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Microplastic pollution in the Thumbprint emperor (*Lethrinus harak*) from Tanzanian coastal waters: Occurrence, abundance, characterization, and relevance as a monitoring species

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A R T I C L E I N F O

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A B S T R A C T

In the present study we collected the Thumbprint emperor (*Lethrinus harak*) from seven landing sites from the coastal waters around Dar es Salaam and Zanzibar (Tanzania) to (i) quantify and characterize microplastics (MPs) in their digestive tracts and (ii) use previously assessed environmental levels in nearshore surface waters and seabed sediments to determine whether *L. harak* could be a relevant biomonitor for MP pollution in the region. *L. harak* (n=387) had an overall frequency of occurrence (FO%) of 48 % and displayed spatial variation between sites with Kunduchi (FO=66.7 %) and Mijimwena (FO=17.1 %) having the highest and lowest FO%, respectively. Fish from Mjimwema had a mean MP content of 0.17 ± 0.38 MPs individual^{-1} whilst fish from Kizimkazi had the highest MP abundance (1.75 ± 2.33 MPs individual^{-1}). Fibers (overall 64.7 %, range across sites 48–86 %) and fragments (17.9 %, 5–25 %) were the most dominant MP types whilst black (46.9 %, 40–58 %) and blue (22.5%, 7–36 %) MPs were the most common colours. Fish length (ρ= -0.09, p=0.09) or weight (ρ=0.07, p=0.18) did not significantly correlate to MP abundance in fish (Spearman rank correlations). Neither MP occurrence nor abundance was linked to MP concentrations in either surface waters or seabed sediments (Spearman rank correlation), but MPs in the fish better reflected MPs in the sediment compared to surface water (two-way ANOVA on ranked data). Whilst *L. harak* presents as a promising candidate to monitor MP pollution along the East African coast due to its ecology, overall, it lacks reliability. Nonetheless, the present study fills important knowledge gaps both geographically on the East African Coast and with an underrepresented taxonomic family (Lethrinidae 'Emporer fishes').

1. Introduction

There is a wealth of scientific literature that documents the distribution, occurrence, and abundance of microplastics (MPs, < 5 mm) in the marine environment worldwide, from the depths of the ocean (Peng et al., 2018, 2020) to the waters (Isobe et al., 2014; Capparelli et al., 2021; Nchimbi et al., 2022a) and sediments (Frias et al., 2016; Mayoma et al. 2020; Ranjani et al., 2021; Nchimbi et al., 2022b) of nearshore coastal areas. MPs have been found within an array of marine life (Kühn and Van Franeker, 2020), with a particular focus on their occurrences and abundances within fish species (Avedo-Santos et at al., 2019, Markic et al., 2020). A recent meta-analysis of the occurrence of MPs in fish globally showed that 728 species, spread over 35 Orders and 178 families, have been collected and evaluated for MPs in their gastrointestinal tracts (Hossain and Olden, 2022) with more species being added continuously. The ingestion of MPs can result in deleterious effects via

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the blockage of the digestive tract such as malnutrition and starvation (Wang et al., 2020) and/or the transfer of plastic associated chemicals from both the manufacturing process and sorbed from the environment (Khan et al., 2022).

Sampling the digestive tracts of resident fish populations has become a recognized approach to provide an initial assessment of MP pollution in the environment, essentially using the fish species as a proxy for environmental levels (Lusher et al., 2013; Sanchez et al., 2014; Neves et al., 2015; Biginagwa et al., 2016; Nadal et al., 2016; Bellas et al., 2016; Güven et al., 2017; Kühn et al., 2018; Calderon et al., 2019; Verlaan et al. 2019; Barboza et al., 2020; Khan et al., 2020; Ríos et al., 2022). However, most of these studies present a 'snapshot' of MPs in their selected species and the occurrence of MPs (i.e. presence or absence of MPs in the sampled individuals) as well their abundance (i.e. MPs per individual) will vary with species characteristics such as size, feeding habits, trophic level and ecological niche (Kühn and Van Franeker, 2020), as well as the time and season of fish sampling (Gouin, 2020; De Witte et al. 2022). Moreover, without linking the occurrence, abundance and morphology of MPs found in the digestive tract of fish to the levels and types found in the waters or sediments, it is not possible to determine whether a given fish species is a reliable biomonitor for MP pollution (Verlaan et al., 2019). The characteristics of a reliable biomonitor of pollution may include, in general terms, a sensitivity to environmental change and the ability to accumulate contaminants, and specifically for fish species and MPs, generalist feeding behaviour and the possible retention of plastic particles in stomachs after ingestion, as described for fish from the Mugilidae family in the north-western Mediterranean Sea (Reboa et al., 2022). The need for reliable biomonitors in the marine monitoring of MPs has been recognised in various regional regulatory frameworks, for example, through the adoption of the European Marine Strategy Framework Directive (MSFD) Descriptor 10.1.3 and the African marine litter monitoring manual focus on the relevance of candidates for biomonitoring. The MSFD technical subgroup on marine litter reported several criteria for fish being used as biomonitors, which include accessibility to sample, presence in high abundance, availability in a wide geographical distribution and covering different ecological niches (MSFD Technical Subgroup on Marine Litter, 2013).

Geographically, discrepancies persist in our knowledge of MPs as a global pollutant with studies from the African continent (with the exception of South Africa) largely absent from the early stages of MP research (Blettler et al., 2018; Khan et al., 2018). However, a significant body of work is now beginning to emerge from East Africa (Honorato-Zimmer et al. 2022) with studies conducted in marine waters (Kosore et al., 2022; Nchimbi et al., 2022a; KeChi-Okafor et al., 2023), sediments (Mayoma et al. 2020, Nchimbi et al., 2022b) and biota (Mayoma et al., 2020, Ombongi et al., 2021). Furthermore, the impact of MPs on native East African fish following laboratory exposures is starting to be investigated, e.g. Wami Tilapia (*Oreochromis urolepis*) (Mbugani et al., 2022a, 2022b). However, as in other parts of the world, few studies have attempted to correlate MP levels and morpholgies across different compartments. An exception, Mayoma et al., (2020) investigated the correlation between MP concentrations in the sediments of the East African Coast around Dar es Salaam and Zanzibar and the cockles (*Anadara antiquata*) that inhabit them. Whilst the site with the highest FO% (frequency of occurrence) was the site with highest MP concentration in sediment, the removal of this one highly influential observation resulted in a non-significant relationship between biotic and abiotic compartments suggesting that the bivalve species was not an effective biomonitor of environmental levels. However, such studies in this region are yet to be conducted with appropriate fish species.

The present study aimed to (i) quantify and characterize MPs within the Thumbprint emperor (*Lethrinus harak*) collected from the coastal waters around Dar es Salaam and Zanzibar and (ii) correlate this to the previously assessed environmental levels in nearshore surface waters (Nchimbi et al., 2022a) and seabed sediments (Nchimbi et al. 2022b) from the same sites to determine whether *L. harak* has relevance as biomonitor for MP pollution in coastal Tanzanian waters. The latter objective is addressed by three specific questions (a) are fish length and weight related to MP occurrences and abundances? (b) do MP levels in *L harak* reflect previously determined concentrations in the nearshore surface waters and seabed sediments? and (c) do the MPs found in *L. harak* reflect the MPs found in the abiotic compartments? Several aspects of the ecology of *L. harak* suggest it as a promising candidate for a biomonitor species. It is a semi-pelagic, non-migratory, generalist macro-benthivore meaning that it occupies much of the water column, is localized to specific areas and feeds on a variety of prey including zooplankton when juvenile, and on mollusks, crabs, echinoderms and worms during adult life stages (Unsworth et al., 2009; Mziray and Kimirei, 2016). *L. harak* is also economically significant along the East African coast and is sold from 5.4 to 10.3 USD per Kg (Kulmiye et al. 2002; Mziray and Kimirei, 2016). Caught by local small-scale artisanal fishers using handlines and basket traps from reefs within the limits of East African marine territorial waters, *L harak* forms a significant source of protein for coastal communities (Mrombo et al., 2019). Other species, such as *Leptoscarus vaigiensis* (Marbled parrotfish), *Siganus sutor* (Shoemaker spinefoot), *Lethrinus mahsena* (Sky Emperor), and *Naso hexacanthus* (Sleek unicornfish) were also considered, but following consultation with local fishermen were described as more difficult to source. Thus, *L. harak* has both ecological and economic importance to the region and, owing to the factors described above, could be of potential relevance as biomonitor of MP pollution.

2. Material and methods

2.1. Study area and fish

In December 2019, *L. harak* (387 fish) were purchased directly from fishermen at the seven selected landing sites at Kunduchi, Mjiwema, and Msasani (Dar Es Salaam), and Fumba, Nungwi, Bububu and Kizimkazi (Zanzibar) (n=35–82) (Fig. 1, Table 1). These sites were chosen because our previous studies had quantified and characterized MPs occurrence and abundance in the nearshore surface waters (Nchimbi et al., 2022a), and beach and seabed sediments (Nchimbi et al., 2022b) of the same locations. The sites also reflected a range of anthopogenic activities and levels of urbanization. As the landing sites are relatively close together, it was important to know that the fish were captured within proximity to the landing site and to ensure that catchment areas do not overlap. This was confirmed as being the practice by the local fisherman. Fish were then purchased whole without the prior removal of their gastrointestinal tracts. The samples were washed with distilled water and stored at 4±2 °C in a clean, cool box with ice, and then transported to the laboratory for further analysis.

2.2. Extraction of MPs from fish digestive tracts

The fish purchased from the fisherman were weighed (g) and their lengths measured (cm). The collected *L. harak* (n=387) had an average length and weight of 27.1±3.8 cm and 254.0±113.2 g, respectively (Table 2). The dissection of the digestive tract was made from buccal cavity to anus and tissue digestion was conducted with 10 M NaOH as previously described in the literature (Biginagwa et al., 2016; Calderon et al., 2019). Briefly, the dissected intestinal tissues were placed in 250 or 500 mL conical flasks to which 10 M NaOH was added in a 5:1 (w/v) ratio. The digestion was placed in a water bath for 24 h at 60°C to digest the organic material. The NaOH method has been shown to digest organic matter with an efficacy >90% whilst importantly having a negligible impact on the plastics, especially when compared to strong acid digestion, which can degrade plastics (Cole et al., 2014). The digested solution was vacuum filtered through a 0.7μm Whatman GF/C glass fiber filter in an 8 cm diameter glass Buchner funnel (De-la-Torre et al., 2019). In cases of incomplete digestion or solid material in the

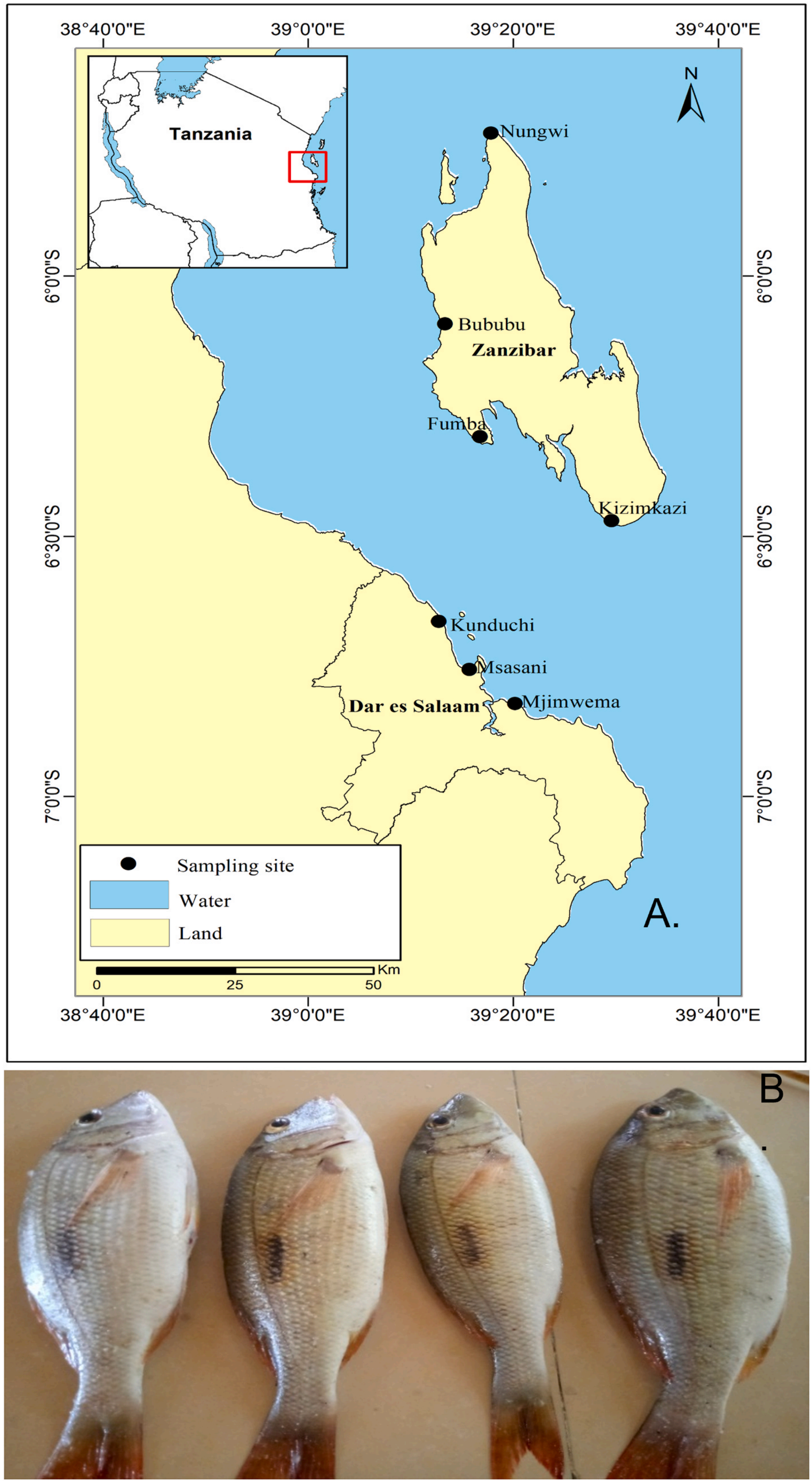


Fig. 1. Map showing the landing sites along the coast of Dar es Salaam (Kunduchi, Mjimwema, Msasani) and Zanzibar (Fumba, Kizimkazi, Nungwi, Bububu) (A) where Thumbprint Emperor (*Lethrinus harak*, picture B) were purchased from local fishermen.

Table 1
Study sites from where *L. harak* were collected, site location, and descriptions of main anthropogenic activities.

#	Site	Site code	Location	Coordinates	Main anthropogenic activities and potential sources of MPs
1	Kunduchi	KDC	Dar es Salaam	06°39′,039°13′	Residential, recreational, and fishing
2	Mjimwema	MJM	Dar es Salaam	06°60′,039°21′	Oil pipes, fishing, and harbor
3	Msasani	MSS	Dar es Salaam	06°44′,039°15′	Recreational, residential, and fishing
4	Fumba	FMB	Zanzibar	06°11′,039°15′	Residential, recreational, and fishing
5	Kizimkazi	KZM	Zanzibar	06°27′,039°28′	Recreational, fishing, and residential
6	Nungwi	NGW	Zanzibar	05°50′,039°12′	Recreational, residential, and fishing
7	Bububu	BBB	Zanzibar	06°87′, 039°21′	Residential, recreational, and fishing

tube, the digested solution was diluted in a 100 mL saline solution (120 g/L NaCl), stirring with a glass rod, and left to precipitate for 10 minutes, followed by vacuum filtration (De-la-Torre et al., 2019). The filter was placed in a clean glass petri dish with a cover, air-dried in a laminar flow, and inspected under a dissecting microscope at x40 magnification. MPs were visually identified by their unnatural coloration (such as bright blue) and/or unnatural shapes (such as fragments with sharp edges) (Hidalgo-Ruz et al., 2012). MPs found per fish were enumerated and categorized according to morphology (fragments, filaments, fibers, films, foams or pellets (Frias et al., 2018)) and color. Images of the suspected MPs were taken with an Olympus uc90 digital camera mounted on an Olympus SZ61 microscope.

2.3. *μFTIR identification of polymers*

The main polymer type of a small selection of MPs recovered from fish digestive tracts (8 in total) was identified by micro-Fourier Transform Infrared (μFTIR) spectroscopy at the National Museum of Denmark. An area of approximately 15 mm^2 (chosen as representative of the whole filter of selected samples using optical microscopy) of the grade GF/C binder-free, glass fibre filters containing the samples was mounted on a gold mirror on PerkinElmer Spotlight 200 micro-spectrometer equipped with MCT (mercury cadmium telluride) detector. Microscopic images were first collected with an aperture size of 100μm. Then a total of 25 spectral scans per pixel with a resolution of 4 cm^{-1} and interferometer speed of 1 cms^{-1} were accumulated across wave number range 600–4000 cm^{-1} in reflectance mode. Background spectra with the same parameters were collected for each sample from a blank area of the filters. Spectra were then analysed using siMPle software (version 1.1. β18. 09. 2020, available at www.simple-plastics.eu). Polymer types were identified by an automated single-spectrum matching function against the available spectral database (Version 1.02 21.07.2019).

2.4. *Quality control*

Quality control to prevent the inadvertent introduction of MPs during sample preparation and analysis steps was conducted as previously described (Nchimbi et al., 2022a, 2022b). Nitrile gloves were worn throughout the laboratory process, from GIT dissection to the end of the isolation method. All work surfaces, and dissection materials were cleaned with 70 % ethanol. The isolation process was performed under an air flow hood except during sample drying. For every sample batch, procedural blanks of distilled water and 10% NaOH were prepared by filling glass test tubes with each and treated in the same manner as the samples. Two filters were previously dried in a laminar flow cabinet and soaked in distilled water, then placed close to the working table in the laboratory and later examined under the stereomicroscope to determine airborne external contamination.

2.5. *Statistical data analysis*

The terms occurence and abundance are often used interchangeably in the MP literature. Here we define occurrence in terms of frequency of occurrence (FO%) within the sampled population and abundance as the number of MPs per individual (MPs $individual^{-1}$). $FO\% = (Ni/N)*100$, where Ni=number of fish containing MPs and N=total number of fish examined (Pegado et al., 2018). All statistical tests were performed in R (version 4.3.1), using RStudio (version 2023.09.0 Build 463). Data were analysed for homogeneity of variance with Levene's tests. Where assumptions of normality were met (e.g. fish length and weight data) comparisons were made with one-way ANOVA with Tukey post hoc test. Non-normally distributed data were compared using non-parametric Kruskal-Wallis test followed by Dunn's post hoc test e.g. to compare MPs abundances between the sites. To establish correlation between variables, a linear model was fitted e.g. mean MP abundance and frequency of occurence (FO%). Owing to small sample sizes and

Table 2
Summary of the number of fish collected at each study site (n), fish biometrics (length and weight) and MP occurrence (%FO), and abundances (MPs per invidual^{-1}) from the present study together with the environmental concentrations reported previously for nearshore surface water (MPs m^3) and seabed sediment (MPs Kg^{-1} dy sediment) in Nchimbi et al., 2022a and b, respectively (n.d.= not determined).

						L. harak MP levels		Environmental concentrations	
#	Site	Site code	n	Length (cm)	Weight (cm)	FO %	MPs $individual^{-1}$	Nearshore surface water (MPs m^3)[a]	Seabed sediment (MPs Kg^{-1} dy sediment)[b]
1	Kunduchi	KDC	72	27.9 ± 3.7	279.4 ± 122.2	66.7	1.39 ± 2.07	0.080 ± 0.034	44.33 ± 2.90
2	Mjimwema	MJM	35	29.1 ± 1.4	287.4 ± 38.8	17.1	0.17 ± 0.38	0.450 ± 0.212	111.01 ± 2.78
3	Msasani	MSS	50	27.8 ± 5.8	307.1 ± 173.8	46.0	1.32 ± 2.49	n.d.	66.70 ± 2.05
4	Fumba	FMB	47	25.5 ± 2.0	199.8 ± 51.1	46.8	1.04 ± 1.72	0.011 ± 0,008	208.33 ± 15.20
5	Kizimkazi	KZM	48	28.5 ± 3.0	281.9 ± 94.4	47.9	1.75 ± 2.33	n.d.	88.84 ± 3.13
6	Nungwi	NGW	82	25.3 ± 2.1	202.8 ± 62.5	47.6	1.22 ± 1.74	0.164 ± 0.09	155.27 ± 3.8
7	Bububu	BBB	53	27.1 ± 4.9	251.8 ± 130.9	45.3	0.81 ± 1.53	0.027 ± 0.007	210.89 ± 15.00

n.d. = not determined.
[a] Data from Nchimbi et al., 2022a
[b] Data from Nchimbi et al., 2022b

non-normality of some of the data, some relationships were investigated using non-parametric Spearman rank correlations e.g. the relationships between MPs abundance and environmental concentrations. Similarly, to determine whether MP types and colours found in fish had agreement with MPs in nearshore water and seabed sediments respectively, percentages of MP colour and type from each source (fish, water, sediment) were transformed to ranks. Ranks were assigned as follows; highest frequency received rank 1, second highest received rank 2 etc. In the case where two or more types/colours had equal frequency, the mean of the ranks of these equal observations were assigned to all relevant observations. A two-way ANOVA with Tukey post hoc test was performed on the rank transformed data as a way to determine rank order concordance. Specific details of each analysis are additionally provided in the relevant Results and Discussion section.

3. Results and discussion

3.1. MPs recovered from the L. harak gastrointestinal tracts

3.1.1. Occurrence and abundance of MPs in Lethrius harak

Of the 387 individuals sampled from the seven landing sites in Dar es Salaam and Zanzibar, 186 were found to contain MPs within their digestive tracts resulting in an overall FO of 48 %. There was variation in the proportion of fish at each site containing MPs with Kunduchi (FO=66.7 %) and Mijimwena (FO=17.1 %) having the highest and lowest FO%, respectively, and the five other sites being close to the overall mean (FO=45.3–47.9 %) (Fig. 2A, Table 2). The higher FO% at Kunduchi could be attributed to the presence of the Tageta River, which runs through the unplanned settlements carrying anthropogenic litter to the coast.

In total 448 MPs were recovered from the 186 fish with MPs in their digestive tracts. MP abundance levels were found to vary in fish from different sites. Fish from Mjimwema had a mean MP content of 0.17 ± 0.38 MPs individual^{-1} which was significantly lower than all other sites except Bububu (0.81 ± 1.53 MPs individual^{-1}) (non-parametric Kruskal-Wallis test followed by Dunn's post hoc test $p<0.001$, Fig. 2B, Table 2). The remaining sites exhibited a range from 1.04 ± 1.72 MPs individual^{-1} in Fumba to 1.75 ± 2.33 MPs individual^{-1} in Kizimkazi and there was no significant difference between them. For both MP occurrence (FO%) and abundance (MPs individual^{-1}) there was no difference between the sites from Dar es Salaam and Zanzibar indictating that geographic separation between the mainland and the island was not a factor in MP burdens in the digestive tracts of *L. harak* collected from different landing sites.

A linear model was fitted to relationship between MP occurrence (FO %) and abundance (MPs individual^{-1}). The relationship was significant ($p = 0.04$, R^2=0.629, Fig. 2C) suggesting that when more fish contain MPs, the number of MPs per fish also increases. However, the sites of Kunduchi and Mijimwena strongly influenced this relationship and both these sites had a Cook's distance >10 x greater than the rest of the observations (0.68 and 1.68 respectively, mean of the remaining observations = 0.03). After removal of these influential observations, the relationship between MP occurrence and MP abundance was not significant ($p = 0.32$, R^2=0.32), primarily driven by very similar FO% values amongst the five remaining sites (FO=45.3–47.9%).

3.1.2. Characteristics and morphology of MPs

Of the 448 MPs recovered from *L. harak* digestive tracts fibers were the most prevalent MP type making up 64.7% of the total and ranging from 48% in Kunduchi to 86% in Bububu across the seven landing sites (Fig. 3A). Fragments were the second largest group of MP type followed by filaments and films, depending on the site. The order for MP types was: fibers (overall 64.7%, range across sites 48–86%) > fragment (17.9%, 5–25%) > filament (9.2%, 0–19%), film (6.9%, 0–20%) > foam (1.3%, 0–7.6%) > pellets (0%, no pellets found). Black coloured MPs were most prevalent (46.9% of the 448 MPs) followed by blue MPs (22.5%). Across the sites, the order for MP colour prevalence was as follows: black (overall: 46.9%, range across sites: 40–58%) > blue (22.5%, 7–36%) > transparent (11.2%, 0–31%) > red (6.5%, 0–11%) > white (5.8%, 0–27%) > others (5.4%, 0–8%) > green (1.8%, 0–4.7%) (Fig. 3D). Micro-FTIR spectroscopy was used to provide chemical information about the plastic type, but this analysis was neither systematic nor comprehensive being limited to very few samples (8 in total). Of the analysed MPs, examples of a blue polyester fiber from an individual from Mjimwema and a polyvinyl chloride fragment from an individual from Msasani are shown in Fig. 4.

3.1.3. MPs in L. harak within the context of coastal fishes

Placing the occurrence of MPs in *L. harak* in the wider context of the marine environment is challenging, not due to the lack of data since numerous studies have been conducted on the ingestion of MPs by fish species worlwide (Hossain and Olden, 2022), but rather the need to make relevant comparisons in terms of both similar coastal locales and of fish traits, such as feeding habits, trophic level and ecological niche (Kühn and Van Franeker, 2020). According to a recent global meta-study on MP ingestion by fish only 3 % of studies are from the African continent (Hossain and Olden, 2022) with no studies conducted along the

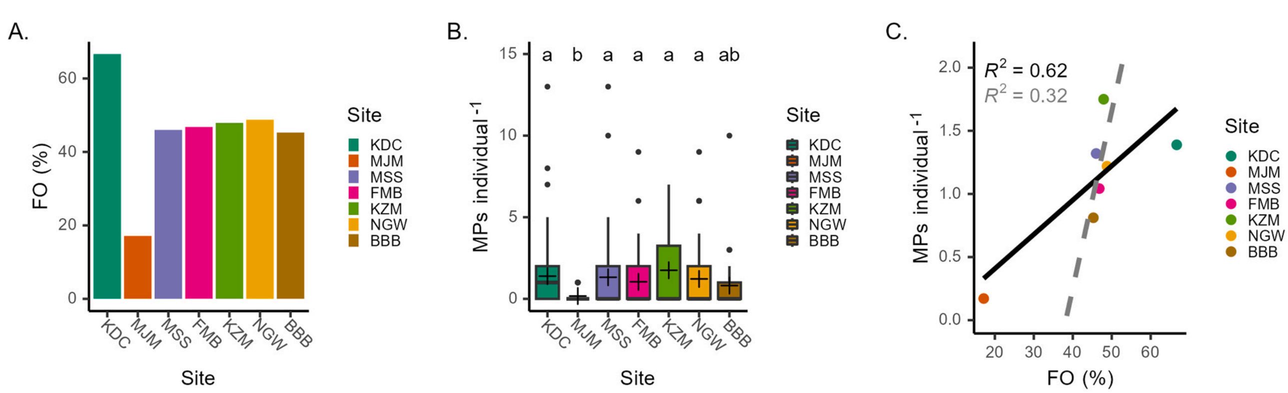


Fig. 2. Occurrence and abundance of MPs in *Lethrinus harak*. A. Frequency of occurrence (FO%) of the number of individuals containing MPs from each site (see Table 1 for site abbreviations). B. Number of MPs per individual (MPs individual^{-1}). Boxplots display minimum/first quartile (= 0 for all sites), median, third quartile, maximum (upper whisker, except if maximum exceeds 1.5 * interquartile range, in which case this value is used instead) and mean (+). Observations more than 1.5 times the interquartile range above the third quartile are considered outliers and are shown with black points. Significant differences between sites are denoted by different letters (non-parametric Kruskal-Wallis test followed by Dunn's post hoc test $p<0.001$). C. A linear model was fitted between %FO and MPs individual^{-1} showing a significant correlation (R^2= 0.62, p=0.04, black line), but two observations, Kunduchi (KDC) and Mjimwema (MJM), were strongly influential based on Cook's distance (see text). Analysis after the removal of these two observations showed a non-significant relationship between MP occurrence and abundance (R^2= 0.32, p=0.32, grey dashed line).

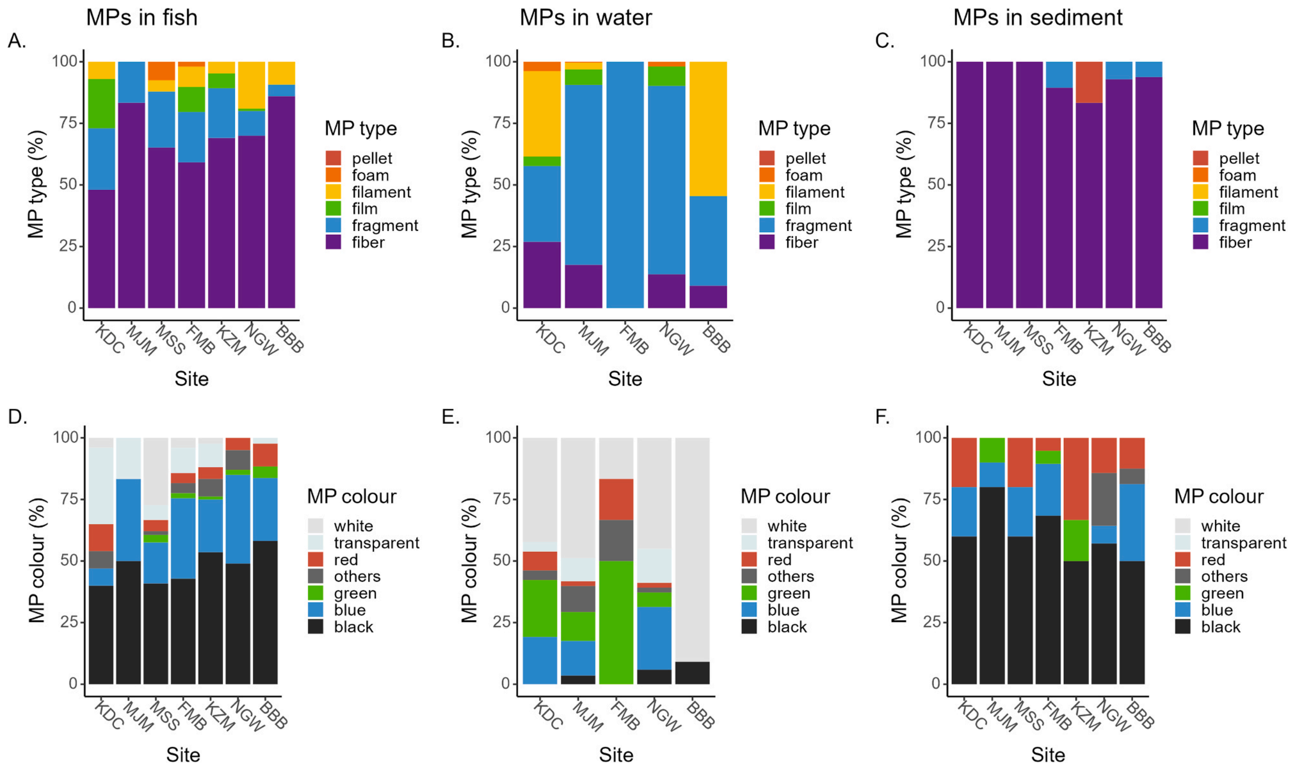


Fig. 3. Type (A-C) and colour (D-F) percentage distributions of MPs recovered from fish (*Lethrinus harak*, A and D), nearshore surface water (B and E, Nchimbi et al., 2022a) and seabed sediment (D and F, Nchimbi et al., 2022b) from sites sampled along the Tanzanian coast. For site abbreviations refer to Table 1.

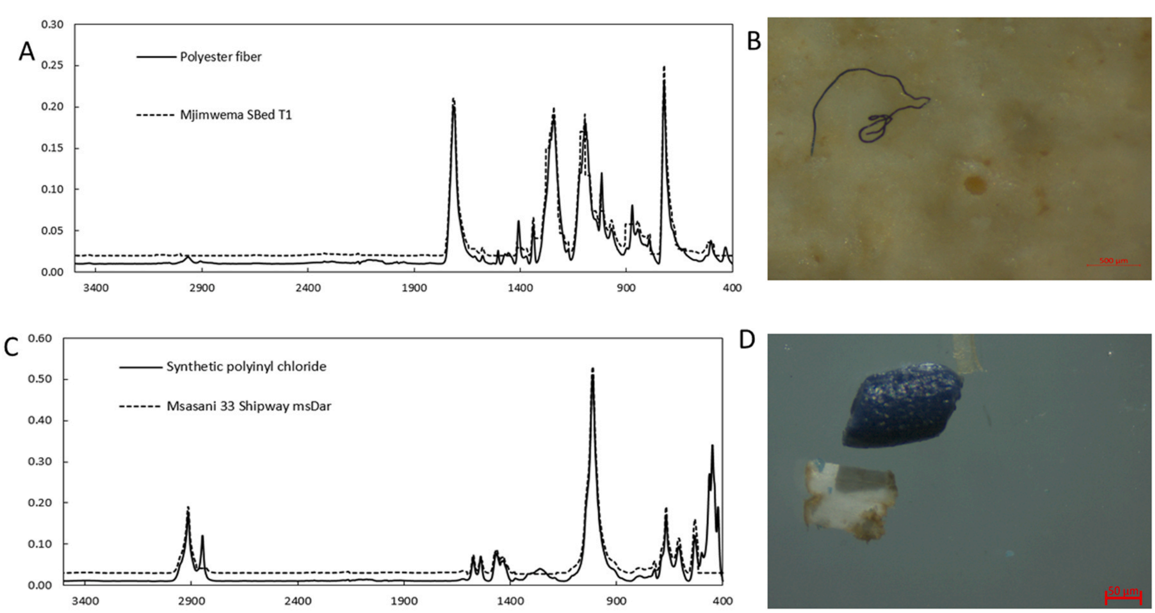


Fig. 4. Examples of MPs recovered from digestive tracts of *Lethrinus harak* and associated ATR-FTIR spectra. (A) blue polyester fiber from an individual from Mjimwema and (B) polyvinyl chloride fragment from an individual from Msasani. Dashed spectra are samples and solid spectra are reference materials.

East African coast and others from freshwaters (Biginagwa et al., 2016, Adeogun et al., 2020). Perhaps the most relevant comparison is to the West African study performed off the coast of Ghana (Adika et al., 2020) in which MPs were found in the gastrointestinal tracts of all 155 fish sampled from 3 species *Sardinella maderensis*, *Dentex angolensis* and *Sardinella aurita* with MPs individual^{-1} of 40.0 ± 3.8, 32.0 ± 2.7 and 25.7 ± 1.6, respectively. The levels of MPs in fish from Adika et al. (2020) exceed that of *L. harak* in the present study.

Further afield the occurrence of MPs in different fish species has been determined as 19.8 % of fish from the Portuguese coast (Neves et al., 2015), 41 % of sampled fish from the Turkish waters of the Mediterranean Sea (Güven et al., 2017) and 58 % from the Balearic Islands (Nadal et al., 2016). This latter study was on the semipelagic species *Boops boops* (Order: Perciformes, Family: Sparidae) and thus shares the trait of partial benthic and partial pelagic living with *L. harak*. MPs were observed in 57.8 % of all sampled *B. boops* (range of 42.22–80.43 % amongst 4 sampling locations) with a mean ingestion of 3.75 ± 0.25 MPs individual^{-1} (Nadal et al., 2016). MP abundance in *B. boops* would appear to be markedly higher than in *L. harak*, but with the exception of Mjimwema (FO%=17.1) MP occurrence in *L. harak* is in range of the values reported for *B. boops*. Whilst the Order of Perciformes (perch-like fish) is the most investigated for MP ingestion (Hossain and Olden, 2022), the family Lethrinidae 'Emporer fishes' has not been well studied. Of the 9 demersal *Lethrinus reticulatus* individuals sampled in the Gulf of Mannar and Palk Bay, Southeast coast of India none contained MPs in their digestive tracts (James et al., 2021). *Lethrinus* spp. collected from an urban coastal environment in Fiji had an average abundance of 16.4 ± 6.0 MPs individual^{-1} from one of the studied sites with one individual having 68 MPs in its digestive tract (Ferreira et al., 2020).

In the present study, fibers were the most prevalent MP type making up 64.7%. The dominance of fibers as the most abundant MP type is well founded in the literature (Neves et al. 2015; Nadal et al., 2016; Bellas et al., 2016; Arias et al., 2019; Ferreira et al., 2020). The reason for fibers being so common has been attributed to their diverse origin, such as the degradation of clothing items, furniture, and fishing gear. However, recent studies have highlighted that not all fibers are of synethetic origin (e.g. acrylic, nylon, and polyester), and natural fibers (e.g. cotton, wool or viscose) may be present within environmental samples (KeChi-Okafor et al., 2023). Indeed, 55 % of 2403 microfibers characterized from water samples from the Kenyan and Tanzanian coast were natural fibers (KeChi-Okafor et al., 2023). The presence of natural fibers in our samples cannot be ruled out, although none were identified using micro-FTIR spectroscopy, and the generic terminology of anthropogenic fibers may be more applicable.

In the context of the global mosaic of piscine MP ingestion, the present study fills important gaps both geographically on the East African Coast and with an underrepresented taxanomic family. Whether *L. harak* is a reliable indicator of environmental MP pollution is discussed in the next section.

3.2. Assessing Lethrius harak as a biomonitor of environmental MP pollution

3.2.1. Water and sediment levels used in the present study

Data from our previous studies describing MP levels in nearshore surface waters (Nchimbi et al., 2022a) and seabed sediments (Nchimbi et al., 2022b) were used in this study to determine whether the occurrence, abundance and types of MPs in *L. harak* reflect those found in different envrionemental compartments. However, from each of our previous studies in which sample collection was conducted in December 2019, only a portion of the data was used in order to match the landing sites and relevant environmental compartments that the fish inhabit. Thus a brief description of the applicable data is warranted. The full study of nearshore surface waters contained 8 sampling sites, but only 5 of those overlapped with the fish landing sites from where *L. harak* were collected. Across these 5 sites, MP concentrations ranged from 0.011 to 0.45 MPs m^3 (Table 2). Type and colour data from these 5 sites is shown in Fig. 3B and E, respectively, showing the dominance of fragments (31–100%) > filaments (0–55%) > fibers (0–27%), and white MPs (42–91%) over green (0–50%), blue (0–25%) and red (0–17%) MPs.

The study investigating the presence of MPs in beach and seabed sediment showed that beach sediments were far more polluted; 83.5% of all MPs recorded in the study were found in beach samples and 16.5% in the seabed sediments (Nchimbi et al., 2022b). However, since *L. harak* does not occupy the beach environment, the beach MPs were not included in the present study. MP concentrations in seabed sediments across the seven sampling sites used in this study ranged from 44 to 211 MPs Kg^{-1} dry weight (Table 2). Fibers were by far the most dominant MP type (83–100% of MPs across all sites) and the only other MP types found were fragments (6–10% at 3 sites) and pellets (17%) at Kizimkazi (Fig. 3C). The colour distribution of MPs in seabed sediments was dominated by black MPs which comprised at least 50% of MPs at each site (50–80%, Fig. 3F). Red (0–33%) and blue (0–31%) MPs were well represented at most sites.

3.2.2. Are fish biometrics related to MP occurrences and abundances?

L. harak lengths and weights across all sites were largely comparable (Table 2), but at Fumba and Nungwi the mean length and weight were significantly lower than at the other 5 sites (one-way ANOVA with post-hoc Tukey test, $p<0.001$, Fig. 5). Owing to the non-normality of the data, the relationship between MP abundance (MP individual^{-1}) and length and weight, respectively, were investigeted using non-parametric Spearman rank correlations. There was no significant relationship for either length ($\rho= -0.09$, $p=0.09$) or weight ($\rho=0.07$, $p=0.18$) meaning that the abundance of MPs in the individual was not a function of the metrics of fish size.

Our results agree with several other studies that describe no significant correlation between fish biometrics and MPs abundance (Güven et al., 2017; Sun et al., 2019; Kalaiselvan et al., 2022). However, several other studies have found significant positive correlations between MP ingestion and fish length and/or weight (Pazos et al., 2017; Horton et al., 2018; Pegado et al., 2018). A positive correlation may be related to a larger body size requiring more food which may increase the likelihood of incidental MP ingestion (Horton et al., 2018). Differences in fish traits, such as feeding habit, are also likely to, in part, explain the differences between studies.

3.2.3. Do MP levels in Lethrius harak reflect environmental concentrations?

Due to small sample sizes (n=5 for nearshore surface water, and n=7 for both seabed sediment and fish) and non-normality of the data, the relationships between MPs in fish (both occurrence (FO%) and abundance (MPs individual^{-1})) and in the environment, nearshore surface water and seabed sediment respectively, were investigated using Spearman rank correlations (Fig. 6). There was no significance in any of the tested relationships, as follows: FO% and MPs in nearshore surface water $\rho = -0.20$, $p = 0.78$ (Fig. 6A), FO% and MPs in seabed sediment $\rho = -0.47$, $p = 0.29$ (Fig. 6B), MPs individual^{-1} and MPs in nearshore surface water $\rho = -0.20$, $p = 0.78$ (Fig. 6C), and MPs individual^{-1} and MPs in nearshore seabed sediment $\rho = -0.68$, $p= 0.11$ (Fig. 6A).

Thus, our results show that neither MP occurrence nor abundance are linked to MP concentrations in either surface waters or seabed sediments. The relationship between abiotic and biotic compartments is not often tested for fish species (Verlaan et al., 2019). There was no correlation in MP concentrations between sediments and surface waters with four fish species from the southern shores of Iran (Agharokh et al., 2022) nor from the study performed in Poyang Lake (China, Yuan et al. 2019). MP concentrations in wels catfish (*Silurus glanis*) did not correlate to MP levels in water or sediments from Ticino River (North Italy) (Winkler et al., 2022). From the same study, MP level from invertebrate hydropsychid larvae also did not correlate with MP levels in the abiotic compartments. In much the same sampling area of the Dar es Salaam coast, MP concentrations in the cockle (*Anadara antiquata*) were not representative of the sediments they inhabit (Mayoma et al., 2020). However other studies describe a positive relationship between environmental MP concentration and those found in sampled biota for some compartments i.e. sediments (Nel et al., 2018; Zhang et al., 2020). Again differences between species, their feeding modes and behaviours are also relevant factors in explaining differences between studies.

3.2.4. Does the type and colour of MP found in Lethrius harak reflect the MPs found in the environment?

Owing to non-normality of the data, the percentages of MP type and colour (combined across sites) for nearshore surface water, seabed sediments and *L. harak* were transformed into ranks. Ranks were assigned with the highest frequency receiving rank 1, second highest receiving rank 2 and so on. A two-way anova was then performed on the rank transformed data, investigating the concordance between MP types and colours between the fish and the two environmental compartments (Fig. 7). The MP contents of fish digestive tracts better reflected MPs found in seabed sediment than in nearshore surface water, in terms of both type and colour. There was rank order concordance between the

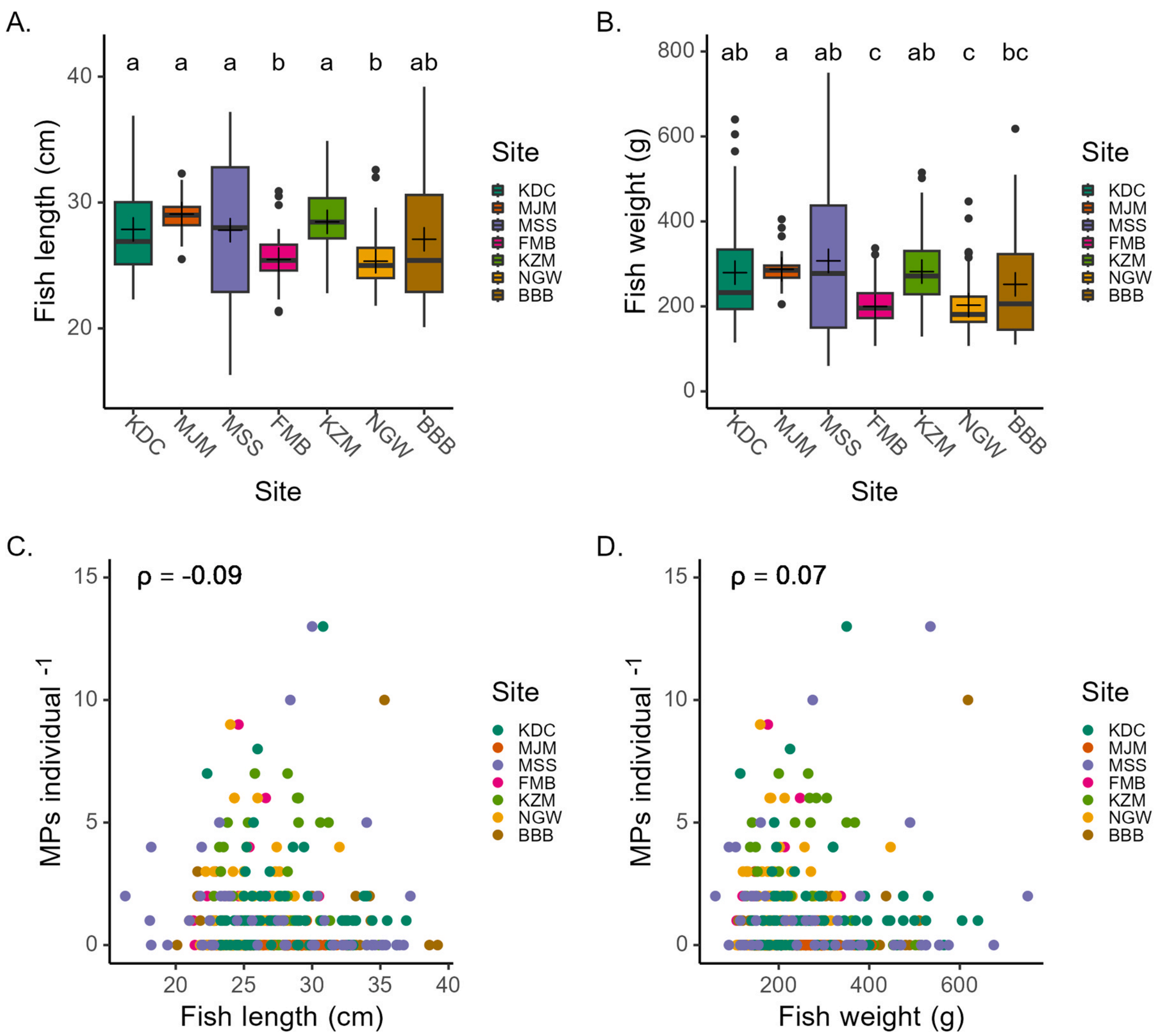


Fig. 5. Length (A, in cm) and weight (B, in g) of individuals collected from the 7 sites along the Tanzanian coast (for site abbreviations refer to Table 1). Boxplots display first quartile, median, third quartile, maximum (upper whisker) and mean (+). Observations more than 1.5 times the interquartile range below the 1st or above the 3rd quartile are considered outliers and are shown with black points. Significant difference between sites are indicated with different letters (one-way ANOVA with post-hoc Tukey test, $p<0.001$ for both length and weight). The relationship between MP abundance in fish from the different sites (MPs individual^{-1}) and length (C) and weight (D), respectively, were investigated using non-parametric Spearman correlations. For both length and weight, there was no monotonous relationship (length: $p = 0.09$, $\rho = -0.09$; weight: $p = 0.18$, $\rho = 0.07$).

two most common MP types namely fibers and fragment (Fig. 7A) which in fish represented >70% of MPs in fish and >80% of MPs in seabed sediments at each site (Fig. 3). Conversely, the prevalent MP types in nearshore surface water were (1) fragments, (2) filaments and (3) films (Fig. 7A). Similarly, for MP colours black and blue were most commonly seen in seabed sediments and fish, whereas white, green and blue MPs were more commonly found in nearshore surface waters (Fig. 7B). Overall, MPs display a grossly similar pattern in fish and sediment, with black being the most common colour from both sources, and fiber being the most common type.

The profile of MP types and colours between surface water and sediment appear to be quite different as has been described previously (Tien et al., 2020) which suggests that sediment loads may not result solely via deposition from the water column, but also the characteristics of the MPs themselves, such as shape, density and degree of biofouling (Horton et al., 2018; Tibbetts et al., 2018; Tien et al., 2020). Whilst some studies report that MP types in fish are not similar to either water or sediment MPs (Tien et al., 2020), in the case of *Lethrinus* spp collected from the coastal waters of Fiji, MPs in the fish reflected those found in the sediment, particularly with the dominance of fibers (Ferreira et al., 2020). MP types and colours also positively correlated between fish and sediment sampled from the Ma'an Archipelago, Shengsi, China, but not between fish and water (Zhang et al., 2020). A possible explanation for the difference between studies could again be the feeding behaviour of the sampled species with generalists exhibiting greater concordance with environmental MP profiles than selective feeders. MPs in the digestive tract of the semi-pelagic generalist *L. harak* may better reflect the profile of MPs in the sediment compared to surface water as it incidentally ingests MPs as they pass through the water column to seabed floor or feeds on species (molluscs, crabs and echinoderms) that reside on the sediment.

3.3. Relevance of *Lethrius harak* as a biomonitor of environmental MPs

In general terms suitable organisms for the monitoring of pollutants should be abundant, widespread, and long-lived (Jones and Kaly, 1996). *L. harak* presents as a promising candidate to monitor of MP pollution along the East African coast. It is semi-pelagic, non-migratory and has a diverse diet. However, on the criteria that MPs in the fish increase with size/age (weight and length) and reflect environmental concentrations and the types of MPs in the abiotic compartment, *L. harak* lacks reliability. Fish length and weight were not accurate predictors of MPs

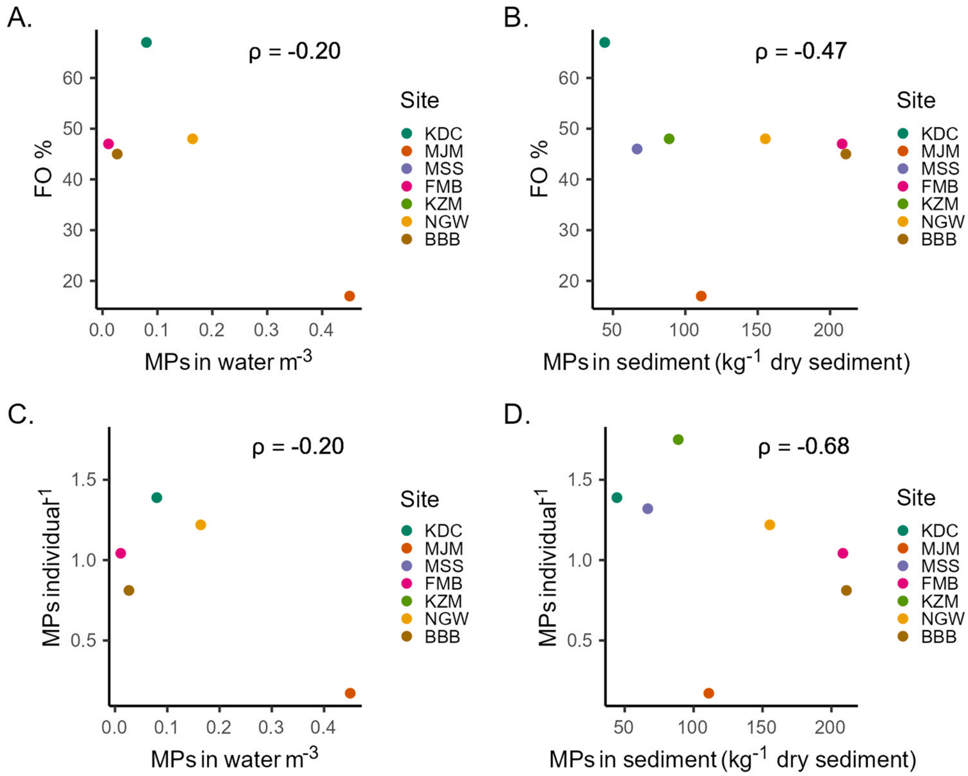


Fig. 6. Relationships between MPs in fish and in the environment determined by Spearman rank correlations owing to non-normality of the data and small sample size. There were no significance between any of the tested relationships: (A) FO% and MPs in nearshore surface water $\rho = -0.20$, $p = 0.78$, (B) FO% and MPs in seabed sediment $\rho = -0.47$, $p = 0.29$, (C) MPs individual^{-1} and MPs in nearshore surface water $\rho = -0.20$, $p = 0.78$, and (D) MPs individual^{-1} and MPs in nearshore seabed sediment $\rho = -0.68$, $p = 0.11$.

found in the digestive tract (Fig. 5) and neither was the MP concentrations found in nearshore surface waters or seabed sediments (Fig. 6). MPs in the *L. harak* digestive tracts exhibited better rank order concordance with MPs found in sediment particularly with the dominance of fibers and black MPs (Fig. 7).

However, the broader discussion of whether any fish species can reliably be used as a proxy for MP pollution remains relevant. There is a wealth of literature on MPs in fish globally, but the majority of these studies are from a single sampling campaign often without considering the environmental exposure concentrations (Verlaan et al., 2019). Thus from the majority of such studies it is not possible to draw a conclusion of a particular species being a relevant biomonitor. Where abiotic and biotic compartments are concurrently sampled, a correlatory relationship is often absent. However, the case for piscince biomonitors for regulatory frameworks has been made (MSFD Technical Subgroup on Marine Litter, 2013, De Witte et al., 2022) and certain species traits such a non-migratory, generalist feeder and long-lived may enhance a species' relevance in this capacity. Whilst *L. harak* would appear suitable according to these traits our analysis indicates that this is not the case.

4. Conclusion

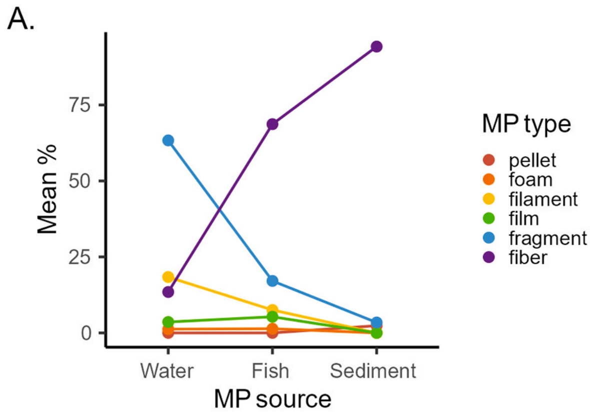
In conclusion, MPs were found in the digestive tracts from *L. harak* at all landing sites along the Tanzanian coast. Whilst both MP occurrence and abundances varied spatially, there was no significance to the relationship between MP occurrence and MP abundance. In keeping with other studies, fibers and black MPs were the most common type and colour, respectively. Correlating the MPs in the fish to those in the nearshore surface waters and seabed sediments showed there was no strong correlation linking environmental and biotic concentrations. However, in terms of type and colour MPs in fish did reflect those in the sediment better than those in surface waters. Like many piscine MP studies, this one gives only a 'snapshot in time' of MP pollution in this region and longitudinal studies are required to fully understand the prevalence of MPs. Indicator species are useful tools for monitoring environmental contaminants and whilst *L. harak* has some promising ecological characterises being semi-pelagic, non-migratory and a generalist macro-benthivore, overall, it appears not to be a reliable biomonitor of plastic pollution. This study is particularly prescient as Tanzania, and Africa in general, engages with the issue of MP pollution and serves to provide a baseline for future work.

CRediT authorship contribution statement

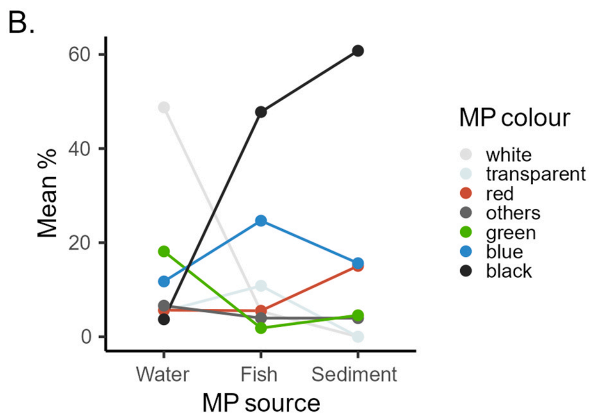
Amina Nchimbi: Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Daniel Shilla:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Charles Kosore:** Writing – review & editing, Methodology. **Dativa Shilla:** Writing – review & editing, Validation, Funding acquisition. **Yvonne Shashoua:** Writing – review & editing, Validation, Funding acquisition, Data curation. **Christina Sørensen:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation. **Farhan Khan:** Writing – review & editing, Writing – original draft, Supervision, 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.



	MP source		
MP type	Water	Fish	Sediment
fiber	a	b	b
fragment	a	ab	b
film	a	a	a
filament	a	ab	b
foam	a	a	a
pellet	a	a	b



	MP source		
MP colour	Water	Fish	Sediment
black	a	b	b
blue	a	a	a
green	a	b	ab
others	a	a	a
red	a	ab	b
transparent	ab	a	b
white	a	b	b

Fig. 7. Rank order concordance between the (A) type and (B) colour of MPs found within *L. harak* and nearshore water and seabed sediments from the same location. Percentages of MP type and colour (described in Fig. 3) were transformed to ranks (i.e. highest frequency received rank 1, second highest received rank 2 etc.). A two-way anova (with Tukey post-hoc test) was performed on the rank transformed data, investigating the effect of MP source (water, fish or sediment), combined with the colour or type. Significant difference between the sources are indicated with different letters the adjacent tables for type and colour respectively. The types and colours of MPs display a grossly similar pattern in fish and seabed sediment, with less concordance between the MPs found in fish and nearshore waters.

Data Availability

Data will be made available on request.

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