Aquatic Toxicology 279 (2025) 107220

Contents lists available at ScienceDirect

Aquatic Toxicology

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

Evaluating microplastic contamination in Omani mangrove habitats using large mud snails (*Terebralia palustris*)

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ARTICLE INFO

Keywords:
Snails
Microplastic
Pollution
Mangrove ecosystem
Oman sea
Polyurethane (PU), Raman spectroscopy

ABSTRACT

This study investigated microplastic pollution in the large mud snail *Terebralia palustris* (Linnaeus, 1767) (Gastropoda: Potamididae) inhabiting the *Avicennia marina* mangrove ecosystems along the Sea of Oman. A modified digestion protocol, combining two methods, was employed to improve the detection of microplastics within the snail tissue. Results indicated that 50 % of the examined snails contained microplastics, with significant variability observed among different lagoons. Snails from the polluted Shinas lagoon exhibited higher levels of microplastics compared to those from the lowest polluted Al-Qurum Natural Reserve (MPA). The most prevalent type of microplastic in snail tissues was fibers, making up 75.7 % of the total. Fragments constituted about 24.2 %. Using portable Raman spectrometry, Polyurethane (PU) was identified as the predominant polymer, accounting for 50 % of the total. This was followed by Acrylic and Polyethylene, each representing 18.75 %, and Polyethylene Vynil Acetate (PEVA) at 12.50 %. Overall, it is clear that while snails do reflect the presence of microplastics (MPs) in their environment, their physical attributes do not strongly correlate with the levels or types of MPs they contain. Additionally, the significant difference between the abundance of MPs in sediment and in snails illustrates that, while snails may serve as general indicators of microplastic pollution, they may not be reliable as precise bioindicators or sentinel species for quantifying the extent of this pollution. Further studies are needed to explore other potential bioindicators in mangrove habitats.

1. Introduction

Among environmental pollutants, marine litter has been found in all ocean compartments worldwide (Bellou et al., 2021). Artificial polymers, such as plastics, constitute the majority of marine litter (Gjyli et al., 2020). By mechanical erosion caused by winds and waves, photo degradation, and biodegradation, large plastic items in the sea gradually break down into microplastics (MPs) (Garcia-Garin et al., 2019). Over the past few years, attention has turned towards MPs, which are small-sized plastic pollutants measuring <5 mm (Bermúdez and Swarzenski, 2021; Ho et al. 2024).

Microplastics (MPs) are classified into primary MPs (≤5 mm in size, produced intentionally) and secondary MPs (formed by the degradation of larger plastics through processes like washing and wear) (Garcia-Muñoz et al., 2023). MPs pose significant environmental risks due to their microscopic size, bioavailability, and capacity to act as vectors for organic contaminants (W. Wang et al., 2020). They have been detected in living organisms, aquatic environments, and sediments globally, causing physical and toxicological harm to marine life (Kolarova and Napiórkowski, 2021). Marine vertebrates such as fish, seabirds, and turtles serve as bio-indicators of marine plastic debris (Jelicich et al., 2022), while invertebrates like gastropod mollusks are valuable for assessing pollutant levels (Radwan et al., 2020). Gastropods accumulate pollutants through ingestion of contaminated food or contact with polluted sediments (Samsi et al., 2017). Their low excretion rates enhance pollutant retention, making them effective indicators of environmental health (Reguera et al., 2018). Mangroves, as vital coastal wetlands, trap marine litter and MPs, acting as pollution barriers (Martin et al., 2019). However, research on MPs in coastal wetlands, particularly in the Middle East, remains limited (Oliveira et al., 2020). In Oman, only one study, conducted in mangrove habitats, has addressed MPs (Al-Tarshi et al., 2024). These findings show the importance of further

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https://doi.org/10.1016/j.aquatox.2024.107220
Received 27 August 2024; Received in revised form 10 December 2024; Accepted 22 December 2024
Available online 29 December 2024
0166-445X/

investigation into MPs in this region. The snail *Terebralia palustris* is critical for mangrove nutrient cycling, may serve as a suitable bio-indicator species due to its sediment-dwelling nature and feeding behavior (Pacific Consultants International, 2004). Identifying such bio-monitors is crucial for developing effective policies to combat plastic pollution and protect marine ecosystems (Garg et al., 2022).

The primary objective of this study was to evaluate the levels of microplastics (MPs) present in the snails *T. palustris* across five distinct mangrove habitats in the Sea of Oman. Three types of lagoon environments were examined: "Natural mangrove" lagoons, characterized by old *Avicennia marina*; "Afforested mangrove" lagoons, where *A. marina* were planted by humans; and "Experimental plantation mangrove lagoons," which are designated for future mangrove forest rehabilitation and closely monitored for successful plantation through regular assessments of sediment and water conditions. All of these mangroves have different levels of microplastic and marine litter (Al-Tarshi et al., 2024). We hypothesized that the large mud snails can be as sentinel species (Bendell et al., 2020) for microplastic pollution in the mangrove habitats. A sentinel species is an organism used to detect pollution and monitor environmental health due to its sensitivity to specific contaminants (Fossi and Panti, 2017).

The specific objectives of the study were to: **1.** Quantify and identify the abundance of microplastics (MPs) in snail tissues from five mangrove lagoons. **2.** Determine the predominant types, size and particle shape present in the snail tissues. **3.** Identify the polymer types using portable Raman spectrometry **4.** Find out the relationship between the abundance of MPs in the snail tissue and their abundance in the sediment samples at the same locations to develop a monitoring program for microplastic pollution in mangrove habitats. This study determines the potential of *Terebralia palustris* as a general indicator of microplastic pollution in mangrove ecosystems, providing a valuable view into environmental contamination levels. It underscores the need for further research to identify more precise bioindicators for quantifying microplastic pollution in mangrove habitats.

2. Materials and methods

2.1. Study locations and sampling

The study was conducted between March and May 2022 in five distinct mangrove lagoons along the Omani coast: Shinas, Harmool, Sawadi, Hafri, and Qurum (Fig.1). Detailed information about each lagoon can be found in **Supplementary Table 2.** Briefly**,** this study included the "Natural mangrove" lagoon situated in Qurum and characterized by old mangrove trees. Sawadi and Harmool represented "Afforested mangrove" lagoons, where trees were planted by humans. Finally, Hafri represented the "Experimental plantation mangrove" lagoon, which was designated for future mangrove forest rehabilitation. All of these mangroves have different levels of MP pollution as suggested by our previous study (Al-Tarshi et al., 2024) .The lowest level of MPs was found in Qurum "Natural mangrove" lagoon and the highest level was observed in Sawadi "Afforested mangrove" lagoon. Lagoons were segmented into three transects along the lagoons, the first one was along the seaward fringe, the second transect was within the forest, and the last was along the landward fringe.

2.1.1. Sediment sampling in mangrove lagoons

For sediment sampling in the lagoon, three transects were established in each research location: (1) Seaward fringe transect, (2) Inside the forest transect, and (3) Landward fringe transect. Each transect covered a distance of approximately 10 m. Within each transect, three replicated sediment samples were collected, resulting in a total of nine

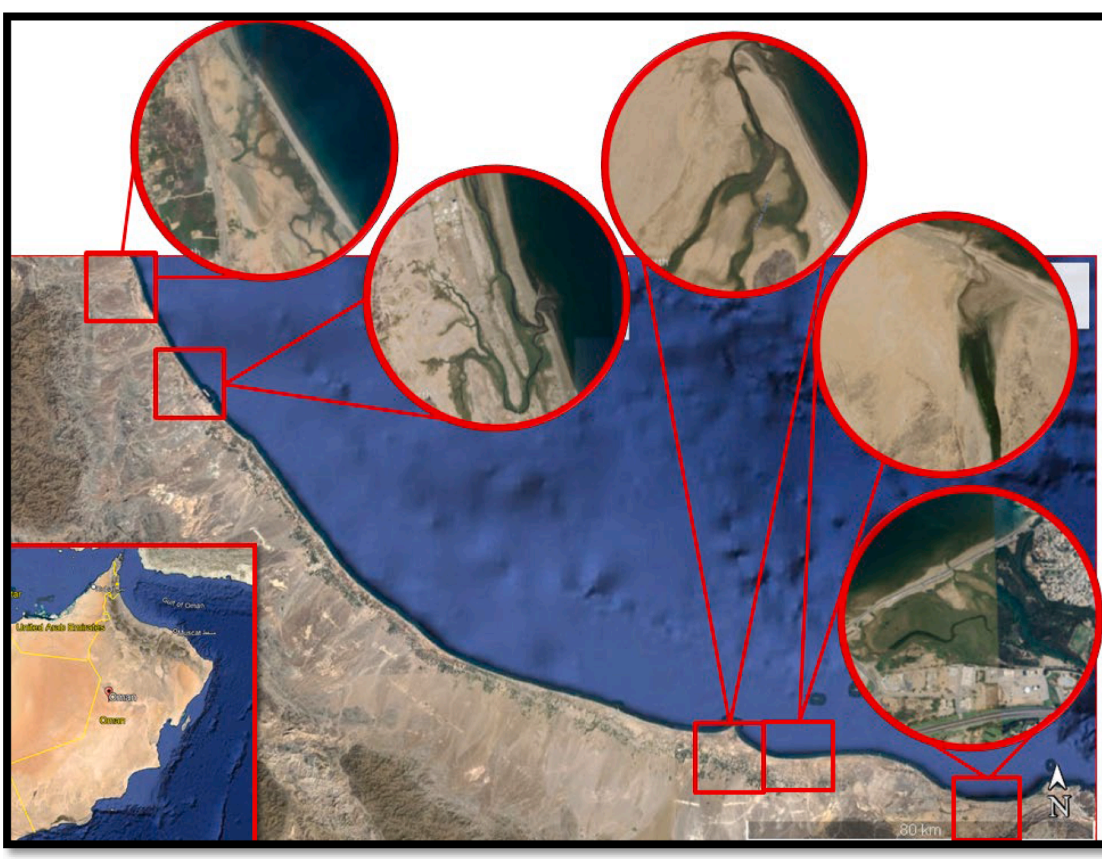

Fig.1. Sampling stations along the Sea of Oman – from left to right Shinas(24°44′24.08″ **N** 56°28′ 17.28″ **E**), Harmool (23°42′ 41.4″ **N**58°04′ 44. 2″ **E**), Sawadi 23°45′41.99″**N** 57°47′ 29.64″ **E**, Hafri 23°43′53.55″ N 57°49′58.44″E, and Qurum Natural Reserv 23°47′14.51″N 57°37′33.34″E.

samples per lagoon. For each sample, around 1 kilogram of sediment was taken from the upper layer, specifically from a depth of 1 to 5 cm. The collected sediment was then stored in non-plastic containers to avoid contamination and preserve the integrity of the samples (Al-Tarshi et al., 2024)

2.1.2. Sampling of large mud snails Terebralia palustris in mangrove lagoons

The large mud snail *Terebralia palustris* was randomly collected from each lagoon, commencing from the seaward fringe, traversing through the forest, and concluding at the landward fringe. In total, 100–120 living snails with an average shell length of 85.98 ± 11.38 mm were gathered during low tide within the mangrove roots (Fang et al., 2023). Following collection, the snails were promptly placed in glass containers on ice, transported to the laboratory, and subsequently frozen at −20 °C for preservation until further analysis (Xu et al., 2020) (**Supplementary Table 1**).

2.2. Snail treatment

Each snail was thawed at 23 °C before analysis (Bendell et al., 2020). The rostro carinal diameter (RCD) of each snail was measured using a Vernier calliper MiTech Metrology Model NO 11,002, China (Loonen et al., 1999) . Then, the shell was broken using a vice and the snail body was removed from the shell. The entire soft body (average weight 50.19 ± 28.44 g) was sectioned with sterilized stainless steel scissors into small pieces. Then, the tissue wet weight was measured using a balance. To prevent contamination by MPs, the experimental bench was cleaned with DI water followed by 75 % ethanol.

2.2.1. Extraction and visualization of microplastic from the sediment

In our previous study (Al-Tarshi et al., 2024), sediment samples underwent a series of steps including sediment drying, pre-treatment, and MPs extraction. The MPs were visualized and photographed by a stereomicroscope coupled with a camera (OLYMPUS SZ61, Japan) under 40X magnification.

2.2.2. Microplastic extraction from the large mud snails "Terebralia palustris"

In this study, a new method for extraction of MPs from the snails was used. It is based on the two existing protocols by (Xu et al., 2020) and (An et al., 2022). The new extraction method was used due to the presence of the slime in the large mud snails (*T. palustris*) which contains a mixture of proteins, glycoproteins, hyaluronic acid, and other compounds. This slime is thick and sticky, helping the snail move smoothly and protect itself (Denny, 1979). Because of its complex structure, breaking down these substances can be tough (ARIBISALA, 2023). So, following the usual methods for fish (Avio et al., 2015), mussels (Mercogliano et al., 2021) and other organisms wouldn't work in this study. Thus, a new protocol was used. Initially, 60 ml of 10 % potassium hydroxide (KOH, FISONS Scientific Equipment Incorporating Griffin & George, UK) was introduced to the samples (each replicate consists of 10 individual snail tissues immersed in 60 ml of KOH), and the solution was then incubated in an incubator (BINDER, USA) at 40 °C for 48 h (Xu et al., 2020). Following incubation, the digested samples went through filtration using stainless steel sieves (IMPACT, UK) ranging from 500 μm to 25 μm, in line with the methodology outlined by An with co-authors (An et al., 2022). At the end, the sieves were rinsed with deionized water (DI) to ensure the full transfer of any residuals adhered to the sieves, followed by backwashing to prevent the oversight of any particles. To digest the remaining tissues, 20 ml of 30 % hydrogen peroxide (H_2O_2) (SIGMA-ALDRICH, Germany) was added, given its effectiveness as a non-destructive treatment for plastic particles (Gulizia et al., 2022). Subsequently, the solution was maintained in an incubator at 40 °C for 24 h. The resulting supernatant was directly filtered through GF/F filter paper (Whatman, China; pore size = 25 μm, diameter = 47 mm) using a vacuum pump (ME 4R NT, Germany). The filter was then placed into a clean glass petri dish, ready for further analysis.

2.2.3. Microscopic and spectroscopic analysis

The analysis of microplastic particles on the filters were conducted employing an optical microscope integrated with a portable Raman spectrometer (BW TEK, A Metrohm Group Company, USA). The Raman spectrometer utilized a 1064 nm excitation laser and a grating with a density of 1200 lines per mm. Observations were made using 100X magnification, specifically with the objectives Olympus M Plan with a numerical aperture (NA) of 0.25 and LM Plan with an NA of 0.50. MP particles present on the filter were visualized and examined using a stereomicroscope (OLYMPUS SZ61, Japan), set at a magnification of 100X. Detailed observations of the particles were conducted, and their characteristics were systematically documented through the capture of photographs using a designated camera. The MPs were determined following the morphological criteria mentioned by Nor with colleagues (Mohamed Nor et al., 2014). During the examination, suspected particles were marked using a marker, and subsequently, these marked particles were specifically targeted for laser examination.

Raman spectra of each particle was replicated >3 times by conducting random point measurements at various locations on each accepted particle. This approach aimed to minimize the impact of localized impurities, such as organic matter or mineral particles (Lenz et al., 2015). A library of references created by Munno with colleagues (Munno et al., 2020) was used as a reference for the identification of MPs. To encompass a broader spectrum of chemical compositions within various polymer types, the library underwent augmentation with several polymer samples. These samples were selected based on differences in characteristics such as flexibility, colour, or form, encompassing variations such as fibrous, solid, film, and foamed structures. Additionally, the reference library was enriched with anticipated non-plastic contaminants and organic materials commonly found in marine environments, including cellulose, methylcellulose, viscose rayon, keratin, and aragonite. This inclusion aimed to enhance the capability of excluding particles that, while resembling plastic, are non-plastic (Anderson et al., 2020).

2.3. Quality assurance quality control

In determining MPs in sediment and snail tissue, a sterile clean bench was used and glassware and equipment were covered to minimize contamination. A rigorous quality assurance protocol, including thorough cleaning of equipment and strict hygiene practices, ensured accurate results. Procedural blank samples served as controls, distinguishing MPs from contaminants. These measures were implemented for reliable microplastic determination in both sediment and *T. palustris* samples.

2.4. Statistical analysis

The normality of the data was assessed using the Shapiro-Wilk normality test, with a significance threshold set at $p > 0.05$. In the case of normally distributed data, a one-way ANOVA was conducted to examine variations in snail width, length, weight, and the number of particles per snail across the five lagoons. The ANOVA test was followed by the Tukey post hoc test. When the data did not follow a normal distribution, the Kruskal-Wallis test was utilized, followed by Dunn's posthoc test. The analyses were performed using PAST4 (https://www.nhm.uio.no/english/research/resources/past/) and software and Origin Lab software. (https://www.originlab.com/).

3. Results

3.1. Microplastic quantification in snail tissues in each lagoon

Al- Qurum Natural Reserve had the lowest level of MPs in sediments compare to other mangrove lagoons (**Supplementary Table 3)**. Harmool, Sawadi and Hafri lagoons had the highest level of MPs pollution. The density of snails was different in all sites (**Supplementary Table 4)**. The highest detected density was in Hafri. Other sites had similar densities of snails. The average abundance of detected microplastics (MPs) in the tissue of snails varied between 0.2 and 1.5 (number MPs/ gram dry weight) across the entire organism. No significant difference in the abundance and size of MPs in tissue was observed across the lagoons (p-value = 0.6932, ANOVA**, Supplementary Table 5**). Notably, the average abundance of MPs was highest in samples collected from the Shinas lagoon area, with 1.50 numbers MPs/ g dry weight (37.5 %). In comparison, the prevalence of MPs in Harmool was approximately 1.0 number MPs/ gram dry weight (25 %). In Sawadi, the average abundance of MPs was about 18 % of MPs/ g dry weight (Fig.2). The lowest average abundance was recorded at Al-Qurum Natural Reserve. These findings shows variations in both the prevalence and abundance of MPs in snail populations, with higher rates observed in the Shinas lagoon area compared to the Al-Qurum Natural Reserve (MPA) lagoon (Fig.2).

3.2. Microplastic characterization (shape, size and polymer type

Two types of microplastics (MPs) were found in the snail tissue: fragments and fibers (Fig. 3). The majority of MPs in the tissue of snails across the five mangrove lagoons were fibers, with an average abundance of 10.6 ± 3.13 MPs/g dry weight. The average abundance of fragments was three times lower, at 3.4 ± 3.21 MPs/g dry weight (Fig. 3). There was no significant difference in the size of MPs between investigated lagoons (p-value = 0.57005). Hafri lagoon had the largest microplastics, with an average size of 0.89±1 mm, while the Qurum lagoon had the smallest particles, with an average size of 0.36±0.44 mm (**Supplementary Figure 1 & Supplementary Figure 2).** Raman spectrometry analysis showed that the most commonly identified polymer among the MPs was Polyurethane (PU) (Figs. 4 and 5), constituting 50 % of the samples with an average of 1.6 ± 1.34 MPs/g dry weight. This was followed by Acrylic and Polyethylene (PE), each accounting for 18.75 % of the MP samples with an average of 0.6 ± 0.55 MPs/g dry weight. Lastly, Polyethylene Vinyl Acetate (PEVA) made up 12.50 % of the MP samples with an average of 0.4 ± 0.89 MPs/g dry weight.

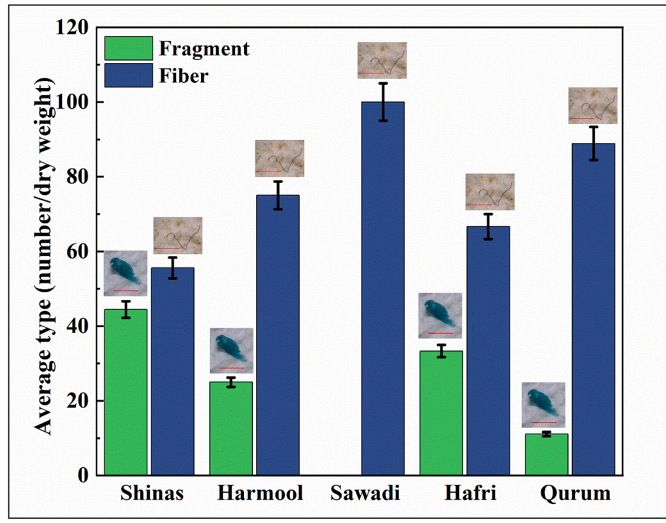

Fig.3. Average abundance of microplastic types in five mangrove lagoons in the Sea of Oman. (**A**) Data represented as mean ± Standard deviation.

3.3. ANOVA test and correlation analysis: MPs abundance, size, form, and polymer type with Terebralia palustris body width, length and weight

The ANOVA results show a statistically significant difference in the abundance of microplastics between sediment and snail groups (p-value = 0.02161). This indicates that the levels of microplastics differ significantly between these two groups. The moderate to high ICC (0.586794) suggests a meaningful difference in microplastic abundance, and the omega squared value (0.4152) indicates that about 41.52 % of the variance in abundance is due to group differences. However, Levene's test from means indicates a violation of the homogeneity of variance assumption, but the Welch F test confirms the ANOVA results, reinforcing the conclusion of significant differences **Supplementary Table 5**.

The correlation analysis unveiled potential connections between the abundance of microplastics (MPs) in snail tissues and various physical characteristics of the snails (**Supplementary Figs. 3, 4 & 5, Supplementary Table 6)**. Specifically, a negative correlation was noted between the quantity of MPs in tissues and both the snail's body length and weight. Conversely, a positive correlation was observed between the number of MPs and the snail's body length. However, it's important to

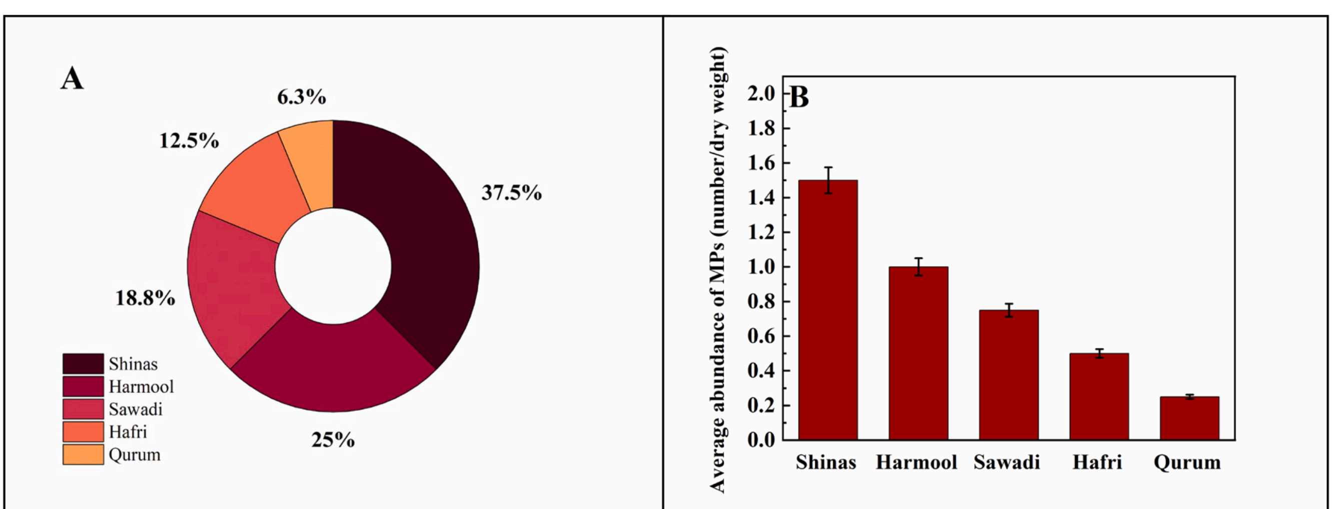

Fig.2. Abundance of MPs in snail tissues across five mangrove lagoons in the Sea of Oman. (**A**) Data illustrated as percentages, (**B**) data represents by mean ± Standard deviation.

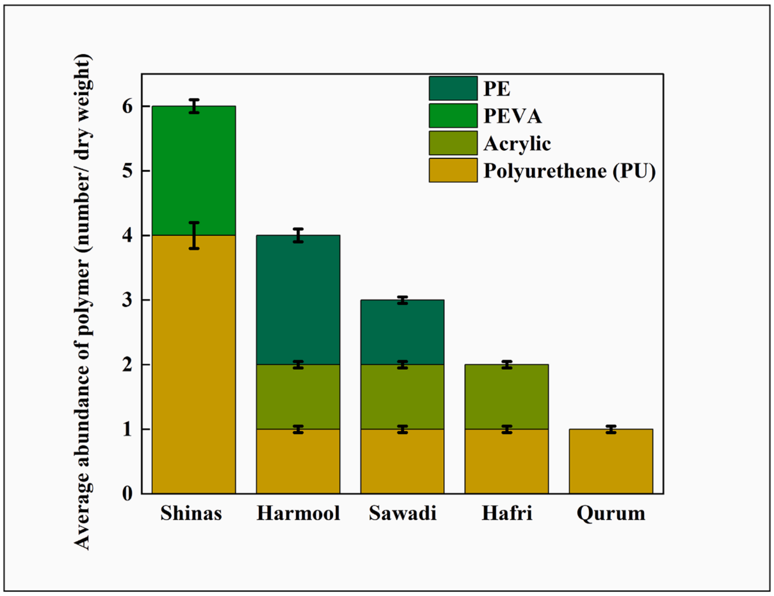

Fig.4. Average abundance of polymers in five mangrove lagoons of the Sea of Oman, data represents by mean ± Standard deviation.

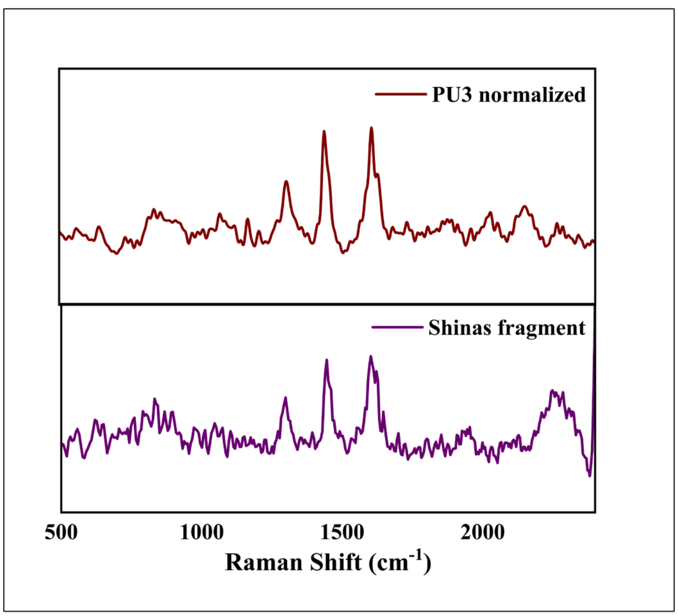

Fig. 5. An example of raman spectrum of fragment from Shinas lagoon and its match with Polyurethane (PU) polymer.

highlight that none of these correlations achieved statistical significance ($p > 0.05$). Additionally, the size of MPs detected in the snails displayed a negative correlation with the snails' physical attributes, including length, width, and weight. Nonetheless, these negative correlations did not reach statistical significance at the 0.05 significance level. Regarding MP types, a positive correlation was detected between the abundance of fragments and the snails' length, width, and tissue weight. Nevertheless, none of these observed correlations were statistically significant ($p > 0.05$). Similarly, for the abundance of fibers, a positive correlation was identified between the number of fibers and the snails' length, width, and tissue weight. However, none of these correlations reached statistical significance ($p > 0.05$). In the case of polymer types, a positive correlation was observed between the number of polymers and the snails' length, width, and tissue weight. Nonetheless, it's crucial to emphasize that none of these observed correlations achieved statistical significance ($p > 0.05$). These findings are further illustrated in **Supplementary Figures 3, 4** and **5.**

3.3.1. *Correlation analysis: MPs abundance in sediment and MPs abundance in the tissue of snails in the same lagoons*

The correlation analysis unveiled potential connections between the abundance of microplastics (MPs) in sediment and snail tissue (**Supplementary Fig. 6**). Specifically, a positive correlation coefficient of 0.30331 was observed between these two variables, indicating a weak relationship. However, the correlation coefficient is not statistically significant p-value = 0.62). This indicates that the observed correlation could have occurred by random chance, and there is no strong evidence to reject the null hypothesis of no correlation between the abundance of MPs in sediment and snail tissue (**Supplementary Fig. 6)**

4. Discussion

In this study, we investigated the presence of microplastics (MPs) in the large mud snails *Terebralia palustris* inhabiting different mangrove lagoons along the Sea of Oman. The objective was to assess the levels of MPs pollution and to validate the use of *T. palustris* as a bioindicator species for MP pollution in the *Avicennia marina* mangrove lagoons in Oman.

4.1. *Microplastics abundance in the snail tissue of Terebralia palustris*

MPs occurred in all tissues of snails in the five distinct mangrove lagoons in the present study. The observed higher levels of microplastics in snails from Shinas, Harmool, Sawdi, and Hafri lagoons may be attributed to differences in their feeding behaviour and habitat preferences. Microplastic differences in snail tissue from Shinas, Harmool, Sawdi, Hafri, and Qurum Natural Reserve mangroves are due to various factors. Al Tarshi and colleagues (Al-Tarshi et al., 2024) found higher pollution in all lagoons except Qurum, linked to nearby urban areas, industries, and shipping routes. Additionally, ecological characteristics like sediment composition and water flow dynamics may enhance microplastic retention in mangrove lagoons (Zamprogno et al., 2021). Snails in Shinas, Harmool, Sawadi, and Hafri could exhibit different feeding behaviors, possibly preferring microplastic-contaminated substrates, thus accumulating more MPs in their tissues. Furthermore, environmental stressors in these lagoons, such as pollution or habitat degradation, may disrupt normal feeding behaviour or physiological processes in snails (Poznańska et al., 2015), leading to increased MPs ingestion . Physiological differences between snails in all lagoons may also influence microplastic accumulation. Regardless of Qurum as MPA, the larger size and tissue composition of snails from Shinas, Harmool, and Sawadi lagoons (**Supplementary Table 1)** revealed potential variations in metabolic rates or detoxification mechanisms compared to those from the Hafri lagoon. These physiological disparities could affect the uptake, retention, or elimination of microplastics within the snails' bodies (Weber et al., 2021). Furthermore, the unique characteristics of the mangrove ecosystems in each lagoon may create distinct microplastic dynamics (Ding et al., 2022). Despite all being mangrove habitats, Shinas, Harmool, and Sawadi lagoons may have specific features such as higher mangrove density, unique root structures, or different sediment compositions that promote the retention and accumulation of MPs (Pacific Consultants Internationa, 2004). Snails inhabiting such environments would consequently experience greater exposure to MPs compared to those in Hafri Lagoon. Al- Qurum Natural Reserve, designated as a Marine Protected Area (MPA), exhibits interesting dynamics regarding MPs abundance in both sediment and the resident mud snail population. Despite a dense mangrove canopy and cover, the sediment within the reserve shows remarkably low levels of MPs, averaging only 0.60 particles/kg (Al-Tarshi et al., 2024). Similarly, the mud snails inhabiting this ecosystem display relatively low levels of MPs in their tissues, with an average concentration of approximately 0.9 number of MPs/gram dry weights. Several factors may contribute to this phenomenon. Firstly, the dense mangrove canopy could serve as a natural filtration system (Wolf, 2012), effectively trapping and retaining MPs before they reach the sediment or are ingested by organisms (Y. Wang et al., 2023). This filtration process may help explain the low levels of microplastics observed in both sediment and snails. Furthermore, the MPA status of Qurum Natural Reserve may limit direct inputs of MPs from anthropogenic sources, thus reducing the overall availability of MPs for ingestion by snails. Additionally, the unique root systems of mangroves and sediment characteristics within the reserve could further diminish MPs availability. Mangrove roots are known to trap and stabilize MPs (Sundaramanickam et al., 2021), while sediment properties like grain size and organic content can influence MPs sorption and retention (Cui et al., 2023). The feeding behavior of snails within the reserve may also contribute to their low MPs accumulation. If these snails primarily feed on organic matter or algae rather than microplastic-laden sediment, their exposure and subsequent ingestion of MPs would be limited.

The absence of a significant correlation between the abundance of MPs in the tissue of snails and the snail's body length, width, and tissue weight indicated that small and big snails in our study accumulate similar amounts of MPs. Similarly, de Vries and colleagues (de Vries et al., 2020) observed no impact of the body length on MP ingestion in various fish species. In contrast, a significant correlation between fish length and the number of MPs in stomachs was detected in sunfish (Peters et al., 2016). The variations in the results between studies might refer to the unique ecological characteristics of investigated species and snail habitats. Mangrove ecosystems are characterized by distinct environmental conditions (Holguin et al., 2001) such as complex food webs, diverse microhabitats (Lee et al., 2014), and varying nutrient availability (Alongi, 2018). These factors can influence the distribution and accumulation of MPs in snail tissues, highlighting the importance of considering ecological dynamics when studying MPs pollution in mangrove habitats.

The exact way in which microplastics (MPs) accumulate in large mud snails *Terebralia palustris* is not fully understood. One possibility is that the snails ingest MPs while feeding on food or sediments. It is also possible that MPs could penetrate the snails' skin. In mangrove lagoons, the ecological interactions and specific feeding behaviors of these snails may influence their ingestion of MPs. Alfaro with colleagues (Alfaro et al., 2007) found that in mangrove lagoons, snails deliberately consume microalgae and filamentous epiphytes, but they may also unintentionally ingest particles from the surrounding environment. The presence of MPs in mangrove habitats, along with the snails' unique feeding habits, likely plays a significant role in the ingestion and accumulation of MPs in these snails (Fang et al., 2023).

4.2. Size of microplastic detected in the tissue of snails *Terebralia palustris*

The smaller average size of microplastics found in the Qurum lagoon, compared to other lagoons, can be attributed to a variety of environmental and anthropogenic factors. The hydrodynamic conditions within the Qurum lagoon, such as water flow patterns and turbulence, likely play a significant role in this phenomenon. Lagoons with multiple openings to the sea, like the Qurum lagoon with its four openings, are subject to higher levels of turbulence and agitation (**Supplementary Fig. 11)**. This increased turbulence can lead to more intense physical degradation processes for plastic items, causing them to break down into smaller fragments (Brouzet et al., 2021). As a result, MPs within the Qurum lagoon may tend to be smaller on average compared to lagoons with calmer hydrodynamic conditions. Additionally, marine organisms, such as filter feeders or deposit feeders, have the capability to ingest larger MPs and later expel them in smaller, fragmented forms (Gonçalves et al., 2019). The Qurum lagoon stands out as one of the lagoons abundant with diverse marine organisms (Pacific Consultants International, 2004). Moreover, microbial activity within the sediment can play a significant role in further degrading MPs over time, thereby contributing to the prevalence of smaller particles. Additionally, sediment characteristics, such as grain size and organic content, can influence the retention and distribution of MPs (Marques Mendes et al., 2021). Finer-grained sediments with higher organic content have been observed to effectively trap and retain smaller MPs, resulting in a higher proportion of smaller particles in the sediment (Mecum, 2019). The high turbulence and presence of four openings to the sea in the Qurum lagoon may indeed be related to the finer sediment characteristics observed in the area. The increased turbulence and water flow patterns associated with multiple openings to the sea could lead to the transportation and deposition of finer sediment particles within the lagoon. This finer sediment, coupled with higher organic content, creates an environment conducive to the retention and accumulation of smaller MPs within the sediment of the Qurum lagoon (Li et al., 2023).

The presence of larger MPs particles in the Hafri lagoon can be attributed to several interconnected factors. Firstly, the low density of mangrove seedlings in the Hafri lagoon, which cover approximately 0.01 ha (Al-Tarshi et al., 2024), means there are fewer roots and branches to act as natural barriers, trapping and breaking down MPs (Noguchi et al., 2012). This lack of vegetation allows larger particles to remain in the water (Deng et al., 2021). Secondly, with only one opening to the sea, the Hafri lagoon experiences reduced water exchange. This limited hydrodynamic activity can result in the accumulation of MPs over time, with insufficient movement to break down larger particles (Quesadas-Rojas et al., 2021) . Additionally, the aquatic organisms in the Hafri lagoon are smaller and less diverse (Pacific Consultants International, 2004). These organisms might not be as effective at breaking down or consuming MPs (Issac and Kandasubramanian, 2021). The overall more stagnant water conditions due to the single sea opening further allow larger particles to settle and persist in the lagoon. Combined, these factors lower mangrove density, limited water exchange, and smaller aquatic organisms contribute to the presence of larger microplastic particles in the Hafri lagoon.

4.3. Type of microplastic

Large mud snails, *T. palustris*, in the five mangrove lagoons of the Sea of Oman predominantly contained MPs in the form of fibers. Globally, fibers are the most common primary MPs in seas and oceans (González-Pleiter et al., 2020). This finding is consistent with previous publications (Neves et al., 2015), (Ventero et al., 2018), (Mcgregor et al., 2020). This stands in contrast to the observations made by previous studies (Bendell et al., 2020) in manila (*Venerupis philippinarum*) and varnish (*Nutallia obscurata*), where fibers were excluded from identification, leading to the detection of only fragments and pellets. A lower occurrence of fragments has been observed in our study. Fragments are resulted from the degradation of larger plastic items (Gerritse et al., 2020). Aquatic organisms may exhibit a preference for ingesting fibers over fragments and pellets due to several factors (Woods et al., 2018). One key factor is the size and shape of fibers, as they are often smaller and more elongated, making them easily mistaken for natural prey, especially by filter-feeding organisms (Sun et al., 2018). Additionally, the buoyant properties of fibers may make them more likely to be suspended in the water column, enhancing their accessibility to a broader range of organisms across different water depths (Dai et al., 2018). The attractiveness of fibers, influenced by physical or chemical properties such as colour, texture, or the presence of biofilms, can also contribute to their higher consumption (Vinod et al., 2020). The bioavailability of additives and the potential digestibility of fibers may further influence their appeal to certain organisms (Guillon and Champ, 2000). Overall, these factors, along with differences in waste management strategies and sources of plastic pollution, contribute to the varying ingestion patterns observed among aquatic organisms (Eerkes-Medrano et al., 2015).

The difference in the abundance between MPs fragments and fibers in sediment compared to their presence in snail tissues can be attributed to various environmental and biological factors. In sediment, MPs fragments may be more prevalent due to their larger size and irregular shape, making them more likely to settle and become embedded within the sediment matrix (Wen et al., 2018). Meanwhile, MPs fibers, being smaller and more elongated, may remain more suspended in the water column or associated with organic matter, reducing their abundance in sediment (Dai et al.,2018). However, despite the higher abundance of fragments in sediment, snails may exhibit selective ingestion preferences (Araújo et al., 2015). They might preferentially consume fibers over fragments due to their smaller size and elongated shape, which could be more similar to natural food sources (Heller, 2015). Consequently, this selective feeding behavior could lead to higher accumulation of fibers in snail tissues despite their lower abundance in sediment. Furthermore, MPs fibers may interact differently with sediment particles and organic matter, making them more accessible to snails (Rebelein et al., 2021). Fibers smaller size and elongated shape could facilitate interactions with organic matter or suspension in the water column, increasing their availability for ingestion by snails compared to fragments (Porter et al., 2023). Additionally, snail feeding behavior and physiological mechanisms for processing and assimilating MPs may contribute to the differential uptake of MPs types (Song et al., 2019). Snails might exhibit preferences for certain types of MPs based on their texture, buoyancy, or chemical composition, leading to higher accumulation of fibers in their tissues (Eerkes-Medrano et al., 2015).

The lack of microbeads or pellets in snail tissues, despite their presence in sediment, can be explained by various biological and ecological factors. Snails have selective feeding behaviors and specialized digestive processes (Connor and Edgar, 1982), that may prevent the ingestion or accumulation of pellets in their tissues. Additionally, their efficiency in transferring ingested particles to their tissues may be limited. Snails might also possess mechanisms for efficiently degrading or excreting MPs (Qu et al., 2020). Furthermore, the presence of MPs in sediment doesn't guarantee their uptake by snails, as uptake dynamics can be influenced by particle characteristics.

4.4. Polymer type of microplastic

The prevalence of Polyurethane (PU) in snail tissues can be attributed to the extensive use of PU materials in marine and other environments, as well as their persistence and resistance to degradation (Gewert et al., 2015). PU materials are widely used in marine applications due to their protective properties for boat hulls, insulation capabilities, and resistance to environmental stresses (Rubino et al., 2020). Since snails often inhabit marine and coastal areas, they are likely to encounter and absorb PU particles from the water and surrounding sediments (Weber et al., 2021). PU's resistance to weathering, corrosion, and biodegradation means it can persist in the environment for long periods (Kaur et al., 2022). This durability leads to the accumulation of PU particles in marine habitats where snails live, making PU more prevalent in their tissues (Song et al., 2019). Additionally, PU materials can absorb and help remove organic substances and contaminants from water bodies (Selvasembian et al., 2021). Snails grazing on surfaces, might ingest PU particles along with these contaminants, resulting in a higher prevalence of PU in their tissues (Rodrigues et al., 2023). The use of PU in products such as cable and wire coatings, drive belts, and hydraulic seals, which are exposed to marine environments (Joshi et al., 2018), further contributes to the accumulation of PU particles in the water and sediments. Snails, living in these environments, can bioaccumulate these persistent particles over time (Dhiman and Pant, 2021). Long-term studies have indicated that PU materials retain their properties even after prolonged exposure to seawater (Yu et al., 2020). This stability means that once PU particles enter the marine environment, they remain intact and available for uptake by marine organisms, including snails.

The other types of MPs, such as Polyethylene (PE) and acrylic, can be found in the tissue of snails due to several interconnected factors, primarily the widespread presence of MPs in aquatic environments. PE was reported as the second most abundant polymer in the mangrove habitats of Oman and is found as the main plastic litter in the lagoons, including plastic bags, packaging materials, and containers (Al-Tarshi et al., 2024). Snails, particularly those in aquatic environments, feed on detritus, algae, and biofilm that accumulate on surfaces (Sheldon and Walker, 1997). Microplastic particles, including PE, easily become part of this biofilm and detritus (Rummel et al., 2017). As snails graze, they inadvertently ingest these MPs. The small size of MPs particles allows them to be mistaken for food by snails (Haque et al., 2023), and once ingested, these particles can accumulate in the digestive system and tissues of the snails (Rodrigues et al., 2023). Since snails' bodies are not equipped to break down or expel these plastic particles effectively (Jitkaew et al., 2023), the concentration of PE in their tissues increases over time.

The presence of acrylic particles in the tissue of snails can be attributed to similar factors. Acrylic is commonly used in a variety of products, including textiles, paints, coatings, and plastics (Mosley, 2017). This extensive use leads to significant amounts of acrylic waste entering aquatic environments, where it can break down into MPs particles (Petrescu et al., 2016). Acrylic particles are durable and resistant to degradation, which means that once they enter the environment, they persist for a long time, increasing the likelihood of being ingested by aquatic organisms such as snails (Ceia and Bessa, 2024).

Both PE and acrylic particles are prevalent in the environment and share similar pathways into the tissues of snails. These pathways include the snails' feeding habits on detritus, algae, and biofilm, where these microplastics accumulate, and the inability of snails to effectively expel the ingested particles, leading to their accumulation in the tissues over time.

5. Conclusions

The study successfully quantified microplastic (MPs) abundance in the tissues and identified the dominant types of MPs, the lack of significant correlation between MPs abundance in snails and sediment highlights the limitations of using *palustris* as direct indicators of microplastic pollution levels. MPs pollution in *T. palustris* can reflect the overall health and changes in the mangrove ecosystem. Additionally, snails can help trace the pathways and accumulation of MPs within the food web, providing insights into how these pollutants move through different trophic levels in the mangrove habitats. *T. palustris* snails can be part of a broader suite of bioindicators, particularly as a sentinel species showing considerable resistance to microplastic pollution. Studying the impacts of MPs on snail behavior, reproduction, and physiology can also offer insights into the broader ecological consequences of MPs pollution.

CRediT authorship contribution statement

Muna Al-Tarshi: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **John Husband:** Writing – review & editing, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation. **Sergey Dobretsov:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

Prof. Sergey Dobretsov and Ms. Muna Al-Tarshi report financial support provided by Oman Ministry of Higher Education Research and Innovation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors extend sincere appreciation to all individuals who participated in the collection of samples from the five mangrove lagoons in Oman. Special thanks to Aisha Al-Baloshi, Shareefa Al-Tarshi, Yamin Al-Tarshi, Wisam Al-Tarshi, Lolwa Al-Marzooqi, Dana Al-Marzooqi, Khawla Al-Tarshi, Said Al-Tarshi, and Nasser Al-Tarshi for their invaluable contributions during the fieldwork. We would also like to express gratitude to the supervisor of marine research lab Mr. Abdullah Al-Kindi for his dedicated efforts in removing the shells of the snails. This research received financial support from the Ministry of Higher Education, Research and Innovation (grants from the Ministry of Higher Education, Research and Innovation: RC/GRG-AGR/FISH/22/01 and Sultan Qaboos University: RC/GRG-AGR/FISH/22/01).

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.aquatox.2024.107220.

Data availability

Data will be made available on request.

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