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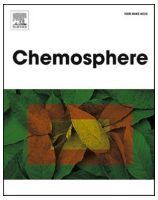


Plastic in regurgitated pellets and mercury contamination of skua chicks on the Antarctic Peninsula

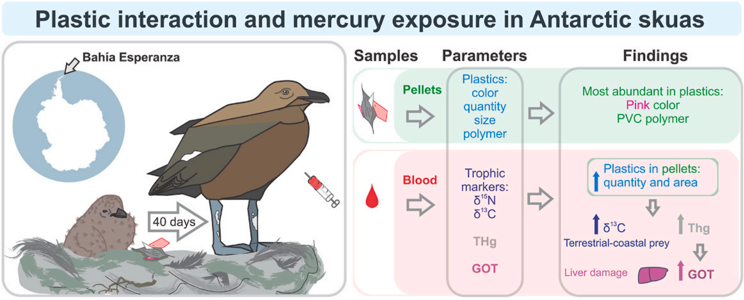
Nadia S. Haidr [a], William F. Mills [b], Micaela S. Carrillo [a], Carlos Edo [c,j], Paco Bustamante [d,e], Juan P. Lozoya [f], Franco Teixeira-de-Mello [g], Diego Montalti [a], Miguel González-Pleiter [i], Andrés E. Ibañez [a,h,*]

[a] *Sección Ornitología, Div. Zool. Vert. Museo de La Plata (FCNyM-UNLP), Paseo Del Bosque s/n, La Plata, 1900, Buenos Aires, Argentina*
[b] *Department of Geography and Environmental Science, University of Reading, Reading, UK*
[c] *Department of Chemical Engineering, Universidad de Alcalá, Alcalá de Henares, Madrid, Spain*
[d] *Littoral Environnement et Sociétés (LIENSs), La Rochelle Université, 2 rue Olympe de Gouges, 17000, La Rochelle, France*
[e] *Institut Universitaire de France (IUF), 1 rue Descartes, 75005, Paris, France*
[f] *Departamento Interdisciplinario de Sistemas Costeros y Marinos, Centro Universitario Regional Del Este. Universidad de la República, Maldonado, Uruguay*
[g] *Departamento de Ecología y Gestión Ambiental, Centro Universitario Regional Del Este, Universidad de la República, Maldonado, Uruguay*
[h] *Biología de Predadores Tope, Instituto Antártico Argentino, Buenos Aires, Argentina*
[i] *Department of Biology, Faculty of Science, Universidad Autónoma de Madrid, Madrid, Spain*
[j] *Natural History Museum of Denmark, University of Copenhagen, Copenhagen, Denmark*

HIGHLIGHTS

- Antarctic skuas chicks at Esperanza Bay mostly ingested pink and PVC based plastics.
- Blood mercury was higher for chicks which pellets had more or larger plastic debris.
- Chicks with higher blood mercury were fed with prey from terrestrial-coastal areas.
- Hepatic enzymes were higher for chicks with higher blood mercury.

GRAPHICAL ABSTRACT



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ABSTRACT

Plastic pollution represents a widespread threat to marine ecosystems. As top predators, seabirds are capable of ingesting substantial amounts of plastic waste, which can cause physical harm and may serve as a route for heavy metal contamination, with potential repercussions on physiology and body condition. This study investigates plastic in regurgitated pellets of brown skua *Stercorarius antarcticus* and south polar skua *S. maccormicki* chicks at Bahía Esperanza/Hope Bay, Antarctic Peninsula, and its association with blood total mercury (THg) concentrations, trophic ecology, anthropogenic activity and health markers. Regurgitated pellets ($n = 445$) were collected from active nests during the chick-rearing period and the plastic content was analyzed (occurrence, size, color and polymer composition). Additionally, THg concentrations and stable isotopes of carbon (δ^{13}C) and nitrogen (δ^{15}N), which are proxies of foraging habitat and trophic level, respectively, were determined in the

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[*] Corresponding author. Sección Ornitología, Div. Zool. Vert. Museo de La Plata (FCNyM-UNLP), Paseo del Bosque s/n, La Plata 1900, Buenos Aires, Argentina.
E-mail address: aeibanez@fcnym.unlp.edu.ar (A.E. Ibañez).

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blood of fully fledged chicks ($n = 39$). A total of 33 plastics were identified in pellets, with pink and polyvinyl chloride being the most common color (45.4%) and polymer (69.7%), respectively. A significant positive relationship was found between blood THg concentrations and the number of plastic in pellets and their surface area. Chicks with higher blood THg concentrations were fed with prey from terrestrial-coastal areas, rather than offshore/pelagic prey. Additionally, increased glutamic-oxaloacetic transaminase activity was associated with higher blood THg concentrations. Based on these findings, our hypothesis is that interaction with plastics may act as an alternative exposure route of Hg to seabirds.

1. Introduction

Plastic contamination has become a major issue in marine environments, entering food webs at many different trophic levels (Bargagli et al., 1998; Ibañez et al., 2020). Plastic ingestion by seabirds was first recorded in the 1960s (Ryan, 2016), and may occur indirectly (secondary ingestion in prey) or directly, as seabirds can easily mistake macro- (>25 mm) or mesoplastics (5-25 mm) for prey or for gastroliths used to facilitate digestion (Waring et al., 2018; Lavers and Bond, 2023). Ingestion in chicks may also occur through intergenerational transfer (Rodríguez et al., 2025). Plastic ingestion has been demonstrated to have harmful and potentially fatal effects on seabirds (Battisti et al., 2019; Lavers et al., 2019; Puskic et al., 2020; Ryan and Jackson, 1987; Sievert and Sileo, 1993). For instance, plastic ingestion was found to have deleterious effects on physiology, leading to renal and liver failure (Lavers et al., 2019), body mass loss (Sievert and Sileo, 1993), physical damage, gut obstruction and nutritional deprivation (Pierce et al., 2004), as well as loss of appetite with subsequent effect on growth rate (Ryan and Fraser, 1988; Sievert and Sileo, 1993). Additionally, the surface of plastic debris is known to be a reservoir for chemical additives and trace elements used during their manufacture, and other pollutants (such as organic compounds and heavy metals) adsorbed from the environment (Bradney et al., 2019; Hirai et al., 2011). Specifically, metals can interact in many ways with plastic either physically by adsorption of cations, chemically by complexation and co-precipitation or, by adsorption onto hydrous oxides (Bradney et al., 2019).

In seabirds, evidence suggests that although heavy metals can be incorporated through the diet (Ibañez et al., 2022a), chronic ingestion of plastic could also lead to exposure to contaminants (Hirai et al., 2011; Lavers and Bond, 2016; but see Mills et al., 2024b). Mercury (Hg) is known to accumulate on the plastic surface by adsorption at much higher concentrations than in the environment (Santos-Echeandía et al., 2020). Hg is a non-essential metal that is present in the environment due to anthropogenic and natural sources (Keane et al., 2023; Mão de Ferro et al., 2014). Antarctica is slowly becoming a storage region for Hg. Its gaseous form (Hg^0) can disperse through long-range atmospheric transport from emission sites, reaching remote sites such as the Polar Regions (Nerentorp Mastromonaco et al., 2017). Natural sources of Hg include volcanic activity and the melting sea ice (Mão de Ferro et al., 2014), whereas human inputs include artisanal and small-scale gold mining and the combustion of coal (Fisher et al., 2023). Additionally, tourism and research stations may also be contributing as local factors in the Antarctic continent (Acero et al., 1996). Once deposited in the marine environment, microorganisms methylate Hg to its most toxic form, methyl-Hg $[CH_3Hg]^+$ (Driscoll et al., 2013), which is, thereafter, incorporated into the food chain and ultimately biomagnified and bioaccumulated by top predators, such as seabirds (Ibañez et al., 2022a; Mills et al., 2022). Hg exhibits negative effects on seabirds, particularly on hepatic and immune functions (Ibañez et al., 2024), body condition (Scheuhammer et al., 2007), egg volume (Fort et al., 2014; Ibañez et al., 2024), behavior (Goutte et al., 2015; Tartu et al., 2015) and breeding success (Mills et al., 2020; Tartu et al., 2014).

Antarctic seabirds are exposed to different contaminants during the breeding and non-breeding periods. Indeed, most Antarctic seabirds show migratory patterns to lower latitudes during their non-breeding season (Mills et al., 2024a), where they can be exposed to other sources of contamination either on their migratory route or on their wintering grounds, where pollutants can be at higher concentrations than breeding sites (Albert et al., 2022). As top predators, skuas are an ideal group to monitor pollutants in the Antarctic and subantarctic region (Ibañez et al., 2020, 2022a, 2024; Mills et al., 2022, 2025). Skuas regurgitate indigestible parts of their prey and non-food items (e.g., rocks, plastics) in the form of compacted discrete masses (pellets) produced in the gizzard (Ibañez et al., 2020). Analyses of pellets indicate that brown skuas (*Stercorarius antarcticus*) and south polar skuas (*S. maccormicki*) exhibit generalist feeding habits, and, in the Antarctic, their diets include penguins (eggs and chicks), other seabirds, fish, mollusks, and krill, among others (Ibañez et al., 2022b; Morales et al., 2025). Their foraging strategies comprise preying, scavenging, fishing and kleptoparasitism (Furness, 1978; Reinhardt et al., 1998; Trivelpiece et al., 1980). Brown skuas, when breeding in sympatry with south polar skuas, monopolize land-based resources such as penguins (eggs and chicks) and other breeding seabirds, forcing south polar skuas to feed in inshore and offshore waters (Grilli and Montalti, 2012). These particularities in diet and foraging behavior between brown and south polar skuas can be an explanatory reason for differences in their Hg load (Goutte et al., 2014a, 2014b; Mills et al., 2025; Tartu et al., 2014, 2015). However, it is unclear whether the interspecific difference in feeding behavior ultimately reflects a different level of exposure to anthropogenic debris ingestion.

Skuas bioaccumulate Hg through their diet (Ibañez et al., 2022a; Mills et al., 2022), and in the Southern Ocean, exhibit higher concentrations at lower latitudes (Carravieri et al., 2017; Ibañez et al., 2022a; Mills et al., 2022, 2025). Moreover, Hg induces negative effects on the immunity and hepatic dysfunction in breeding skuas (Ibañez et al., 2024). At Bahía Esperanza/Hope Bay, brown skuas were found to suffer incidental consumption of macro- and mesoplastics available in their breeding site as a byproduct of anthropogenic activities and in relation to the breeding stage, which could represent an alternative route of Hg entrance (Ibañez et al., 2020). Throughout the breeding season, plastic ingestion was higher in areas of high anthropogenic activities and during chick-rearing when skuas broaden their foraging niche (Ibañez et al., 2020). Building from this, chicks are well-suited for Hg studies, since concentrations in their tissues reflect their recent and local exposure (Carravieri et al., 2020; Burger and Gochfeld, 2004). Considering all these, we hypothesize that plastics may be an alternative source of Hg contamination of skua chicks, which ultimately affects their health status. Focusing on meso- and macroplastics detected by stereomicroscopy in pellets, the present study aims to: (i) Describe plastics found in skua pellets (including presence, surface area, colour and polymer composition), (ii) Examine how plastic ingestion differed in relation to species, anthropogenic activity and diet; (iii) Assess the main drivers of THg concentrations at this site, including plastic, anthropogenic activity and diet; (iv) examine relationships between THg concentrations with health status markers.

2. Material and methods

2.1. Study area

Fieldwork was conducted during the 2022/2023 breeding season (from December to February) at Bahía Esperanza, northern Antarctic

Peninsula (63°24′S, 57°01′W) (Fig. 1a). At this location, from November to February/March, brown skuas and south polar skuas breed in sympatry with a high avian diversity that includes one of the largest Adélie penguin (*Pygoscelis adeliae)* colonies, with approximately 100,000 breeding pairs (Santos et al., 2018). Here, brown skuas feed mainly on penguin eggs and chicks during their reproductive cycle (Ibañez et al., 2022b). This location has two distinctive areas (Fig. 1b), one with High Anthropogenic Activity (HAA), due to its closeness to the Argentinean (Esperanza) and Uruguayan (Ruperto Elichiribehety) Antarctic research stations, and one with Low Anthropogenic Activity (LAA), which is less disturbed and farther away from research stations or tourism activities (Carlini et al., 2007; Ibañez et al., 2020). At Bahía Esperanza, brown and south polar skua populations reach their maximum number during mid-January, with around 42 nests (Ibañez et al., 2022b). During the breeding season of 2022/2023, 39 breeding pairs (28 brown skua pairs, 4 mixed couples and 7 south polar skua pairs) were counted.

2.2. Sample collection

2.2.1. Pellet collection and analysis

Fresh regurgitated pellets ($n = 445$) were collected from 22 brown skuas and 3 south polar skua nests surrounding areas (within 2 m from the nest), every four days. To ensure a sampling of only new regurgitated pellets, nesting areas were cleaned upon arrival at the colony discarding all previously produced pellets. The sampling period encompasses the period from egg hatching to fledging (40-45 days old), and coincides with the timeframe of chick pellet production. Previous studies have shown that chicks regurgitate more pellets than expected per meal (Votier et al., 2001), and that the number of pellets in the nesting area increases greatly once the chick hatches (Ibañez et al., 2022b). Therefore, we assume that most pellets found in nests are likely produced by chicks. In addition, and contrary to adults which perform foraging trips and can or might regurgitate pellets farther away from the nest, chicks remain within the original nesting area producing pellets *in situ*. Although, we acknowledge that this approach does not consider smaller plastic particles (microplastics), which may also contribute to contaminant exposure, we consider plastics in pellets found in the nesting area as a proxy of the plastic load that chicks were exposed to.

Once in the laboratory, pellets were dried at room temperature, placed in nylon stockings and stored in cardboard boxes until their analysis. Pellets were disassembled in a Petri dish and plastic-like debris larger than 5 mm (meso- and macroplastics) were visually identified on those pellets, collected, dried and sorted by type (fragment, fiber, film) and color (pink, blue, brown, green, grey, white, transparent) following Verlis et al. (2013). Plastics were then measured and photographed with a Euromex-Edublue stereomicroscope equipped with a USB digital camera with a 0.01 mm precision. Photographs of plastic debris were scaled and their total area was measured and calculated with the ImageJ software (Schneider et al., 2012). Debris polymer composition was analyzed with Attenuated Total Reflectance Fourier Transform Infrared (ATR-FTIR). ATR-FTIR spectra were obtained in a Thermo-Scientific Nicolet iS10 apparatus with a Smart iTR-Diamond ATR module, using the OMNIC version 9.1.26 software (Thermo Fisher Scientific Inc., Massachusetts, USA). Spectra were taken at a range of 4000–800 cm^{-1} with a 4 cm^{-1} resolution (data spacing of 0.483 cm^{-1}) using 32 scans. Between samples, the ATR-crystal was cleaned with isopropanol, and background signal was updated between sample analyses. The obtained spectra were compared in the Omnic 9.1.26 (ThermoFisher Scientific Inc., Massachusetts, USA) with spectra of the software and libraries generated with reference material. Particles were classified as plastics when the match confidence was >70% (Edo et al., 2025).

2.2.2. Blood sampling

Skua chicks were identified with a hook-and-loop tape, which included a unique identifier for the nest and chick. Once chicks were at their fully fledged stage, they were captured by hand from the nest and the tape was removed. Handling time was kept to a minimum, not exceeding 8 min, to avoid negative effects and stressful responses. After capture, blood samples (1.5 ml) were taken from the brachial vein with a 25-G needle from chicks of brown skuas ($n = 29$, LAA $n = 19$, HAA $n = 10$) from 19 nests (LAA $n = 13$, HAA $n = 6$) and south polar skuas ($n = 10$, LAA $n = 7$, HAA $n = 3$) from 6 nests (LAA $n = 4$, HAA $n = 2$). Blood samples were preserved at 4°C for 6 h, and then centrifuged for 10 min at 2000 rpm to isolate the red blood cells (RBCs) from the serum (Ibañez et al., 2022a, 2024; Mills et al., 2022). Serum and RBCs were stored frozen at −20°C prior to subsequent laboratory analyses. Glutamic-oxaloacetic transaminase (GOT), a hepatic enzyme involved in metabolic reactions and a marker of hepatic health, was measured in serum (Ibañez et al., 2024) with colorimetric commercial kits (Wiener Lab) using an automatic analyzer (Ibañez et al., 2024).

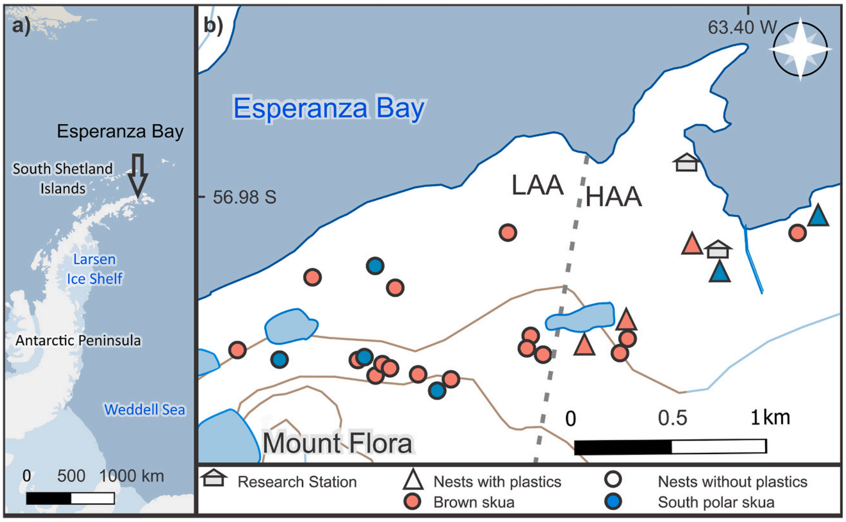

Fig. 1. a) Map of the Antarctic Peninsula with the location of Bahía Esperanza b) Close up of the study site at Bahía Esperanza. Dots points to the studied nests of brown skuas (pink) and south polar skuas (blue) chicks, exposed (triangles) and not exposed to plastic (circles). Dashed line separates the High Anthropogenic Activity area (HAA) from the Low Anthropogenic Activity area (LAA). Maps was created using QGIS and Quantartica developed by the Norwegian Polar Institute.

2.3. *Total Hg determinations*

Hg partitions preferentially into the cellular component of blood (Tavares et al., 2013) and, for skuas, blood total Hg (THg) concentrations are almost exclusively in the form of methyl-Hg (>90%) (Renedo et al., 2020). THg has a half-life of 30-60 days in the RBCs of adults of the closely-related great skua *S. skua* (Bearhop et al., 2000a). Although in growing skua chicks there are no reports about this parameter, in other seabird chicks, blood THg has been estimated to have a half-life of 5-10 days (Fournier et al., 2002; Monteiro and Furness, 2001). The shorter half-life relative to the adult has been attributed to the rapid growth of body tissues and feathers (Lewis and Furness, 1991; Renedo et al., 2021). RBCs were freeze-dried and homogenized to measure THg concentrations with an Advanced Mercury Analyzer spectrophotometer (Altec AMA 254 Altec®) at the laboratory Littoral Environnement et Sociétés (LIENSs, France) at La Rochelle Université (La Rochelle, France) as previously described (Chouvelon et al., 2009). For each sample, two or three aliquots were analyzed (range: 0.17 to 3.38 mg dry weight [dw]) until the relative standard deviations were <10%. Blanks were analyzed at the beginning of each set of samples and to assess accuracy and reproducibility of the measurements, lobster hepatopancreas TORT-3 (National Research Centre, Canada; certified THg concentration: 0.292 ± 0.022 μg g^{-1} dw) was used as certified reference material (CRM). The CRM was analyzed at the beginning of each set of samples and for every 10 blood samples. Mass of the CRM was adjusted to match a comparable amount of Hg in the samples. The measured value of the CRM (0.30 ± 0.01 μg g^{-1} dw, $n = 15$) was in agreement with the certified value and corresponded to a recovery of 102.2 ± 0.9%. The limit of detection of the AMA was 0.1 ng. THg concentrations are given in μg g^{-1} dw.

2.4. *Stable isotope analyses*

Stable isotope analysis is a valuable tool to investigate trophic drivers of contaminant exposure in seabirds (Bearhop et al., 2000b; Petalas et al., 2025). Particularly, stable isotope ratios of carbon (^{13}C:^{12}C, expressed as $\delta^{13}C$) and nitrogen (^{15}N:^{14}N, $\delta^{15}N$) are among the most commonly isotopes analyzed in avian blood (Bearhop et al., 2000b; Morales et al., 2025). Stable isotope analyses were run on freeze-dried RBCs. For great skuas, $\delta^{13}C$ and $\delta^{15}N$ values have half-lives of 15.7 and 14.4 days in the blood, respectively (Bearhop et al., 2002). Therefore, there is a reasonable overlap with the half-life of THg in the blood. Due to the low lipid content of avian red blood cells, lipids were not removed from blood samples (Cherel et al., 2005). Subsamples of homogenized material (~0.2 mg) were weighed into tin capsules using a microbalance (Sartorius Cubis™). Stable isotope values of $\delta^{13}C$ and $\delta^{15}N$ were determined at the University of Reading Chemical Analysis Facility using a continuous flow-isotope ratio mass spectrometer coupled to a ThermoFisher™ DeltaV Advantage fitted with an Isolink CNSOH Temperature Conversion Elemental Analyzer (TC/EA) and smart function. Results are expressed in the conventional δ-values in parts per thousand or per mil (‰) relative to Vienna PeeDee Belemnite (VPDB) for carbon, and atmospheric N_2 (AIR) for nitrogen. All samples were analyzed in triplicate. Data were corrected for linearity and instrument drift by analysing in-house standards every five samples. Replicate measurements of international and in-house standards indicated analytical errors of <0.2 ‰ for $\delta^{13}C$ and $\delta^{15}N$ values.

2.5. *Data analysis*

Data were analyzed using R version 4.5.0 (R Core Team, 2015) in R studio 2025.05.0 (Posit team, 2025). Figures were generated with the ggplot2 package (Wickham, 2016).

Isotopic niches for each species, and for skuas with and without plastic interaction were calculated using SIBER (Jackson et al., 2011), that calculates Standard Ellipses Areas Corrected for small sample size (SEA_C), and a Bayesian estimation (SEA_B) on the posterior distribution of the covariance matrix for each group which is a proxy of niche width. The Bayesian probability of one group's area being larger than the other was also calculated, as well as the overlapping area of isotopic niches. Linear mixed models were used to examine if there were differences between $\delta^{13}C$ and $\delta^{15}N$ values for each species, and for those skuas that evidenced plastic interaction and those that did not. Linear mixed models were run with the lme4 package (Bates et al., 2015), and nest identity was set as a random effect in all models because chicks from the same nest could not be treated as independent samples. Model assumptions were evaluated to see if they met normality and homoscedasticity. Dataset analyzed includes those nests with related data from chicks that were captured.

To study if the presence of plastic in pellets (plastic presence, number of plastics and plastic surface area), zone (HAA and LAA) and/or trophic markers ($\delta^{13}C$ and $\delta^{15}N$ values) were drivers of blood THg, linear mixed models were run. THg values were log transformed. Selected models of predictor variables were ranked according to the Akaike Information Criteria (AIC) adjusted for small sample sizes (AIC_C), the models with the lowest AIC_C values and within a range of 2 AIC_C units were considered to have received the most support (Burnham and Anderson, 2002). Finally, to study health markers levels and its relation to plastic exposure and THg concentrations, LMMs were conducted.

2.6. *Ethics approval*

All applicable international, national and institutional guidelines for sampling, care and experimental use of animals for the study were followed as established by Article III, Annex II of the Madrid Protocol, Law 24.216 (Taking, Harmful Intrusion and introduction of Species) within the framework of the projects evaluated and approved by the Environment Office of the Instituto Antártico Argentino and Dirección Nacional del Antártico (permits number 2022-FEAMB-CT-GA-22). In addition, all protocols conducted in this project were evaluated and approved by the Institutional Committee for the Care and Use of Study Animals (CICUAE 002.03.2022) of Natural Science and Museum Faculty (FCNyM-UNLP).

3. Results

3.1. *Plastics in pellets: polymer and color composition*

Plastic debris was only found in pellets from nests located near research stations (i.e. the HAA area), while no plastic was found in the LAA area (Fig. 1b; Fig. 2a). From all studied nests, 24% (6/25) contained pellets with meso- and macroplastics. Of those nests, 83.3% (5/6) belonged to brown skuas, and one belonged to south polar skuas. A total of 33 meso- and macroplastics were recovered from pellets of these nests. The mean (±SD) length of plastics was 22.6 ± 14.0 mm (range: 6.4 - 77.3 mm), with areas of 229.8 ± 298.2 mm^2 (10.3 - 1517.3 mm^2). The most common plastic color was pink ($n = 15$; 45.4%) followed by white ($n = 9$; 27.3%) (Fig. 2b). Other colors found were brown ($n = 3$; 9.1%), grey ($n = 2$; 6.1%), blue ($n = 1$; 3.0%), green ($n = 1$; 3.0%), orange ($n = 1$; 3.0%) and transparent ($n = 1$; 3.0%). ATR-FTIR analysis highlighted a high abundance of polyvinyl chloride (PVC; n = 23, 69.7%) (Fig. 2c), with minor contributions of polypropylene (PP, $n = 5$; 15.1%), polystyrene (PS, $n = 3$; 9.1%), and polyethylene (PE, $n = 2$; 6.1%) (Fig. 2c).

3.2. *Stable isotopes values and seabird-plastic interaction*

No interspecific differences were observed in $\delta^{13}C$ values (LMM, est = 0.03, p = 0.849), whereas south polar skuas exhibited higher $\delta^{15}N$ values than brown skua chicks (LMM, est = 0.96, p < 0.001) (Table 1). Brown skuas exhibited a greater isotopic niche width than south polar skuas (Table 1, Fig. 3); Bayesian probability (p_b) of south polar skua niche being larger than brown skuas was 0.0. The overlap between the

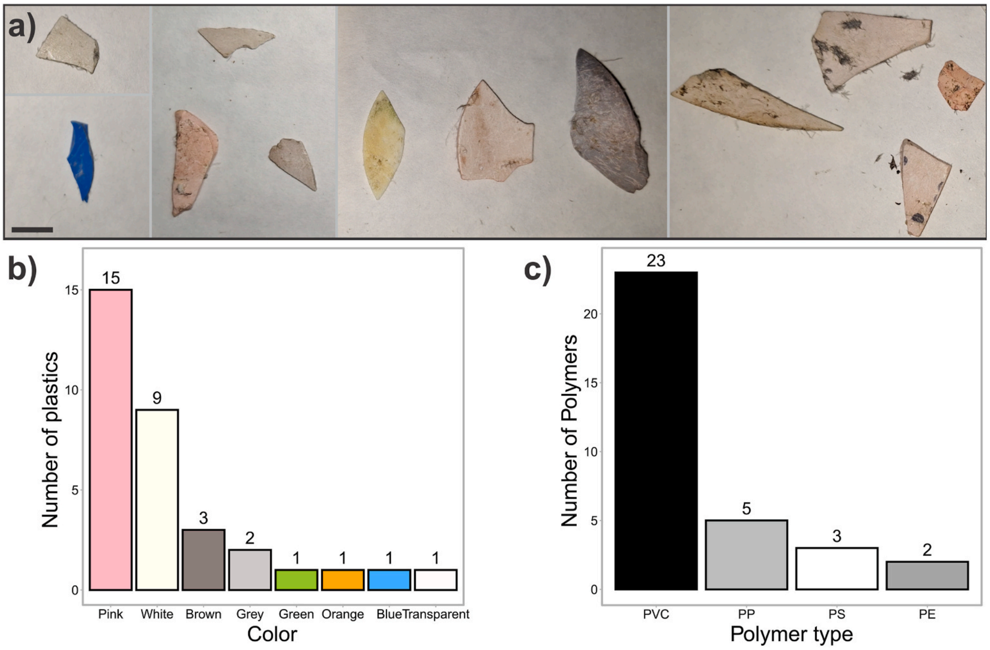

Fig. 2. a) Representative picture of the plastic debris found in regurgitated pellets from breeding skuas during the chick rearing stage. b) Abundance of plastic debris color. c) Polymer composition. Abbreviations: PVC, polyvinylchloride; PP, polypropylene; PS, polystyrene; and PE, polyethylene. Scale bar = 10 mm.

Table 1

Stable isotopes values (mean ± SD) and SIBER analyses of skuas. Metrics include δ^{13}C, δ^{15}N, Total area (TA), Standard Ellipse Areas (‰2) corrected for small sample sizes (SEAC), the overlap of areas, and the Bayesian Standard Ellipse Areas (SEAB, ‰2), with its probability (pb). Comparisons are made between species, and between plastic presence/absence in pellets of the total sample and within the HAA.

	δ^{13}C Mean ± SD (‰)	δ^{15}N Mean ± SD (‰)	TA (‰^{2})	SEA$_C$ (‰^{2})	Overlap (‰^{2})	SEA$_B$ (‰^{2})	p$_B$
Brown skuas	−23.1 ± 0.4	9.3 ± 0.8	3.71	1.03	0.07	0.98	0.0
South polar skuas	−23.1 ± 0.14	10.3 ± 0.5	0.43	0.22		0.19	
Plastic	−22.9 ± 0.2	9.5 ± 0.9	1.07	0.78	0.58	0.67	0.81
No plastic	−23.1 ± 0.4	9.6 ± 0.9	3.57	1.03		0.97	
HAA plastic	−22.9 ± 0.3	9.0 ± 0.4	1.07	0.78	0.07	0.64	0.62
HAA no plastic	−23.1 ± 0.3	10.4 ± 0.9	0.33	0.72		0.57	

species standard ellipse areas corrected was 7%.

No differences in the δ^{13}C and δ^{15}N values were observed between skua chicks that interacted with plastic debris and those that did not (LMM, est = 0.16, p = 0.29; LMM, est = −0.08, p = 0.86, respectively) (Table 1). Isotopic niches of skuas with plastic debris had smaller areas than those that evidence no plastic interaction (Table 1 and Fig. 3b); Bayesian probability (p_b) was 0.81. The overlap between groups standard ellipse corrected areas was 58%.

Within the HAA, slight differences in the isotopic values were observed in skua chicks that had evidence of plastic debris interaction from those that did not (Table 1). Within the HAA, isotopic niche of skua chicks with plastic debris interaction had larger SEA$_C$ values than those that evidence no plastic in their diet (Table 1 and Fig. 3c); Bayesian probability (p_b) was 0.62. The overlap between group standard ellipse areas which were corrected scaled to contain 95% of the bivariate distribution was 7.2%.

3.3. Drivers of blood THg concentrations

Mean (±SD) blood THg concentrations of skua chicks at Bahía Esperanza was 0.10 ± 0.12 μg g^{-1} dw (Table 2). To account for non-independence among sibling chicks, we performed an ANOVA between models with and without (null model) nest as a random effect. We found a significant nest influence in THg chick load ($X^2 = 39.13$, $p < 0.001$) (Fig. S1).

The most parsimonious LMM explaining THg concentrations included the number of plastics in pellets as a fixed effect ($p < 0.001$) (Table S1). An equally plausible model (i.e., $\Delta AIC_C < 2.0$) included the number of plastics and plastic surface area ($p < 0.001$) as fixed effects (Table S1). Models that included zone, plastic presence, δ^{13}C or δ^{15}N received less support. Both the number of plastics in regurgitated pellets and the surface area of plastic debris were positively associated with blood THg concentrations in skua chicks (LMM, est = 0.025 $p < 0.001$ and est = 0.0001 $p < 0.001$, respectively) (Fig. 4). This association was also observed within brown skuas that had plastic evidence in their pellets (LMM number of plastic, est = $9.858e^{-02}$ p = 0.001; plastic surface, est = $5.193e^{-04}$ $p < 0.001$). Blood THg was unrelated to δ^{13}C and δ^{15}N.

3.4. THg concentrations and hepatic function markers

A positive relationship (LMM, est = 85.76, p = 0.001) was found between blood THg and GOT activity in skua chicks (Fig. 5). For skuas exposed to plastic contamination, no significant relationship was observed between GOT activity and number of plastics (LMM, est = 0.63, $p > 0.05$).

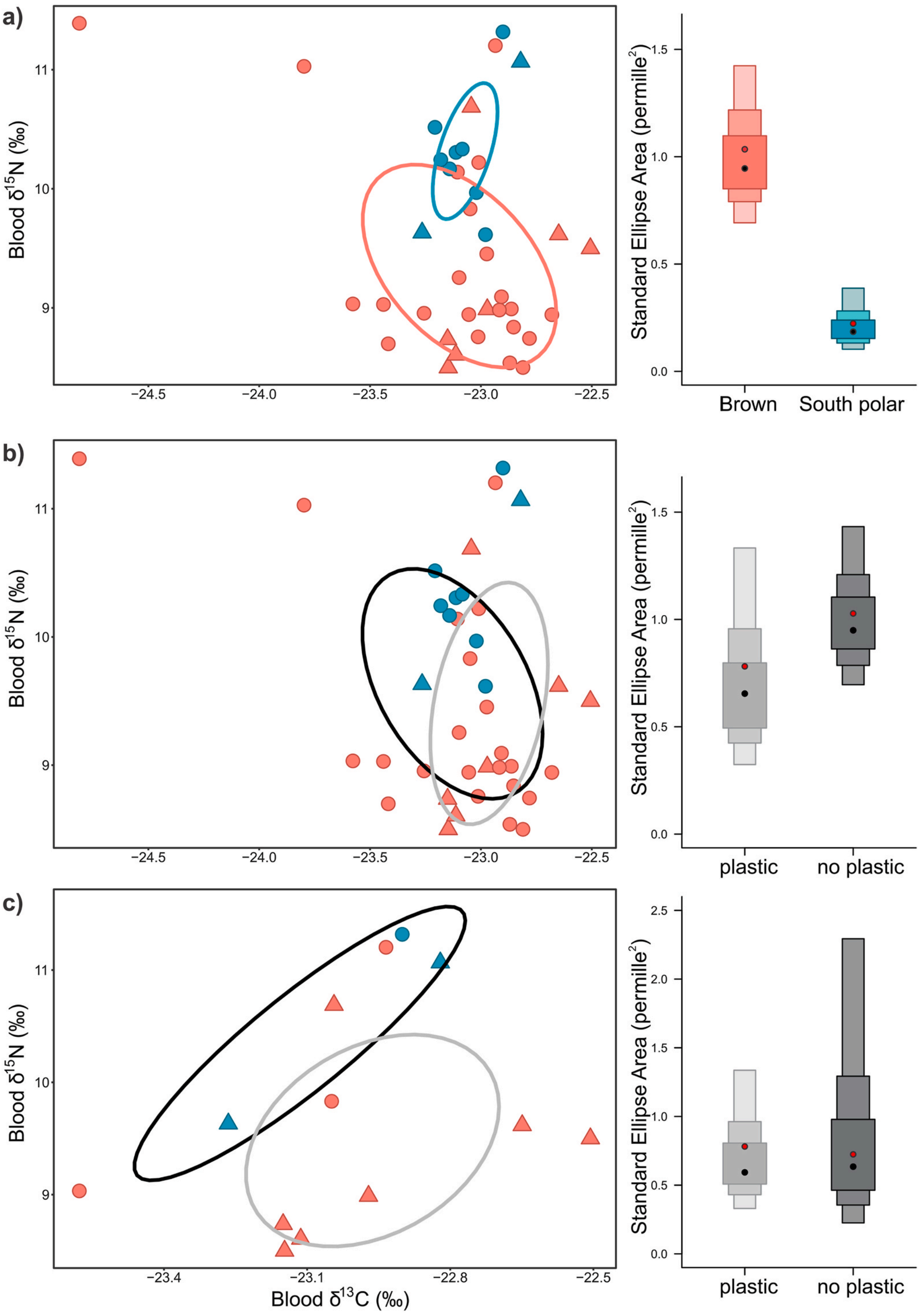

Fig. 3. δ^{13}C vs. δ^{15}N values of chicks of brown skuas (pink) and south polar skuas (blue) at Bahía Esperanza, Antarctic Peninsula. Left: biplot with the Corrected Standard Ellipses Areas (SEAc) and the boxplot of the δ^{13}C and δ^{15}N distribution per group; right: Bayesian Standard Ellipse Area (SEA$_B$) of a) brown (pink), and south polar (blue) skuas; b) skuas exposed (grey, triangles) and not exposed to plastic debris (black, circles); c) skuas exposed (grey, triangles) and not exposed to plastic (black, circles) from the HAA area. Abbreviation: P, plastic; NP, no plastic.

4. Discussion

4.1. *Plastics in pellets: polymer and color composition*

During chick-rearing, plastic was only found in regurgitated pellets from brown and south polar skuas breeding in the HAA area at Bahía Esperanza, and no plastics were found in the LAA area. This could be mainly due to the fact that overall HAAs have more plastic availability as reported for this site (Ibañez et al., 2020; Lozoya et al., 2026), and other Antarctic locations (Absher et al., 2019; Golubev, 2020). A large percentage of birds worldwide are known to have incidentally ingested plastics and many times evidenced by their presence in regurgitated pellets (Caldwell et al., 2020; Ibañez et al., 2020; Lavers and Bond, 2016; Ryan, 1987; Santos et al., 2021). Particularly, plastic ingestion in some seabird chicks is reported to have increased over the decades (Lavers and Bond, 2016). Skuas are highly exposed to plastic pollution in the

Table 2
Blood THg concentrations (μg g^{-1} dw) in chicks of brown skuas and south polar skuas at Bahía Esperanza, Antarctic Peninsula. Mean, standard deviation, minimum and maximum values are shown for the total dataset, both species, skuas with evidence of plastic interaction, skuas with no plastic interaction recorded, for each zone, and for skuas with evidence of plastic interaction and no plastic interaction within the HAA.

		THg μg g^{-1} dw		
	n	Mean ± SD	Min	Max
Total	39	0.101 ± 0.064	0.065	0.390
Brown skuas	29	0.101 ± 0.074	0.065	0.390
South polar skuas	10	0.102 ± 0.025	0.077	0.154
Plastic	9	0.161 ± 0.118	0.072	0.390
No plastic	30	0.083 ± 0.011	0.065	0.109
HAA	13	0.138 ± 0.103	0.072	0.39
LAA	26	0.083 ± 0.012	0.065	0.109
HAA plastic	9	0.182 ± 0.141	0.083	0.39
HAA no plastic	4	0.1 ± 0.031	0.072	0.154

Southern Ocean and Antarctica with evidence found in their pellets, scats and their gastrointestinal content (Bottari et al., 2026; Golubev, 2020; Ibañez et al., 2020; Lenzi et al., 2022; Ryan, 1987). As skuas are visual foragers, the interaction with debris and its ingestion might be due to incidentally picking plastic from their environment by confusion with a prey or gastroliths, or from trophic transfer from their prey (Carrillo et al., 2025; Lavers and Bond, 2023; Provencher et al., 2019; Roman et al., 2019).

Among the plastics recovered from regurgitated skua pellets, pink was the most abundant color followed by white (Fig. 2). This result is consistent with plastic color found in skua pellets from Isla 25 de Mayo/ King George Island (South Shetland Islands) (Lenzi et al., 2022), although other studies have shown no specific patterns (Ryan and Fraser, 1988). Color frequency seems to be related to their prey similarity and foraging strategies (Roman et al., 2019; Ryan, 1987). Pink color is abundant among their prey (i.e., penguin flesh, krill), as well as in the plastic debris found in this study (Fig. 2b). For animals feeding at sea by surface-seizing, color contrast with sea-water (as perceived from above) may also serve as a visual cue. Hence, white plastic debris could be a good match (Ryan, 1987) and a plausible explanation for its high frequency in skua pellets. Regardless of color availability in their environment being a limiting factor for color picking, seabirds have shown to select colors at a significantly different frequency from the available ones, also for their nesting areas (Hidalgo-Ruz et al., 2021; Verlis et al., 2014).

FTIR analysis indicated that the most abundant plastic polymer was PVC followed by PP, PS and PE in minor amounts (Fig. 2). These polymers are some of the most abundant found in the coastline of Bahía Esperanza (Lozoya et al., 2026), surface waters around the Antarctic Peninsula (Caruso et al., 2022), and in seabird regurgitations over the world (Bilal et al., 2023; Furtado et al., 2016). These polymers originate from local sources, such as sewage (treated or untreated), from tourism, fishing and research vessels, and scientific research stations. Widely used as a material for construction, packaging and plumbing, PVC is closely associated with research stations and related infrastructure in Antarctica (Gurumoorthi and Luis, 2023). Indeed, the lack of plastics identified from nests in LAA areas indicates that anthropogenic activity occurring near nests is an important source of plastic to skuas on the northern Antarctic Peninsula. Furthermore, PVC is one of the most common polymers found to be ingested by other seabirds such as auks (Otsuki et al., 2024) and Procellariiformes (Van Hassel et al., 2024), and it is known for its rapid adsorption rates for heavy metals such as Hg (Santos-Echeandía et al., 2020; Spedding and Hamilton, 1982). Therefore, plastic debris, together with its polymeric composition and chemical capacity to adsorb additional metal, represents a major concern due to the potential adverse effects on wildlife.

4.2. *Plastic and diet*

Generalist seabirds with flexible feeding behaviors and more varied diets tend to exhibit a higher occurrence of plastic than specialist ones (Ryan, 1987; Schutten et al., 2024). In this study, closely related skua species exhibited interspecific differences in their isotopic niche, likely reflecting differences in resource utilization during the chick-rearing period. Brown skua chicks showed a greater isotopic niche than south polar skuas. There is a low isotopic niche overlap between them. These results are in line with previous studies in other Antarctic locations where brown skuas and south polar skuas breed in sympatry (Grilli and Montalti, 2012). RBCs δ^{15}N values in south polar skuas chicks were higher than in brown skua chicks, suggesting that they are fed on prey from higher trophic levels. The lower δ^{15}N values in the brown skuas could result from the secondary ingestion of penguin stomach contents, which mainly fed on krill *Euphausia superba* (Silvestro and Casaux, 2023), and may distort the apparent prey spectrum underestimating prey of higher trophic levels (Grilli and Montalti, 2012; Morales et al., 2025). At Bahía Esperanza, the diet of south polar skua chicks highly relies on fish (Ibañez *unpublished data*), whereas chicks of brown skua are mainly fed on penguins and in minor amounts on other seabirds (Ibañez et al., 2022b). Furthermore, the greater isotopic niche breadth

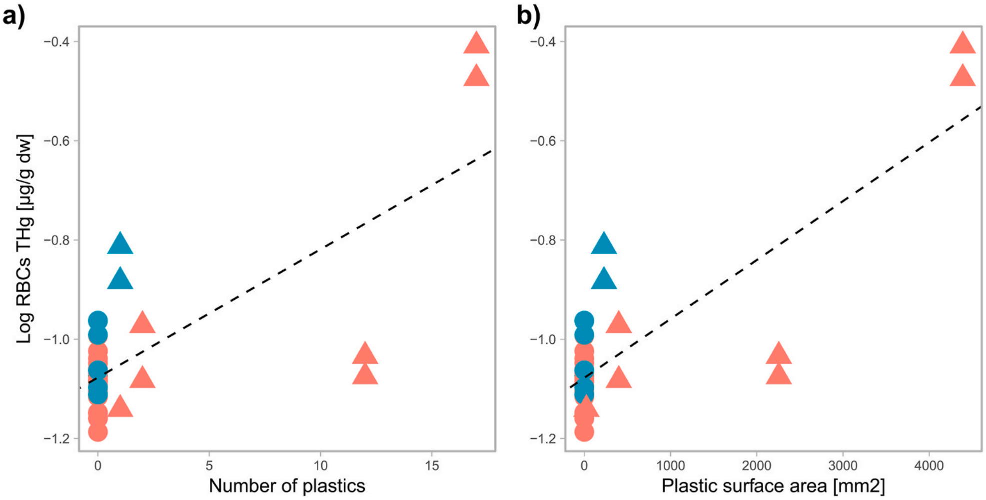

Fig. 4. Relationship between Log blood THg concentration (μg g^{-1} dw) and a) number of plastics in regurgitated pellets and b) plastic surface area (mm^2) in brown skuas (pink) and south polar skuas (blue) chicks from Bahía Esperanza that had plastic evidence in their pellets (triangles).

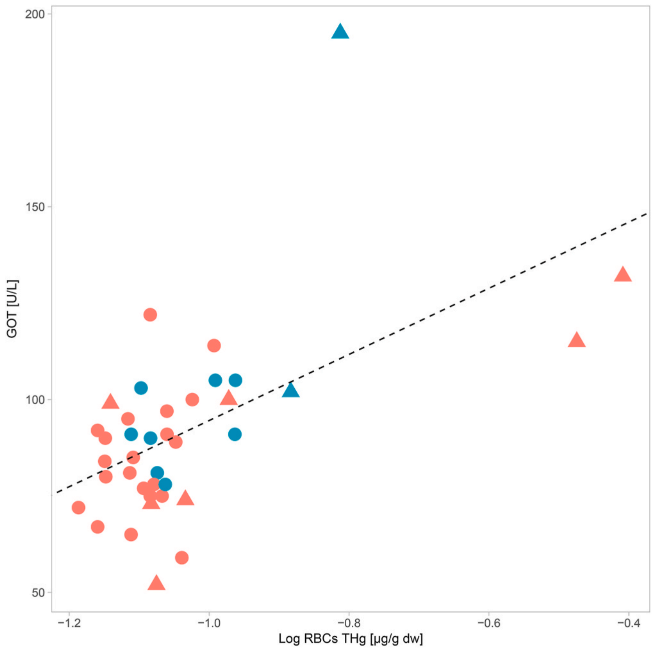

Fig. 5. Relationship between THg (μg g^{-1} dw) and GOT (U/l) in brown skuas (pink) and south polar skuas (blue) chicks at Bahía Esperanza.

observed in brown skua chicks is supported by the dietary flexibility and the increase in the trophic niche breadth reported in adults (Ibañez et al., 2022b).

Due to their generalist feeding habits and their visual and surface feeding strategies, skuas have been found to exhibit a high risk of plastic ingestion and incidence (Ibañez et al., 2020; Lenzi et al., 2022; Roman et al., 2019; Ryan, 1987). In areas where plastic debris are available, a generalist foraging strategy correlates with an increased threat of plastic consumption (Acampora et al., 2017; Caldwell et al., 2020; Ibañez et al., 2020; Lenzi et al., 2016; Provencher et al., 2015; Ryan, 1987; Schutten et al., 2024; Wayman et al., 2024). In support of this, brown skuas exhibited a broader foraging niche (i.e. more generalist) and experienced more frequent exposure to plastic contamination than south polar skuas (5 nests with plastics versus 1 nest with plastics, respectively) in the HAA. Stable isotopes values showed no differences in the isotopic niche breadth between skua chicks that were exposed to plastic and those that were not (Fig. 3b–Table 1), and isotopic niche overlap between groups was considerable (approximately 58%). Skua chicks with evidence of plastic interaction exhibited slightly higher δ^{13}C values, which relates to a more inshore/terrestrial feeding habitat (Hobson et al., 1994), where plastics are usually more abundant and accessible (Lozoya et al., 2026). In contrast, the niche of skuas with no evidence of plastic ingestion tended to be more pelagic, with more negative δ^{13}C values (Bond and Jones, 2009; Hobson et al., 1994). No differences were observed for δ^{15}N values (between groups that interacted or did not with plastics) likely reflecting that both fed on similar prey. Hence, the plastic-seabird interaction may be associated with the available debris in the area where skuas nest and forage (Ibañez et al., 2020; Roman et al., 2019). Information on plastic availability in the nesting area as well as in coastal areas, melting ice streams and surrounding area of the nests might shed light to this matter.

4.3. Plastic as a potential driver of THg concentrations

Blood THg concentrations of skua chicks at Bahía Esperanza were lower than those found for brown and south polar skua chicks in northern and southern locations (Carravieri et al., 2017), for chicks of great skuas from Great Britain (Bearhop et al., 2000b), and for adult skuas from Bahía Esperanza (Ibañez et al., 2022a). Variation of THg in chicks from the same nest was low, and they were significantly different than between nest variation (see section 3.3 and Fig. S1). Additionally, a latitudinal trend was found for skua chicks in Antarctica and the sub-antarctic, as well as in the northern hemisphere, such that THg concentrations are higher at lower latitudes (Bearhop et al., 2000b; Carravieri et al., 2017).

Feathers act as a means of excreting mercury in birds (Lewis and Furness, 1991). In some birds, 70% of the Hg body load is concentrated in feathers (Honda et al., 1986). In great skua chicks, feathers THg was between 5 and 8 times higher than blood THg (Bearhop et al., 2000b). Chicks actively excrete Hg through their growing juvenile feathers; hence their blood THg might not be representing the entire Hg exposure during their first weeks of life (Honda et al., 1986). Additionally, THg concentration in seabird tissues seems to be high at hatching due to mother transfer then decreases due to deposition in growing feathers, and then increases again when deposition into grown feathers is no longer possible (Ackerman et al., 2011). Despite the low values of blood THg measured here (Table 2), we found that THg concentrations in chicks are associated with number of plastics – found in their pellets – and their surface area.

In the majority of studies conducted, Hg concentrations are linked to diet and trophic level (Ibañez et al., 2022b; Mills et al., 2022); however models that included stable isotopes were not the best fit to explain THg variation within our study. This might be because skuas at Bahía Esperanza rely mainly on penguins (Ibañez et al., 2022a). We acknowledge that dietary intake is likely the primary driver of THg concentrations in the colony. However, subtle THg differences among chicks may be partially associated with plastic interaction. It is also important to note that our assessment was restricted to meso- and macroplastics recovered from regurgitated pellets, and therefore does not account for smaller particles potentially retained within the gastrointestinal tract. Inclusion of microplastic burdens could potentially strengthen the observed patterns, but such analyses would require invasive sampling procedures that were beyond the scope of the present study. As such, our findings should be interpreted as reflecting the detectable fraction of plastic ingested, rather than the total plastic burden. Although establishing causal relationships between plastic interaction and pollutant concentrations in seabirds remains challenging due to multiple ecological drivers and limited sample sizes (Roman et al., 2020; Mills et al., 2024b), our results suggest a potential association between plastic interaction and variation in THg concentrations among skua chicks.

Many studies have suggested that the amount of metal adsorbed is dependent on plastic surface and its sorption points (Bradney et al., 2019; Rochman et al., 2014). Plastic surface can adsorb trace elements such as Hg (Bradney et al., 2019; Rochman et al., 2014) from the atmosphere (Spedding and Hamilton, 1982), sea surface (Nerentorp Mastromonaco et al., 2017), or from the snow surface (Angot et al., 2016) that washes the debris found around the research stations. Bahía Esperanza records some of the highest THg concentration among coastal Antarctic flora (Camacho et al., 2015), plausibly due to the anthropogenic activity. Thus, Hg availability to be absorbed by plastics would be high for this location.

Trace elements in plastic can be part of its inherent composition when incorporated as additives during manufacturing (Turner et al., 2020; Wang et al., 2017). Most of the plastics found in pellets are PVC based (Fig. 2c), a polymer known to be very prone to adsorb Hg at a very high concentration on its surface (Spedding and Hamilton, 1982) due to its intrinsic irregular form and polarity (Bradney et al., 2019; Rochman et al., 2014). PVC can have additives (such as biocides to prevent bacterial growth) which can contain compounds based on Hg, among others (Turner et al., 2020). In addition, the link between Hg and PVC is also historical: Hg-based catalysts ($HgCl_2$) were used in acetylene-based vinyl chloride monomer production, a route that has been progressively replaced by Hg-free technologies. However, this should not imply the presence of Hg residues in the finished PVC product to our knowledge (Johnston et al., 2015; Liu et al., 2020; Qiao et al., 2024). Interestingly, Hg release rates can vary markedly across materials and PVC exhibits adsorption-desorption behavior that can favor Hg remobilization under certain conditions (Gao et al., 2023). The most frequently found polymer in this study – PVC – known properties and its type of interaction with Hg could be a good candidate to explain THg levels in skua chicks. PVC could be acting as an entry way for Hg (either adsorbed or as an additive in PVC) which can diffuse, during digestion (Holmes et al., 2020), reaching skua chick blood and tissues. Based on our results, we can hypothesize that not only plastic debris consumption, but also its intrinsic polymeric composition might have a relationship with skua chicks THg load at Bahía Esperanza.

Plastic influence on contaminant tissue levels such as metals and POPs has been reported in previous studies and some attributed to adsorption of contaminants from plastic surface (Lavers et al., 2014; Lavers and Bond, 2016; Davranche et al., 2019; Roman et al., 2020; Schutten et al., 2024; Tanaka et al., 2013), supporting our findings (Fig. 4, Supplementary Table 1). In fact, *in vitro* studies have shown mobilization of metals from polyethylene in simulating avian gastric conditions by diffusion model (Holmes et al., 2020). Even when this relationship has not been found in some seabirds studies (Pollet et al., 2024; Mills et al., 2024b), evidence otherwise is overwhelming and increasing year by year. Therefore, plastic interaction with seabird shows a correspondence to Hg concentration and, with further exploration, might offer an additional explanation for Hg load in skuas chicks.

4.4. Effects of plastic and THg concentrations on liver function

Plastics possess intrinsic toxic properties and become progressively more hazardous as they adsorb pollutants such as Hg from the environment (Roman et al., 2020). Additionally, upon ingestion, macro- and mesoplastics can fragment into smaller components leading to the formation of microplastics and nanoplastics which harm organisms (Ellos et al., 2025). Both plastics and Hg, may induce deleterious effects on seabird physiology and body condition (Haldar et al., 2023; Ibañez et al., 2024; Provencher et al., 2016; Scheuhammer et al., 2007; Sievert and Sileo, 1993). Harmful impacts of plastics include transference of pollutants (Mills et al., 2024b; Roman et al., 2020) with multiorganic dysfunction and neurodegeneration (de Jersey et al., 2025; Ellos et al., 2025). Meanwhile, Hg exposure induces neurological, immune, endocrine and hepatic disruption, even at sublethal concentrations (Ibañez et al., 2024; Tartu et al., 2013) and can, ultimately, have short-to long-term fitness consequences for seabirds (Bustnes et al., 2007; A. Goutte et al., 2014a, 2014b; Ibañez et al., 2024).

The liver is the major organ involved in detoxification, making it more susceptible to pollutants and tissue damage. The GOT enzyme is an adequate biochemical marker of impaired liver function and damage (Choi et al., 2017; Yang et al., 2015). In this study, increased GOT activity was observed in skua chicks with higher blood THg concentrations (Fig. 5). We did not find a significant relationship between plastic presence and GOT activity (Section 3.4). This might be due to the fact that, as commented before, we did not assess total load of plastic ingestion, as only meso- and macroplastic were considered. Microplastics can have longer retention times and higher surface area-to-volume ratios, potentially enhancing contaminant transfer and their biological effects (Teuten et al., 2009; Provencher et al., 2019). Therefore, the lack of association between mesoplastics and GOT activity may reflect that the physiologically relevant exposure is mediated by smaller particles not explicitly quantified here and/or other factors. Although, we found differences of THg concentration within our sample system related to plastic presence, diet is probably the main source of Hg in skuas (Carravieri et al., 2017; Ibañez et al., 2022a). Therefore, we would not expect plastic presence itself to have a direct correspondence with GOT levels.

Our results of THg impact on liver activity are also supported by previous studies on adult skuas and other organisms, in which the exposure to Hg contamination negatively affected GPT activity (Ibañez et al., 2024), increased the activity of GOT, GPT and gamma glutamyl-transferase in rodents (Wadaan, 2009), and induced hepatotoxicity in zebrafish (Macirella et al., 2016). Our observations in GOT activity in response to blood Hg concentration may indicate hepatotoxicity in skua chicks.

CRediT authorship contribution statement

Nadia S. Haidr: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **William F. Mills:** Writing – review & editing, Investigation, Funding acquisition. **Micaela S. Carrillo:** Investigation, Conceptualization. **Carlos Edo:** Writing – review & editing, Methodology, Investigation. **Paco Bustamante:** Writing – review & editing, Investigation, Funding acquisition. **Juan P. Lozoya:** Writing – review & editing, Funding acquisition, Conceptualization. **Franco Teixeira-de-Mello:** Writing – review & editing, Investigation, Conceptualization. **Diego Montalti:** Writing – review & editing, Supervision. **Miguel González-Pleiter:** Writing – review & editing, Investigation, Conceptualization. **Andrés E. Ibañez:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.chemosphere.2026.144990.

Data availability

Data will be made available on request.

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