observed in the LD and HD groups further suggest that the platelet response may depend on the exposure dose. The transient decline followed by an increase in the LD group could reflect physiological adaptation, whereas the stronger thrombocytosis in the HD group may be associated with increased thrombopoiesis or platelet mobilisation. As the largest increases occurred towards the end of the experiment, the findings are also consistent with a response developing during repeated exposure, although a cumulative effect cannot be established from these observations alone. Previous animal studies have reported similar haematological changes following microplastic exposure. In fish, including tilapia (*Oreochromis niloticus*) and zebrafish (*Danio rerio*), chronic exposure to microplastics led to abnormalities in RBC, WBC and platelet counts, together with increased oxidative stress markers, inflammatory responses and histopathological alterations in haematopoietic organs and other tissues (Kim et al., 2021; Rashid et al., 2025). Importantly, some studies have also observed initial haematological abnormalities followed by partial recovery, potentially reflecting compensatory responses during prolonged exposure (Kim et al., 2021). In the present study, PLT counts remained relatively stable between the fourth and seventh blood samplings (days 10–19), before increasing markedly later in the experiment. Studies in mammalian models have also reported increased platelet counts following microplastic exposure. In mice exposed to PS-MPs (1 µm) administered in drinking water (0.01 mg/day), a significant increase in PLT counts was observed after six weeks (Petrov et al., 2026). Similar increases were reported in mice orally exposed to 5 µm PS-MPs at 0.5 mg/day for 28 days, and in rats exposed to microplastics for the same period (Sun et al., 2021; Yahaya et al., 2024). Inflammation has been proposed as one possible explanation for these findings. Pro-inflammatory cytokines, particularly IL-6, can stimulate thrombopoietin production, thereby increasing PLT generation and potentially contributing to reactive thrombocytosis during prolonged inflammation. This pathway could partly explain the elevated PLT counts observed in the HD group. Evidence from human studies also suggests that microplastics may affect circulating blood cells. Microplastics have been detected in human blood, indicating the potential for direct interactions with blood components (Leslie et al., 2022). *In vitro* studies using human PLT have shown their activation, increased aggregation and procoagulant responses following exposure to

micro- and nanoplastics. These effects may involve inflammatory mediators and interactions between activated PLT, leukocytes and endothelial cells, potentially contributing to vascular inflammation and haemostatic disturbances (Arribas Arranz et al., 2024; Popa and Tabaran, 2025). Although most studies analysed oral exposure or used *in vitro* models, their findings are consistent with the increased PLT counts observed following repeated intravenous PS-MP exposure in the present study. These results suggest that prolonged exposure to circulating PS-MPs may affect PLT homeostasis.

Conclusions

Repeated exposure of sheep to microplastics at levels comparable to those reported in humans resulted in significant changes in body weight gain and haematological parameters. The observed alterations suggest possible inflammatory responses and systemic disturbances. Further research is required to elucidate the toxicokinetics of polystyrene microplastics, the mechanisms underlying their effects and the implications for human health, while emphasising the importance of reducing environmental plastic pollution.

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Conflict of interest

The Authors declare that there is no conflict of interest.

References

Aardema H., Vethaak A., Kamstra J.H., Legler J., 2024. Farm animals as a critical link between environmental and human health impacts of micro-and nanoplastics. Micropl. Nanopl. 4, 5, https://doi.org/10.1186/s43591-024-00082-w

Abdel-Zaher S., Mohamed M.S., Sayed A.E.-D.H., 2023. Hemotoxic effects of polyethylene microplastics on mice. Front. Physiol. 14, 1072797, https://doi.org/10.3389/fphys.2023.1072797

Alva P.P., Thomas T.A., 2025. Microplastics: a global threat to life and living. Environ. Monit. Assess. 197, 725, https://doi.org/10.1007/s10661-025-14160-w

Arribas Arranz J., Villacorta A., Rubio L., García-Rodríguez A., Sánchez G., Llorca M., Farre M., Ferrer J.F., Marcos R., Hernández A., 2024. Kinetics and toxicity of nanoplastics in ex vivo exposed human whole blood as a model to understand their impact on human health. Sci. Total Environ. 948, 174725, https://doi.org/10.1016/j.scitotenv.2024.174725

Bajt O., 2021. From plastics to microplastics and organisms. FEBS Open Bio. 11, 954-966, https://doi.org/10.1002/2211-5463.13120

Banerjee A, Shelver WL., 2021. Micro- and nanoplastic induced cellular toxicity in mammals: A review. Sci Total Environ. 755 (Pt 2), 142518, https://doi.org/10.1016/j.scitotenv.2020.142518

Chang X., Li Y., Han Y., Fang Y., Xiang H., Zhao Z., Zhao B., Zhong R., 2024. Polystyrene exposure induces lamb gastrointestinal injury, digestive disorders and inflammation, decreasing daily gain, and meat quality. Ecotoxicol. Environ. Saf. 277, 116389, https://doi.org/10.1016/j.ecoenv.2024.116389

Chen X., Xuan Y., Chen,Y., Yang F., Zhu M., Xu J., Chen J., 2024. Polystyrene nanoplastics induce intestinal and hepatic inflammation through activation of NF-κB/NLRP3 pathways and related gut-liver axis in mice. Sci. Total Environ. 935, https://doi.org/10.1016/j.scitotenv.2024.173458

Christodoulides A., Hall A., Alves N.J., 2023. Exploring microplastic impact on whole blood clotting dynamics utilizing thromboelastography. Front. Public Health. 11, 1215817, https://doi.org/10.3389/fpubh.2023.1215817

da Silva Brito W.A., Mutter F., Wende K., Cecchini A.L., Schmidt A., Bekeschus S., 2022. Consequences of nano and microplastic exposure in rodent models: The known and unknown. Part. Fibre Toxicol. 19, 28, https://doi.org/10.1186/s12989-022-00473-y

de Souza S.S., Freitas Í.N., Gonçalves S.d.O., da Luz T.M., Araújo A.P.d.C., Rajagopal R., Balasubramani G., Rahman M.M., Malafaia G., 2022. Toxicity induced via ingestion of naturally-aged polystyrene microplastics by a small-sized terrestrial bird and its potential role as vectors for the dispersion of these pollutants. J. Hazard. Mater., 434, 128814, https://doi.org/10.1016/j.jhazmat.2022.128814

Deng Y., Chen H., Huang Y. et al., 2022. Long-term exposure to environmentally relevant doses of large polystyrene microplastics disturbs lipid homeostasis via bowel function interference. Environ. Sci. Technol. 56, 15805-15817, https://doi.org/10.1021/acs.est.1c07933

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

Dzierżyński E., Gawlik P.J., Puźniak D., Flieger W., Jóźwik K., Teresiński G., Forma A., Wdowiak P., Baj J., Flieger J., 2024. Microplastics in the human body: Exposure, detection, and risk of carcinogenesis: a state-of-the-art review. Cancers (Basel), 16, 3703, https://doi.org/10.3390/cancers16213703

Gouin T., Ellis-Hutchings R., Pemberton M., Wilhelmus B., 2024. Addressing the relevance of polystyrene nano- and microplastic particles used to support exposure, toxicity and risk assessment: implications and recommendations. Part Fibre Toxicol. 21, 39, https://doi.org/10.1186/s12989-024-00599-1

Guo X., Cheng C., Wang L., Li D., Fan R., Wei X., 2023. Polystyrene nanoplastics induce haematotoxicity with cell oxeiptosis and senescence involved in C57BL/6J mice. Environ. Toxicol. 38, 2487-2498, https://doi.org/10.1002/tox.23886

Kim J.H., Yu Y.B., Choi J.H., 2021. Toxic effects on bioaccumulation, hematological parameters, oxidative stress, immune responses and neurotoxicity in fish exposed to microplastics: A review. J. Hazard. Mater. 413, 125423, https://doi.org/10.1016/j.jhazmat.2021.125423

Lackner M., Branka M., 2024. Microplastics in farmed animals - a review. Microplastics 3, 559-588, https://doi.org/10.3390/microplastics3040035

Leonard S.V.L., Liddle C.R., Atherall C.A., Chapman E., Watkins M., Calaminus S.D.J., Rotchell J.M., 2024. Microplastics in human blood: Polymer types, concentrations and characterisation using μFTIR. Environ. Int. 188, 108751, https://doi.org/10.1016/j.envint.2024.108751

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

Lett Z., Hall A., Skidmore S., Alves N.J., 2021. Environmental microplastic and nanoplastic: Exposure routes and effects on coagulation and the cardiovascular system. Environ. Pollut. 291, 118190, https://doi.org/10.1016/j.envpol.2021.118190

Li Y., Chen L., Zhou N., Chen Y., Ling Z., Xiang P., 2024. Microplastics in the human body: A comprehensive review of exposure, distribution, migration mechanisms, and toxicity. Sci. Total Environ. 946, 174215, https://doi.org/10.1016/j.scitotenv.2024.174215

Lu L., Wan Z., Luo T., Fu Z., Jin Y., 2018. Polystyrene microplastics induce gut microbiota dysbiosis and hepatic lipid metabolism disorder in mice. Sci. Total Environ. 631-632, 449-458, https://doi.org/10.1016/j.scitotenv.2018.03.051

Maitz M.F., Lenz R., Winkler S., Abschke M.F., Werner C., Fischer D., 2025. Weathered microplastics in human blood: unraveling the effect of structural changes at the particle surface on coagulation and platelet activation. Micropl. Nanopl. 5, 33, https://doi.org/10.1186/s43591-025-00139-4

Młotkowska P., Marciniak E., Roszkowicz-Ostrowska K., Misztal T., 2020. Effects of allopregnanolone on central reproductive functions in sheep under natural and stressful conditions. Theriogenology 158, 138-147, https://doi.org/10.1016/j.theriogenology.2020.09.010

Młotkowska P., Osuch B., Marciniak E., Zięba D.A., Konopka A., Misztal T., 2026. Effects of microplastics on the central reproductive neuroendocrine system in a sheep model. Int. J. Mol. Sci. 27, 2316, https://doi.org/10.3390/ijms27052316

Petrov L., Tsvetanova E., Georgieva A., Andreeva M., Pramatarov G., Petrov G., Dobrev K., Alexandrova A., 2026. Effect of polystyrene microplastic exposure on blood parameters in mice. Microplastics 5, 74, https://doi.org/10.3390/microplastics5020074

Płuciennik K., Sicińska P., Duchnowicz P., Bonarska-Kujawa D., Męczarska K., Solarska-Ściuk K., Miłowska K., Bukowska B., 2023. The effects of non-functionalized polystyrene nanoparticles with different diameters on human erythrocyte membrane and morphology. Toxicol. In Vitro. 91, 105634, https://doi.org/10.1016/j.tiv.2023.105634

Popa R.P., Tabaran A.F., 2025. A systematic review of the toxicokinetics of micro- and nanoplastics in mammals following digestive exposure. Appl. Sci. 15, 6135, https://doi.org/10.3390/app15116135

Prata J.C., da Costa J.P., Lopes I., Duarte A.C., Rocha-Santos T. 2020., Environmental exposure to microplastics: An overview on possible human health effects. Sci. Total Environ. 702, 134455, https://doi.org/10.1016/j.scitotenv.2019.134455

Rashid E., Hussain S.M., Ali S., Kucharczyk D., Nowosad J., Al-Ghanim K.A., 2025. Polystyrene microplastics exposure in freshwater fish, *Labeo rohita*: evaluation of physiology and histopathology. Sci. Rep.15, 12888, https://doi.org/10.1038/s41598-025-95811-3

Remigante A., Spinelli S., Gambardella L. et al., 2024. Internalization of nano- and micro-plastics in human erythrocytes leads to oxidative stress and estrogen receptor-mediated cellular responses. Free Radic. Biol. Med. 223, 1-17, https://doi.org/10.1016/j.freeradbiomed.2024.07.017

Schwaerzer G., 2025. Microplastics in the bloodstream can induce cerebral embolism and neurological impairment. Nat. Cardiovasc. Res. 4, 120, https://doi.org/10.1038/s44161-025-00615-3

Strzetelski J., 2014. IZ PIB-INRA Feeding Recommendations for Ruminants and Feed Tables; IZ PIB-INRA, Krakow, Poland

Subaramaniyam U., Allimuthu R.S., Vappu S., Ramalingam D., Balan R., Paital B., Panda N., Rath P.K., Ramalingam N., Sahoo D.K., 2023. Effects of microplastics, pesticides and nano-materials on fish health, oxidative stress and antioxidant defense mechanism. Front. Physiol.14, 1217666, https://doi.org/10.3389/fphys.2023.1217666

Sun R., Xu K., Yu L. et al., 2021. Preliminary study on impacts of polystyrene microplastics on the hematological system and gene expression in bone marrow cells of mice. Ecotoxicol. Environ. Saf. 218, 112296, https://doi.org/10.1016/j.ecoenv.2021.112296

Turini L., Foggi G., Mantino A. et al., 2024. Changes in hematological and hematochemical parameters in lactating dairy sheep according to different pasture management and heat stress risk: A longitudinal study. Vet. Anim. Sci. 27, 100419, https://doi.org/10.1016/j.vas.2024.100419

Volsa A.M., Iacono E., Merlo B., 2025. Micro-nanoplastics pollution and mammalian fertility: A systematic review and meta-analysis. Theriogenology 238, 117369, https://doi.org/10.1016/j.theriogenology.2025.117369

Wu P., Lin S., Cao G., Wu J., Jin H., Wang C., Wong M.H., Yang Z., Cai Z., 2022. Absorption, distribution, metabolism, excretion and toxicity of microplastics in the human body and health implications. J. Hazard. Mater. 437, 129361, https://doi.org/10.1016/j.jhazmat.2022.129361

Yahaya T.O., Ibrahim A.B., Kalgo A.S., Adewale M.K., Emmanuela C.C., Abdulkadir B., Musa A., Bello U., 2024. Microplastics exposure altered hematological and lipid profiles as well as liver and kidney function parameters in albino rats. Environ. Anal. Health Toxicol. 39, e2024021, https://doi.org/10.5620/eaht.2024021

Yang L., Yang W., Li Q., Zhao Z., Zhou H., Wu P., 2025. Microplastics in agricultural soils: sources, fate, and interactions with other contaminants. J. Agric. Food Chem. 73, 12548-12562, https://doi.org/10.1021/acs.jafc.5c03682

Yong C.Q.Y., Valiyaveettil S., Tang B.L., 2020. Toxicity of microplastics and nanoplastics in mammalian systems. Int. J. Environ. Res. Public Health. 17, 1509, https://doi.org/10.3390/ijerph17051509

Zhu L., Xie C., Chen L., Dai X., Zhou Y., Pan H., Tian K., 2023. Transport of microplastics in the body and interaction with biological barriers, and controlling of microplastics pollution. Ecotoxicol. Environ. Saf. 255, 114818, https://doi.org/10.1016/j.ecoenv.2023.114818