scientific reports

Check for updates

OPEN

Telomere length as a genomic biomarker for assessing microplastic-induced damage in farmed gilthead sea bream

Alessandra Iannuzzi[1]✉, Sara Albarella[2], Filomena Del Piano[2], Ramona Pistucci[1], Pietro Parma[3], Emanuele D'Anza[2], Giovanni Piccolo[2], Maria Carmela Ferrante[2]✉, Francesca Ciotola[2] & Vincenzo Peretti[2]

Microplastics are widespread pollutants in aquatic environments and pose significant risks to aquatic organisms, including species vital to aquaculture. The gilthead sea bream, extensively farmed in the Mediterranean, is frequently exposed to these contaminants, leading to potential long-term health consequences. Telomere length, a reliable marker of genomic integrity and cellular aging, offers a promising approach for assessing the biological effects of environmental stressors like microplastics. This study investigates the impact of microplastic exposure on telomere length in gilthead sea bream, evaluating its potential as a genomic biomarker for detecting microplastic-induced damage. Juvenile sea breams were divided into three groups: a control group and two experimental groups exposed to relatively low (25 mg/kg b.w./day) and high (250 mg/kg b.w./day) doses of polystyrene microplastics for 21 days. Telomere length was measured using qPCR, and statistical analyses were conducted to compare the T/S ratio between the groups. The results showed significantly shorter telomeres in fish exposed to both low and high doses of polystyrene microplastics compared to controls, with a clear dose-dependent effect ($p < 0.05$). These findings indicate that microplastic exposure compromises genomic stability in gilthead sea bream, supporting the use of telomere length as a rapid and sensitive biomarker for environmental monitoring in aquaculture. The study highlights the potential of telomere length as a valuable tool for evaluating fish health in polluted environments, contributing to the development of sustainable practices in aquaculture.

Keywords Telomere length, qPCR, Genomic biomarker, Gilthead sea bream, Microplastic

Telomeres are essential nucleoprotein structures that cap the ends of eukaryotic chromosomes, composed of repetitive DNA sequences (TTAGGG)n and a specialized set of binding proteins known as the Shelterin complex. These structures play a crucial role in maintaining genomic integrity by protecting chromosome ends from being recognized as DNA damage, thereby preventing inappropriate repair activities that could result in chromosomal fusions and genomic instability[1]. However, telomeres gradually shorten with each round of cell division due to the end-replication problem, where DNA polymerase cannot completely replicate the ends of linear chromosomes[2]. This progressive telomere length (TL) reduction is further exacerbated by oxidative stress and other environmental insults, ultimately leading to replicative senescence when telomeres become critically short[3]. The dynamics of TL have garnered significant attention due to their implications in cellular aging, genomic stability, and overall organismal health. TL is increasingly recognized as a potent biomarker for assessing biological aging and the cumulative impact of environmental stressors on cellular health[4]. Recent research has highlighted the complex interplay between genetic, epigenetic, and environmental factors in determining TL. For example, oxidative stress is a major contributor to telomere shortening, particularly affecting the G-rich sequences of telomeres, which are highly susceptible to oxidative lesions[5]. The relevance of TL as a biomarker has been established not only in human health but also in the welfare and longevity of farm animals[6]. Studies on the Agerolese cattle breed, known for its extended productive lifespan, revealed a strong correlation between

[1]Institute for Animal Production System in Mediterranean Environment, National Research Council, 80055 Portici (Naples), Italy. [2]Department of Veterinary Medicine and Animal Production, University of Naples Federico II, via Delpino 1, 80137 Naples, Italy. [3]Department of Agricultural and Environmental Sciences, University of Milan, via Celoria 2, 20133 Milan, Italy. ✉email: alessandra.iannuzzi@cnr.it; ferrante@unina.it

TL and age, with longer telomeres observed in this breed compared to the more intensively selected Holstein Friesian cattle[7]. Additionally, TL has been proposed as a reliable marker for assessing sperm quality in livestock, as evidenced by studies on bovine sperm, where TL was positively correlated with sperm motility, viability, and overall reproductive potential[8]. These findings underscore the potential of TL as a biomarker for genomic stability across different species, including aquatic organisms.

In the context of aquaculture, particularly in the farming of gilthead sea bream (*Sparus aurata L.*), there is a growing need for reliable biomarkers to assess the health and welfare of fish throughout their production cycle. Gilthead sea bream is one of the most farmed species in the Mediterranean region, with Italy being a leading producer. This species is widely appreciated for its high commercial value and relevance in human consumption. Furthermore, its ecological role as a predatory species at a high trophic level makes it particularly prone to bioaccumulating and biomagnifying chemical xenobiotics, including emerging pollutants in marine ecosystems. Due to these characteristics, S. aurata has gained increasing attention as a model organism in toxicological studies. The species' direct exposure to a wide range of pollutants, including microplastics, highlights its suitability as a sentinel organism for evaluating the effects of environmental contaminants on aquatic health.

Despite its recognized value, toxicological studies on Sparus aurata remain relatively limited. Some evidence points to oxidative stress and altered gene expression after exposure to antibiotics, but little is known about the genomic effects of microplastics in this species. This study addresses this critical knowledge gap by evaluating the impact of microplastic exposure on telomere length in gilthead sea bream. To the best of our knowledge, this represents the first study investigating the effect of microplastics on telomere dynamics in Sparus aurata[9]. This novel approach adds significant originality and scientific relevance, offering new insights into the potential mechanisms through which microplastics exert genomic toxicity in aquaculture species.

Moreover, this species is a well-recognized experimental model for toxicological investigations[10]. As aquaculture practices expand, the demand for sensitive and cost-effective indicators of animal welfare has increased[11]. This species is frequently exposed to various environmental stressors, including pollutants such as microplastics, within its aquaculture environment[12]. Understanding how these pollutants affect the genomic stability of gilthead sea bream is crucial for ensuring the sustainability of aquaculture practices and for assessing potential adverse effects of microplastic exposure on aquatic species.

Environmental pollutants, particularly microplastics, pose significant threats to aquatic ecosystems. Microplastics, defined as plastic particles smaller than 5 mm, are ubiquitous in the world's oceans, originating from the breakdown of larger plastic debris, synthetic textiles, and industrial products[13]. These pollutants threaten aquatic organisms through physical ingestion and chemical toxicity, as microplastics can adsorb and concentrate harmful organic pollutants and heavy metals from the surrounding water[14]. Experimental studies have demonstrated that microplastics can cause intestinal blockage, reduced feeding efficiency, and impaired energy metabolism in fish, particularly after high and prolonged exposure. Moreover, microplastic ingestion contributes to oxidative stress and inflammation in aquatic species, which can exacerbate telomere attrition and genomic instability[15–21].

Measuring TL in farmed gilthead sea bream exposed to microplastics could provide valuable insights into the genomic damage caused by these pollutants, helping to identify potential biomarkers for monitoring fish health in aquaculture settings. The use of TL as a biomarker is gaining traction in assessing the impact of environmental stressors on fish health[22].

Telomere shortening has been linked to decreased survival and increased predation risk in various animal species[23]. Additionally, microplastics have been shown to transfer contaminants through the aquatic food web, with potential toxic effects at higher trophic levels[24]. The bioaccumulation of chemical xenobiotics adsorbed on microplastics can exacerbate oxidative stress and telomere erosion in fish, ultimately affecting their health and fitness[14]. Furthermore, microplastic ingestion has been linked to metabolic and immune disruptions in aquatic species, reinforcing the urgency of studying their long-term effects on aquaculture species[25]. These findings underscore the need for further investigation into the long-term consequences of microplastic exposure on both aquaculture species and natural ecosystems.

The potential application of TL as a biomarker for monitoring the effects of microplastic pollution on aquatic organisms is compelling. Microplastics have been shown to induce a range of cellular responses, including oxidative stress, inflammation, and genotoxicity, all of which could contribute to accelerated telomere shortening[26,27]. As microplastics continue to accumulate in aquatic environments, their impact on the health and survival of farmed fish could pose significant challenges to the productivity and sustainability of aquaculture systems[28].

In conclusion, this study aims to address a critical gap in understanding how microplastics affect the genomic stability of aquatic organisms, using gilthead sea bream as a model species. To the best of our knowledge, this is the first study to evaluate the effects of microplastic exposure on telomere length in gilthead sea bream, highlighting a novel aspect of microplastic toxicity in aquaculture species.valuable Using TL as a biomarker, we seek to provide new insights of microplastic exposure, offering a valuable tool for monitoring fish health and informing sustainable practices in aquaculture. TL has been recognized as a biomarker for environmental stress, but it is important to note that its reduction is not exclusively linked to microplastic exposure. Other environmental stressors, such as oxidative stress, pollutants, and nutritional deficiencies, may also contribute to telomere attrition[3].

The findings of this research will not only advance our knowledge of telomere biology in aquatic organisms but also contribute to developing more effective strategies for managing the growing threat of microplastic pollution in our oceans. Moreover, the results could clarify the mechanisms through which microplastics exert their toxicity.

Treatment					
I.C.[d]	U. I.C.[e]	T/S avg[a]	T/S s.d.[b]	S.E.M.[c]	L.
CT	1,040	0,224	0,048	0,940	1,139
LD	0,801	0,288	0,055	0,687	0,914
HD	0,557	0,255	0,071	0,403	0,711

Table 1. Descriptive statistics of the T/S value. [a]: T/S average. [b]: T/S Standard deviation. [c]: Standard Error of the Mean. [d]: Lower limit of the 95% confidence interval. [e]: Upper limit of the 95% confidence interval.

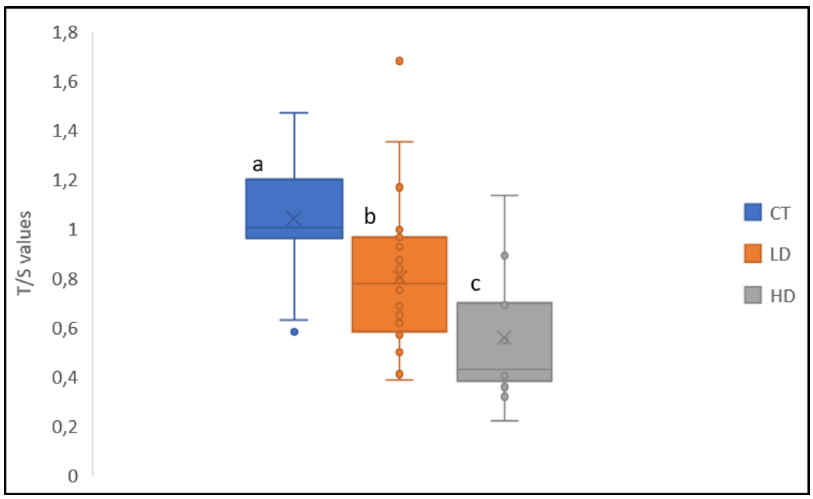

Fig. 1. Different letters indicate a statistical difference at $p < 0.05$. CT: control. LD: low dosage. HD: high dosage.

	CT	LD	HD
CT	-	2.00E-0.2	6.10E-0.6
LD	-	-	3.98E-0.2
HD	-	-	-

Table 2. p-values of the group's comparison. CT: control. LD: low dosage. HD: high dosage.

Results

Throughout the 21-day experimental period, both standard and contaminated diets were well accepted by all fish, with no signs of distress or mortality observed.

The q-PCR efficiency (e) was 97.2% for the telomere and 98.4% for scg (single copy gene). The quantification cycle (Cq) values presented a standard deviation (SD) < 0.3, and the RTL was measured as the ratio of telomere repeats to a scg (T/S ratio) for each sample and calculated using the ΔΔCt method with the Pfaffl correction[29]. Two independent standard curves (for telomere and scg sequences) were generated by acquiring SYBR Green fluorescence signals at two different temperatures, 75 °C for T and 86 °C for scg, in each cycle.

The T/S ratio decreased significantly in both treatment groups, with the high-dose group showing the greatest reduction in RTL (mean T/S ratio: 0.557 ± 0.255) compared to the control group (mean T/S ratio: 1.040 ± 0.224) (Table 1; Fig. 1). This suggests a dose-dependent relationship between microplastic exposure and telomere shortening, supporting the hypothesis that microplastics induce genomic instability through oxidative stress and cellular damage (Table 2).

Discussion

This study provides strong evidence that exposure to microplastics (MPs) induces a dose-dependent shortening of telomeres in *Sparus aurata*. Fish exposed to the highest dose of polystyrene (PS)-MPs (250 mg/kg b.w./day) exhibited the most significantly shorter TL, followed by those in the low-dose group (25 mg/kg b.w./day). Fish in the control group had significantly longer telomeres compared to both treated groups, indicating that microplastic exposure compromises genomic stability. This observation supports the hypothesis that microplastics accelerate telomere attrition, most likely through mechanisms involving oxidative stress and cellular damage.

The observed dose-dependent correlation between microplastic exposure and TL reduction aligns with existing research linking oxidative stress to faster telomere shortening. Microplastics, particularly polystyrene, have been shown to induce oxidative stress by generating reactive oxygen species (ROS), which damage cellular structures, including DNA. Telomeric DNA, which is rich in guanine, is especially susceptible to oxidative stress[25]. One of the critical ways in which microplastics are thought to harm marine organisms is through the induction of oxidative stress. Del Piano et al. showed the increase of the intestinal oxidative and nitrosative stress and impairs the antioxidant defense system gastrointestinal blockages[16]. Increased ROS production can accelerate telomere shortening, leading to genomic instability and, ultimately, cellular senescence[30]. The significantly shorter telomeres in the high-dose group further supports the notion that greater MP exposure results in more substantial genomic damage.

The control group, which was not exposed to MPs, showed longer telomeres, reinforcing the notion that microplastic-induced oxidative stress is a driving factor in telomere erosion. TL, as a biomarker of genomic integrity, provides valuable insight into the cellular-level impacts of environmental pollutants. In contrast, traditional measures such as growth rate or body weight, while useful, may not capture the more subtle, long-term effects of chronic exposure to stressors like microplastics.

The use of TL as a biomarker is particularly relevant in aquaculture, where fish are exposed to a variety of environmental stressors, including pollution. Microplastics are a pervasive pollutant in aquatic environments, and their ingestion by fish poses significant risks to health. MPs not only cause physical blockages in the digestive system but also have the capacity to adsorb toxic chemicals and heavy metals, which can be transferred to organisms that ingest them[14]. Experimental evidence has demonstrated that microplastics can cause intestinal blockage, impacting feeding efficiency and energy metabolism in fish. Studies have shown that microplastic ingestion can lead to physical obstruction in the gastrointestinal tract, reducing nutrient absorption and causing digestive distress, particularly when exposure levels are high and prolonged[16,18]. This reinforces the need for further research to evaluate the long-term effects of microplastic accumulation in aquaculture species and potential mitigation strategies to reduce dietary exposure.

Additionally, the analyses in this study were conducted under blind conditions, meaning that researchers were unaware of group assignments during data collection and analysis. This approach ensured unbiased results, as the impact of microplastics on TL was only revealed after the data were unblinded. The clear distinction in TL between the control, low-dose, and high-dose groups supports the robustness of these findings and emphasizes the dose-dependent nature of the effect. The high-dose group, which exhibited the most pronounced telomere attrition, provides further suggestion that relatively high dose of microplastic could exacerbate the oxidative stress that in turn accelerates telomere erosion.

These results have significant implications for the sustainability and welfare of farmed fish populations. Telomere shortening is associated with several negative health outcomes, including reduced reproductive success, increased susceptibility to diseases, and shortened lifespan[31]. Prolonged exposure to microplastics could therefore impair the long-term productivity and health of aquaculture species like *Sparus aurata*. Monitoring TL could provide aquaculture practitioners with an early warning system for genomic instability, allowing for earlier interventions to mitigate the effects of environmental stressors before they manifest in more visible health problems such as reduced growth or increased mortality.

The impact of microplastic pollution on Sparus aurata could compromise fish health and aquaculture productivity. Telomere shortening has been linked to reduced reproductive success, increased susceptibility to diseases, and lower overall survival rates, which may negatively impact fish farms. Moreover, microplastics can adsorb and transfer toxic chemicals, which could pose additional risks to aquaculture sustainability and food safety[14,24,28].

The growing body of evidence linking microplastic exposure to oxidative stress, inflammation, and genotoxicity supports the findings of this study, which demonstrate that MPs contribute to accelerated telomere shortening. This telomere attrition reflects underlying genomic instability, which could have long-term consequences for the health and survival of affected species. The use of TL as a biomarker in this context provides a powerful tool for assessing the biological effects of environmental pollutants on fish, particularly in aquaculture settings. While our findings indicate a dose-dependent reduction in telomere length associated with microplastic exposure, it is important to consider that telomere attrition is a multifactorial process. Other stressors, including environmental pollutants, oxidative stress, and nutritional imbalances, can also contribute to this effect[2,32].

Future research should explore the potential for cumulative telomere damage over longer exposure periods, as well as the interaction between microplastic exposure and other environmental stressors, such as water quality and diet. Studies investigating the potential for mitigating strategies, such as antioxidant supplementation, to counteract oxidative damage and preserve telomere integrity in farmed fish are also warranted. Given the increasing prevalence of microplastics in aquatic environments, understanding their full impact on genomic stability and overall health in aquatic species will be crucial for the sustainability of both aquaculture practices and aquatic ecosystems.

Conclusion

The dose-dependent reduction in telomere length observed in this study highlights the potential detrimental effects of microplastic exposure on genomic stability in farmed gilthead sea bream. Given the crucial role of telomere integrity in fish health, these findings suggest that TL could serve as a valuable biomarker for monitoring the impact of environmental pollutants in aquaculture settings. Microplastic-induced telomere attrition may contribute to reduced growth performance, increased disease susceptibility, and compromised reproductive success, all of which can negatively affect aquaculture productivity. Understanding these mechanisms is essential for developing mitigation strategies that enhance fish welfare and ensure the sustainability of aquaculture

operations. Future research should focus on assessing long-term effects, investigating potential interactions with other environmental stressors, and exploring strategies to minimize microplastic contamination in aquaculture environments.

Methods

Ethical approval

This study was approved by the Italian Ministry of Health and the Ethics Committee of the Federico II University of Naples, Italy (Ethical approval number 1057/2020-PR). All procedures were conducted in an indoor Recirculating Aquaculture System (RAS) at the Department of Veterinary Medicine and Animal Production, University of Naples Federico II (Italy), under the authorizations of the Italian Ministry of Health (n. 78/2013-A and 25/2019-UT), in compliance with the guidelines of the European Communities Council (2010/63/UE).

This study has been conducted and reported in adherence to the ARRIVE guidelines (Animal Research: Reporting of In Vivo Experiments). All experimental procedures involving Sparus aurata were designed to ensure ethical compliance, scientific rigor, and transparency. Specific measures, including sample size determination, randomization, and blinding, were implemented where applicable to reduce bias and enhance reproducibility. Detailed description of the experimental protocols and results have been provided to facilitate critical appraisal and replication of the findings; for some aspects, a bibliographic reference to a more detailed previous work has been included.

Experimental design and animal husbandry

Eighty-four juvenile gilthead sea breams (Sparus aurata) were sourced from a local fish farm (Soc. Coop. Acquamarina, Villa Literno - Italy) and acclimatized for 7 days in 1000 L tanks. During this period, they were daily observed to assess their overall health and exclude any sick or abnormally behaving individuals from the experiment. At the end of this period, the fish were weighed and randomly distributed into three tanks. At the beginning of the experimental procedure, the mean body weight (± SD) was 219.5 ± 6.9 g for the CON group, 140.9 ± 14.9 g for PS1, and 171.97 ± 12.7 g for PS2. The RAS was equipped with thermostatic control, mechanical sand filters, skimmers, cartridge filters, biological filters, and UV lamps. Water quality parameters were constantly maintained as follows: daily water renewal < 1%, artificial day length of 12 h, temperature 22 ± 1.5 °C, salinity 33.0 ± 2.0 g/l, dissolved oxygen 6.5 ± 1.1 mg/l, pH 7.9 ± 0.5, total ammonia nitrogen < 0.3 mg/l, nitrite < 0.01 mg/l, and nitrate < 38 mg/l. Daily, water temperature was measured using a mercury thermometer, pH using an Orion digital pH meter, and dissolved oxygen using an oxygen meter (OXI 330, WTW, Weilheim, Germany). Bi-weekly, total ammonia nitrogen ($N–NH_3$), nitrite-nitrogen ($N–NO_2$), and nitrate-nitrogen ($N–NO_3$) were determined using colorimetric methods, through commercial kits and a spectrophotometer (Hanna Instruments, C-203, Leighton Buzzard, UK). The water was subjected to prolonged mechanical filtration (sand filter, skimmer, and 5 µm cartridge filter) before use, which also served to mature the biofilter. Continuous filtration throughout the experimental period helped minimize the potential presence of polystyrene microplastics (PS-MPs) from management operations. Access to the enclosure was restricted, and personnel wore 100% cotton lab clothing (coats, gloves, etc.). Plastic materials were avoided and replaced with glass and metal tools to reduce contamination risks.

After a 14-day acclimation to the new conditions, the experimental treatments began, with fish being fed approximately 1% of their average body weight per tank each day. The experimental groups were as follows: (1) tank 1 and 2 control group (n = 28) (CT), which was fed a standard diet (Supplementary material, Stab 1); (2) tank 3 and 4 low-dosage group (n = 28) (LD) receiving 25 mg/kg b.w./day of PS-MPs, and (3) tank 5 and 6 high-dosage group (n = 28) (HD) receiving 250 mg/kg b.w./day of PS-MPs. These PS-MPs doses were chosen based on previous studies that used similar doses, polymer types, and exposure times in teleost fish[33]. The CT group was fed twice daily (at 9 a.m. and 6 p.m.) with the standard diet, while the LD and HD groups were fed the PS-MPs enriched diet at 9 a.m. and the standard diet at 6 p.m. Administering the enriched diet in the morning ensured complete consumption of the ration, driven by the animals' hunger after overnight fasting. The feed ration was gradually distributed and visually monitored to ensure all fish accessed the pellets, minimizing the effects of feeding hierarchy and avoiding uneaten pellets. Fish tanks were siphoned daily in the morning (changing approximately 10–15% of the water) immediately after the morning meal to remove debris and uneaten food, which were minimal due to the feeding protocol (Supplementary Table 1). Fish in all groups grew normally, regardless of the diet administered, and by the end of the experimental period, the mean body weights (± SD) were 249.31 ± 11.1 g for CON, 164.5 ± 17.2 g for PS1, and 198.8 ± 13.0 g for PS2.

After 21 days of exposure, fish were anaesthetized (tricaine methanesulfonate-MS222, 50 ppm; Sigma-Aldrich, St. Louis, MO, USA) and blood samples were collected from the caudal vein using an insulin syringe.

DNA extraction

Genomic DNA was extracted using the Wizard Genomic DNA Purification Kit (Promega), following the manufacturer's protocol. The yield and purity of the DNA were measured for each sample using a NanoDrop ND-1000 spectrophotometer (Thermo Scientific). All samples meet the following quality criteria: yield > 30 ng/µl, 260/280 ratio > 1.7, and 260/230 ratio > 1.8. The integrity of the DNA was further evaluated by gel electrophoresis.

qPCR method

All methods for qPCR followed the guidelines and regulations for qPCR experiments[34] and TL measurement using qPCR approaches[35]. One golden sample was repeated on each plate and included in the calculation of Relative TL (RTL). RTL was measured using a 96-well CFX RT-PCR System (Bio-Rad) with a 20 µL total reaction mix containing 30 ng of genomic DNA, iTaq Universal SYBR Green Supermix (Bio-Rad), and forward

and reverse primers for telomeres (T) and GAPDH (used as scg), following Cawthon et al.[36]. The scg primer sequences were: forward (F): 5′-ATCTGAGACTTGTGACAT – 3'; reverse (R): 5′-GTGTTAATTGGTAATGAC TATT – 3. The specificity of the primers was confirmed by the dissociation curve and agarose gel electrophoresis. The thermal profile and cycling design were: 3 min at 95 °C; 2 cycles of 15 s at 94 °C and 15 s at 49 °C; 40 cycles of 30 s at 94 °C, 40 s at 58 °C with the signal acquisition, 10 s at 70 °C, 10 s at 74 °C with the signal acquisition; melt curves were generated by increasing temperatures from 65 to 95 °C, in 0.5 °C steps at the end of the thermal cycling.

Each sample was assayed in triplicates (intra-assay) in three different runs (inter-assay) with negative control (NTC), and a standard curve for each primer evaluated the amplification efficiency and linearity. To evaluate qPCR amplification efficiency, a standard curve was prepared. Four concentrations of gilthead sea bream genomic DNA, obtained from a mix of four samples, were prepared by four-fold serial dilutions and aliquoted in triplicate.

Statistical analysis

Statistical analyses focused on the T/S ratio in the three groups: control (CT), low dosage (LD), and high dosage (HD). Given that these values were not normally distributed, the non-parametric Kruskal-Walli's test, with Bonferroni correction for α, was used to determine statistical differences between the groups. A p-value of < 0.05 was considered statistically significant.

Data availability

All data generated or analysed during this study are included in this published article and its supplementary information files.

Received: 5 November 2024; Accepted: 15 September 2025
Published online: 21 October 2025

References

1. O'Sullivan, R. J. & Karlseder, J. Telomeres: protecting chromosomes against genome instability. *Nat. Rev. Mol. Cell. Biol.* **11** (3), 171–181. https://doi.org/10.1038/nrm2848 (2010). Epub 2010 Feb 3. PMID: 20125188; PMCID: PMC2842081.
2. Blackburn, E. H. Telomere States and cell fates. *Nature* **408**, 53–56. https://doi.org/10.1038/35040500 (2000).
3. von Zglinicki, T. Oxidative stress shortens telomeres. *Trends in Biochemical Sciences, 27(7), 339–344* 27(7), 339–344 (2002).
4. Wang, Q., Zhan, Y., Pedersen, N. L., Fang, F. & Hagg, S. Telomere length and All-Cause mortality: A Meta-analysis. *Ageing Res. Rev.* **48**, 11–20. https://doi.org/10.1016/j.arr.2018.09.002 (2018).
5. Mukherjee, A. K. et al. Correction: Telomere length-dependent transcription and epigenetic modifications in promoters remote from telomere ends. *PLoS Genet.* **16**, e1009152. https://doi.org/10.1371/journal.pgen.1009152 (2020).
6. Iannuzzi, A., Iannuzzi, L. & Parma, P. Molecular cytogenetics in domestic bovids: A review. *Anim. (Basel)*. 13. https://doi.org/10.3390/ani13050944 (2023).
7. Iannuzzi, A. et al. Characterization of telomere length in Agerolese cattle breed, correlating blood and milk samples. *Anim. Genet.* **53**, 676–679. https://doi.org/10.1111/age.13227 (2022).
8. Iannuzzi, A. et al. Evaluation of bovine sperm telomere length and association with semen quality. *Theriogenology* **158**, 227–232. https://doi.org/10.1016/j.theriogenology.2020.09.019 (2020).
9. Fernandez, R. et al. The antibacterials ciprofloxacin, Trimethoprim and sulfadiazine modulate gene expression, biomarkers and metabolites associated with stress and growth in Gilthead sea Bream (Sparus aurata). *Aquat. Toxicol.* **250**, 106243. https://doi.org/10.1016/j.aquatox.2022.106243 (2022).
10. Capo, X. et al. Quantification of differential tissue biomarker responses to microplastic ingestion and plasticizer bioaccumulation in aquaculture reared sea Bream Sparus aurata. *Environ. Res.* **211**, 113063. https://doi.org/10.1016/j.envres.2022.113063 (2022).
11. McLennan, D. et al. Telomere elongation during early development is independent of environmental temperatures in Atlantic salmon. *J. Exp. Biol.* **221** https://doi.org/10.1242/jeb.178616 (2018).
12. Cappello, T. et al. Impact of environmental stressors on the health of farmed fish in aquaculture systems. *Mar. Pollut. Bull.* **145**, 119–125 (2019).
13. Chain, E. P. o. C. i. t. F. Presence of microplastics and nanoplastics in food, with particular focus on seafood. *EFSA J.* **14**, e04501. https://doi.org/10.2903/j.efsa.2016.4501 (2016).
14. Rochman, C. M., Hoh, E., Kurobe, T. & Teh, S. J. Ingested plastic transfers hazardous chemicals to fish and induces hepatic stress. *Sci. Rep.* **3**, 3263. https://doi.org/10.1038/srep03263 (2013).
15. Ahmed, A. S. S. et al. Microplastics in aquatic environments: A comprehensive review of toxicity, removal, and remediation strategies. *Sci. Total Environ.* **876**, 162414. https://doi.org/10.1016/j.scitotenv.2023.162414 (2023).
16. Filomena, D. et al. Giuseppina Mattace Raso, rosaria Meli, Maria Carmela ferrante impact of polystyrene microplastic exposure on Gilthead seabream (Sparus aurata Linnaeus, 1758): differential inflammatory and immune response between anterior and posterior intestine. *Sci. Total Environ.* https://doi.org/10.1016/j.scitotenv.2023.163201 (2023).
17. Del Piano, F. et al. Subchronic oral exposure to polystyrene microplastics affects hepatic lipid metabolism, inflammation, and oxidative balance in Gilthead seabream (Sparus aurata). *Ecotoxicol. Environ. Saf.* **279**, 116455. https://doi.org/10.1016/j.ecoenv.2024.116455 (2024).
18. Jovanovic, B. Ingestion of microplastics by fish and its potential consequences from a physical perspective. *Integr. Environ. Assess. Manag.* **13**, 510–515. https://doi.org/10.1002/ieam.1913 (2017).
19. Revel, M., Châtel, A. & Mouneyrac, C. Micro(nano)plastics: A threat to human health? *Curr. Opin. Environ. Sci. Health*. **1**, 17–23. https://doi.org/10.1016/j.coesh.2017.10.003 (2018).
20. Ruiz, C. E., Esteban, M. Á. & Cuesta, A. Microplastics in Aquatic Environments and Their Toxicological Implications for Fish. (2016). https://doi.org/10.5772/64815
21. Barboza, L. G. A., Vieira, L. R., Branco, V., Carvalho, C. & Guilhermino, L. Microplastics increase mercury bioconcentration in gills and bioaccumulation in the liver, and cause oxidative stress and damage in dicentrarchus labrax juveniles. *Sci. Rep.* **8**, 15655. https://doi.org/10.1038/s41598-018-34125-z (2018).
22. Molbert, N., Angelier, F., Alliot, F., Ribout, C. & Goutte, A. Fish from urban rivers and with high pollutant levels have shorter telomeres. *Biol. Lett.* **17**, 20200819. https://doi.org/10.1098/rsbl.2020.0819 (2021).
23. Angelier, F., Parenteau, C., Trouve, C. & Angelier, N. The behavioural and physiological stress responses are linked to plumage coloration in the rock pigeon (Columbia livia). *Physiol. Behav.* **184**, 261–267. https://doi.org/10.1016/j.physbeh.2017.12.012 (2018).

24. Carbery, M., O'Connor, W. & Palanisami, T. Trophic transfer of microplastics and mixed contaminants in the marine food web and implications for human health. *Environ. Int.* **115**, 400–409. https://doi.org/10.1016/j.envint.2018.03.007 (2018).
25. Kadac-Czapska, K., Osko, J., Knez, E. & Grembecka, M. Microplastics and oxidative Stress-Current problems and prospects. *Antioxid. (Basel)*. **13** https://doi.org/10.3390/antiox13050579 (2024).
26. Panizzolo, M. et al. Biomarkers of oxidative stress, inflammation, and genotoxicity to assess exposure to micro- and nanoplastics. A literature review. *Ecotoxicol. Environ. Saf.* **267**, 115645. https://doi.org/10.1016/j.ecoenv.2023.115645 (2023).
27. Del Piano, F. et al. Subchronic exposure to polystyrene microplastic differently affects redox balance in the anterior and posterior intestine of Sparus aurata. *Anim. (Basel)*. 13. https://doi.org/10.3390/ani13040606 (2023).
28. Gall, S. C. & Thompson, R. C. The impact of debris on marine life. *Mar. Pollut Bull.* **92**, 170–179. https://doi.org/10.1016/j.marpolbul.2014.12.041 (2015).
29. Pfaffl, M. W. A new mathematical model for relative quantification in real-time RT-PCR. *Nucleic Acids Res* 29, e45, (2001). https://doi.org/10.1093/nar/29.9.e45
30. Demanelis, K. et al. Determinants of telomere length across human tissues. *Science* **369** https://doi.org/10.1126/science.aaz6876 (2020).
31. Neil, B. & Metcalfe, C. A. A. Oxidative stress as a life-history constraint: the role of reactive oxygen species in shaping phenotypes from conception to death. *Funct. Ecol.* **24** https://doi.org/10.1111/j.1365-2435.2010.01750.x (2010).
32. Paul, L. Diet, nutrition and telomere length. *J. Nutr. Biochem.* **22**, 895–901. https://doi.org/10.1016/j.jnutbio.2010.12.001 (2011).
33. Asmonaite, G., Sundh, H., Asker, N. & Carney Almroth, B. Rainbow trout maintain intestinal transport and barrier functions following exposure to polystyrene microplastics. *Environ. Sci. Technol.* **52**, 14392–14401. https://doi.org/10.1021/acs.est.8b04848 (2018).
34. Bustin, S. A. et al. The MIQE guidelines: minimum information for publication of quantitative real-time PCR experiments. *Clin. Chem.* **55**, 611–622. https://doi.org/10.1373/clinchem.2008.112797 (2009).
35. Lindrose, A. R. et al. Method comparison studies of telomere length measurement using qPCR approaches: A critical appraisal of the literature. *PLoS One*. **16**, e0245582. https://doi.org/10.1371/journal.pone.0245582 (2021).
36. Cawthon, R. M. Telomere length measurement by a novel monochrome multiplex quantitative PCR method. *Nucleic Acids Res.* **37**, e21. https://doi.org/10.1093/nar/gkn1027 (2009).

Author contributions

E.D. collected blood samples, extracted DNA, and performed quality control checks. R.P. measured RTL by qPCR. A.I. and P.P. performed post qPCR quality controls and were responsible for the data curation. The statistical analysis was performed by R.P. under supervision of P.P. A.I. visualized data and drafted the first manuscript. A.I., P.P., F.C., S.A. and M.F. reviewed and edited the first draft. All authors reviewed and edited the final draft. M.C.F., F.C. and V.P. supervised the project and acquired funding. All the authors were involved in project planning. A.I. was the project principal investigator.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1038/s41598-025-20438-3.

Correspondence and requests for materials should be addressed to A.I. or M.C.F.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.