Abundance of microplastic pollution and the impact of land-use and ocean currents on plastic pollution in the Maldives.

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Abstract

Approximately 4.8 to 12.7 million tonnes of plastics enter the marine environment annually contributing to 5 trillion pieces of plastic in the global oceans and surface waters. Plastics in the marine environment can exist as macro, meso, and microplastics and due to its durability and longevity, once they are introduced into the environment, it can persist and be distributed globally by ocean currents and winds. Regardless of the high abundance of plastic pollution in the environment and its various negative impacts on marine ecosystems, human health, and the economy of countries such as the Maldives that depend on biodiversity-based economic sectors such as tourism and fisheries, research regarding causes of plastic pollution and sources of microplastics and its abundance is scarce. This study aims to quantify microplastic pollution in the Maldives and to identify sources of plastic pollution by investigating the effects of land-use and ocean currents on plastic pollution in the Maldives.

A combination of field and laboratory methods was used to collect beach sediment samples, log macro and mesoplastics and to isolate, identify and quantify microplastic pollution on three different islands of varying land-use intensity (Industrial, Urban and Rural) in the Maldives. Additionally, Geographic Information System (GIS) was used to map ocean currents and identify the influence of ocean currents on microplastic distribution on the Maldivian islands.

The results of this study shows that there is a significant level of microplastic pollution at the studied islands: K. Thulusdhoo, K. Villingli and B. Dhonfanu. Additionally, it also showed that the pollution levels at these three islands were higher compared to other coastal areas in the Indian Ocean, as well as other regions of the world. Furthermore, the results showed that the microplastic abundance at Thulusdhoo, an industrial island, was statistically different to both Dhonfanu which is a rural island and the urban island, Villingili proving that land-use influences plastic pollution. However, the difference between the Urban and Rural islands, despite the Urban island having a higher microplastic abundance was not significant, indicating that other factors such as ocean currents also influence microplastic abundance. The ocean current direction and speed along with the difference in the shape and size of microplastic found on the islands proves that ocean currents were also an influencing factor in microplastic abundance on the Maldivian islands.

(9985 words)

List of abbreviations

PP = Polypropylene
PE = Polyethylene
HDPE = High density polyethylene
LDPE = Low density polyethylene
PS = Polystyrene
EPS = Expanded polystyrene
PES = Polyester
PET = Polyethylene terephthalate
PA = Polyamides
PU = Polyurethane
PVC = Polyvinyl chloride
GDP = Gross domestic product
RPM = Rotations per minute
RCF = Relative centrifugal force
NaCl = Sodium chloride
$ZnCl_2$ = Zinc Chloride
NaI = Sodium Iodide
H_2O_2 = Hydrogen Peroxide
UV = Ultraviolet
FTIR = Fourier Transform Infrared
FITC = Fluorescein isothiocyanate
DAPI = 4’,6-diamidino-2-phenylindole
Cy3 = Cyanine-3
SMOC = Surface and Merged Ocean Currents
K = Kaafu*
B = Baa*
F = Faafu*
Lh = Lhaviyani*

*Dhivehi alphabet letters given to atolls

Contents

1. Introduction

Plastic usage has become very common across various aspects of life such as in construction, technology, and healthcare, but not limited to these areas. Due to its properties such as cheapness, durability, low weight and being easily disposable, which makes it so useful, also means that it can be discarded unnecessarily and persist in nature if not managed properly after use (Horton, 2022). Despite its ubiquitousness in the environment, from the most remote mountains to the deepest trenches in the ocean, and its serious threats in ecosystems (Chiba *et al.*, 2018), existing research regarding microplastic sources, distribution, fate, and impacts is scarce (Horton, 2022). Moreover, the lack of standardisation in microplastic research disables comparison between the limited studies (Horton, 2022). This section includes the location and context of study along with the scientific background on global plastic pollution levels, more specifically microplastics and pollution in the Maldives. Additionally, the influence of ocean currents on plastic distribution and impacts of plastic pollution on the marine environment and economy of Maldives, along with published research, knowledge gaps and the direction of this research will also be highlighted.

1.1. Scientific Background

1.1.1. Plastic pollution

Worldwide production and use of plastics have increased since the 1950s and has been used in different applications due to its durability (Lehtiniemi *et al.*, 2018) with the global production surpassing 300 million tonnes per year since 2014 (Law, 2017; Lebreton *et al.*, 2017). Due to inadequate waste management and low-recycling rates, a significant volume of the plastic produced enters, persists and is ubiquitous in the marine ecosystems including the shoreline, seabed, sea surface and oceans. Plastics can enter the environment from various pathways, such as beach littering by locals and tourist activities, rivers, atmospheric transport and directly at sea from fishing, aquaculture, and shipping activities (Garcés-Ordóñez, 2020; Lebreton *et al.*, 2017). Approximately 4.8 to 12.7 million tonnes of plastics enter the marine environment annually (Duncan *et al.*, 2019; Eriksen *et al.*, 2014; Jambeck *et al.*, 2015) which makes up 80 to 85% of the marine litter (Auta *et al.*, 2017) contributing to 5 trillion pieces of plastic in the global oceans and surface waters (Duncan *et al.*, 2019; Eriksen *et al.*, 2014; Jambeck *et al.*, 2015). The most common polymers in plastic waste are polypropylene (PP), low density polyethylene (LDPE), high density polyethylene (HDPE), polyethylene terephthalate (PET), polystyrene (PS), expanded polystyrene (EPS), polyester (PES), polyamides (PA), polyurethane (PU) and polyvinyl chloride (PVC) (Andrady, 2017; Castelvetro *et al.*, 2021; Gewert *et al.*, 2015). Plastic particles can be classified by size into macro (>25 mm), meso (25-5 mm), and micro (<5 mm) plastics (Egessa *et al.*, 2020). A substantial amount of the surface plastics are microplastics making up 92.4% of the total (Barnes, 2019). Microplastic pollution was first identified in the 1970s and was not acknowledged scientifically until the beginning of the 21st century (Patti *et al.*, 2020; Thompson, 2004).

1.1.2. Microplastics

Microplastics can be either primary or secondary (Patti *et al.*, 2020; Thompson, 2004). Primary microplastics are those which are produced for certain industrial and domestic use such as exfoliating facial scrubs, synthetic clothing, cosmetics, toothpastes, insect repellents and resin pellets or nurdles used in the plastic industry as raw materials for production of products such as food packaging (Atugoda *et al.*, 2021; Auta *et al.*, 2017; Cássio *et al.*, 2022). Primary microplastics can be introduced into the environment through wastewater treatment plants and industrial drainage systems (Auta *et al.*, 2017).

Secondary microplastics are formed from breakdown of larger plastic pieces by chemical, physical, biological, or mechanical processes. The primary processes responsible for secondary microplastic production are breakdown by photo-degradation and mechanical abrasion (Andrady, 2011; Thushari & Senevirathna, 2020). Exposure of larger plastic debris to sunlight with ultraviolet (UV) radiation leads to oxidation of polymers and breakdown of the structural integrity. These plastics are further subjected to physical and mechanical forces such as wave abrasion and turbulence producing smaller and rounded plastic particles (Thushari & Senevirathna, 2020). Degradation of plastics can be affected by oxidative characteristics of the atmosphere and hydrolytic properties of seawater such as salinity; higher salinity and lower temperatures reduces photo-degradation, increasing persistence (Cole *et al.*, 2011; Thushari & Senevirathna, 2020).

1.1.3. Ocean currents in the Indian ocean

Once introduced to the environment, plastics can be dispersed by surface ocean currents due to its buoyancy and durability and washed ashore where beaches act as plastic debris sinks (Eriksen *et al.*, 2014). Monsoons drive wind and ocean surface currents that influences movement and beaching of microplastics in the Northern Indian Ocean. However, wind and ocean currents have less effect in the Southern Indian Ocean (Mheen *et al.*, 2020). A significant proportion of the worlds' ocean plastic enters the Indian Ocean (Pattiaratchi *et al.*, 2022) with up to 20% of riverine plastic and 15% of all coastal plastic (Jambeck *et al.*, 2015; Lebreton *et al.*, 2017). Additionally, it is predicted that the Indian Ocean contains the second highest amount of marine plastics following the North Pacific Ocean (Eriksen *et al.*, 2014). The largest plastic input into the Northern Indian Ocean is from the Bay of Bengal; hence, countries bordering the Bay of Bengal, specifically, Myanmar, Bangladesh, Malaysia, India, Sri Lanka, Pakistan, Indonesia, Thailand, and the Maldives are heavily affected by beaching plastics (Figure 1).

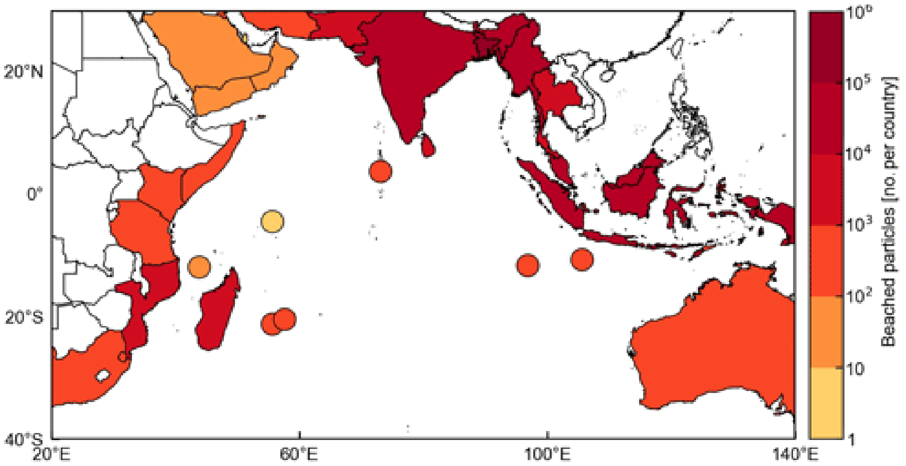

Figure 1. *Countries in the Indian Ocean most impacted by beached plastics (Pattiaratchi et al., 2022).*

Maldives receives a relatively large percentage of the ocean plastics despite not having its own riverine plastic source, as both the Southwest and Northeast Monsoon currents flow past the Maldives in reversing directions throughout the year (Mheen *et al.*, 2020), carrying plastics between the Bay of Bengal and the Arabian Sea (Pattiaratchi *et al.*, 2022). During the Northeast Monsoon, currents flow from Bay of Bengal, westwards past Sri Lanka into the Arabian sea and vice-versa in the southwest monsoon (Figure 2).

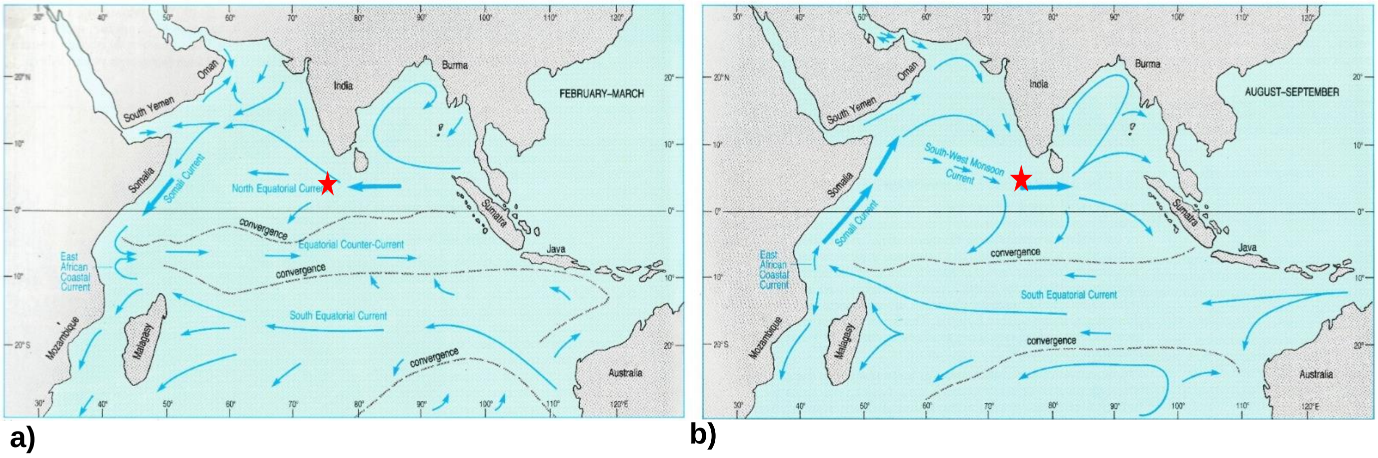

Figure 2. *Ocean currents in the Indian Ocean* ***a)*** *southwestward ocean currents in northeast monsoon between January and March* ***b)*** *northeastward ocean currents in southwest monsoon between May and November (Colling, 2001).* ★*- Maldives*

Distribution of microplastics by ocean currents in the Indian Ocean was also shown in a study carried out by Pattiaratchi *et al.* (2022) by conducting a tracking stimulation which stated that 40% of the nurdles from the X-Press Pearl ship accident off the coast of Sri Lanka will beach in countries in the northern Indian Ocean such as the Maldives.

1.1.4. Pollution in the Maldives

Maldives was ranked the fourth largest producer of mismanaged waste in 2019 (Barnes, 2019; Patti *et al.*, 2020). Total plastic footprint of the Maldives accounts for 12% of the country’s total waste and the plastic waste constitutes approximately 43,134 tons per year, with PET bottles making up 10% of this plastic waste (MOPA, 2021). 143 million PET bottles are locally produced annually. Surveys carried out estimates that 57 million plastic bottles of water are consumed per year by households in the Maldives, suggesting high levels of single-use plastics usage (MOPA, 2021).

Research carried out in Lhaviyani (Lh.) Atoll Naifaru island (Figure 3), an inhabited island in the Maldives showed that the sites had one of the highest concentrations of microplastics found anywhere globally (Patti *et al.*, 2020). The concentration of microplastics on Naifaru (55 - 1127.5 microplastics/kg), as well as inhabited islands in Faafu (F.) Atoll (197

- 822 particles/ kg) studied by Saliu *et al.* (2019), both had higher microplastic pollution levels than in Tamil Nadu, India (3 - 611 particles/kg) (Patti *et al.*, 2019).

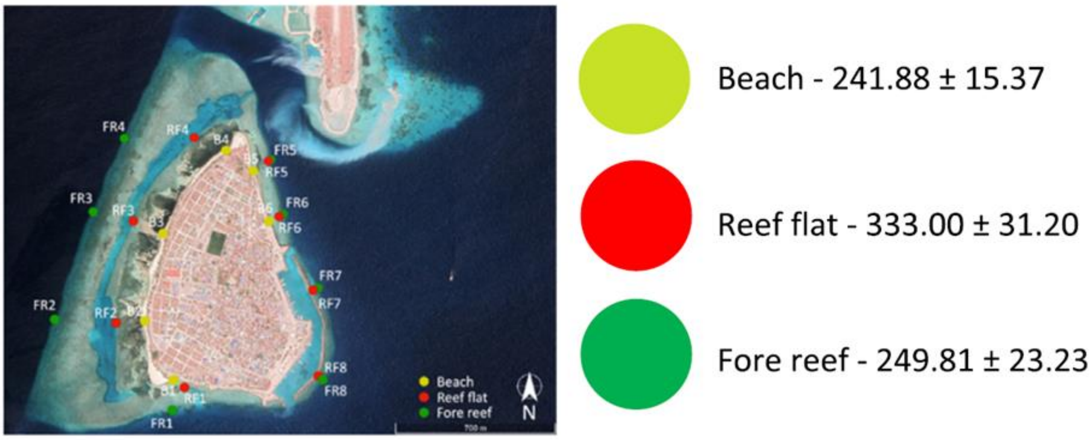

Figure 3. *Microplastic pollution abundance in Naifaru measured in particles/kg of sand (Patti et al., 2020).*

1.1.5. Effects of plastic pollution

Plastic pollution can have various negative impacts on marine ecosystems. Studies state that plastics are mistaken for food and ingested by over 220 marine species including bivalves, turtles, and fish (Shiyana *et al.*, 2022). Plastic waste kills up to 100000 mammals and sea turtles, and 1 million seabirds per year (Miller and Spoolman, 2012). Macroplastics can harm marine organisms by entanglement and ingestion (Ling *et al.*, 2017). Annual review for admission at the Olive Ridley Project (2020) Rehabilitation Centre shows that the main reason for admission was entanglement (Figure 4). Plastic pollution is also one of the main threats for Hawksbill turtles which are classified as critically endangered on the Maldives National Red List (Köhnk, 2022). Ingestion of plastics can lead to loss of mobility, decreased growth, reduced reproduction and death, impacting biodiversity (Thushari & Senevirathna, 2020). Additionally, plastics can cause leaching of harmful substances into the digestive tract reducing immunity and survival (Browne *et al.*, 2013; Imhof *et al.*, 2017). It can also act as vectors of harmful microorganisms and invasive species (Imhof *et al.*, 2017; Kirstein *et al.*, 2016) that can modify ecosystem composition and structure (Thushari & Senevirathna, 2020).

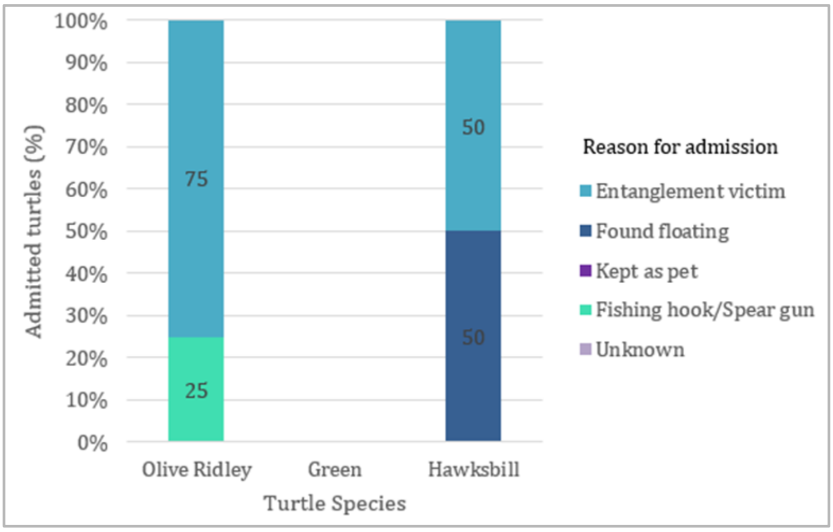

Figure 4. *Reasons for turtle admission at the Olive Ridley Project Rehabilitation Centre in the Maldives, showing that entanglement was the reason for 75% of the Olive Ridley and 50% of the Hawksbill admissions (Olive Ridley Project, 2020).*

Moreover, biomagnification of plastics can impact higher trophic levels including humans (Ling *et al.*, 2017). Toxic chemicals and metals in or absorbed by plastics can also accumulate causing adverse health impacts (Thushari & Senevirathna, 2020). FAO states that fish contributes over 20% of the animal protein in a daily diet in countries such as the Maldives and Sri Lanka, leading to high levels of plastic pollution causing adverse health impacts (Kapinga & Chung, 2020).

Plastic pollution decreases aesthetic value and ecosystem health due to biodiversity loss which can be economically threatening for countries such as the Maldives that economically depend on tourism and fisheries (Thushari & Senevirathna, 2020). Tourism consists of 24.4% of GDP in 2018 (Kapinga & Chung, 2020). Due to the impact of plastic pollution on the ecosystem, quality and quantity of fish catch has decreased, impacting income and available food in countries such as the Maldives (Kapinga & Chung, 2020). Additionally, according to IUCN (2009), 71% of national employment and 89% of GDP depends on biodiversity-based sectors that can be impacted by plastic pollution (Figure 5). Therefore, plastic pollution has various negative impacts on the environment, human health and economy.

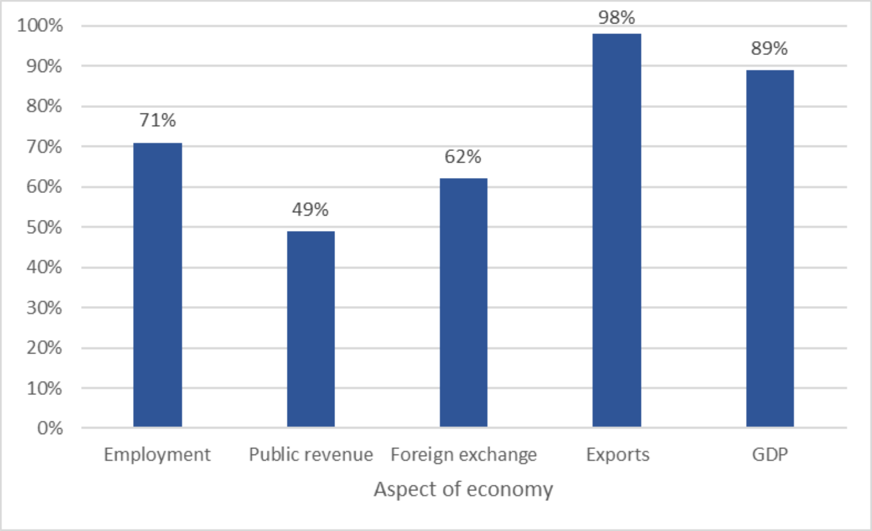

Figure 5. *contribution (%) of biodiversity-based sectors to different aspects of Maldivian economy (IUCN, 2009).*

1.2. Existing research and Rationale

Existing research on plastic pollution is scarce despite its ubiquitousness and impact on marine ecosystems, human health, and economy. Literature available is inconsistent due to different sampling protocols and units used in quantification, making it problematic to compare quantified plastic pollution in the Maldives and identifying the main sources (Corinaldesi *et al.*, 2022). Study carried out in Naifaru (Patti *et al.*, 2020) was done by sampling sediment from the beach, fore reef, and reef flat of the island and conducting analysis by density separation using zinc chloride ($ZnCl_2$) and a Stereo Zoom microscope. Meanwhile, the study done in F. Atoll (Saliu *et al.*, 2018) tested sediment and seawater samples from two sides of the atoll and performed density separation with sodium chloride (NaCl) and sodium iodide (NaI) . Both studies also had other differences in sample handling and preparation techniques. This, therefore, suggests the need for research on macro, meso and microplastic abundance on beaches, and how it is affected by ocean currents and land-use to enable identification of sources of pollution.

1.3. Study site

This study was carried out in the Maldives with samples collected from three different islands in Baa (B.) and Kaafu (K.) atolls (Figure 6), intentionally selected for their different land-uses, to enable identification of effects of land-use on microplastic abundance and the main sources of plastic pollution in the Maldives. The samples were collected from, B. Dhonfanu (Figure 6.a) which is a rural island, K. Thulusdhoo (Figure 6.b.) which has industrial zones and K. Villingili (Figure 6.c.), an urban island located in the greater Male’ area, capital of Maldives (The President's Office, 2022).

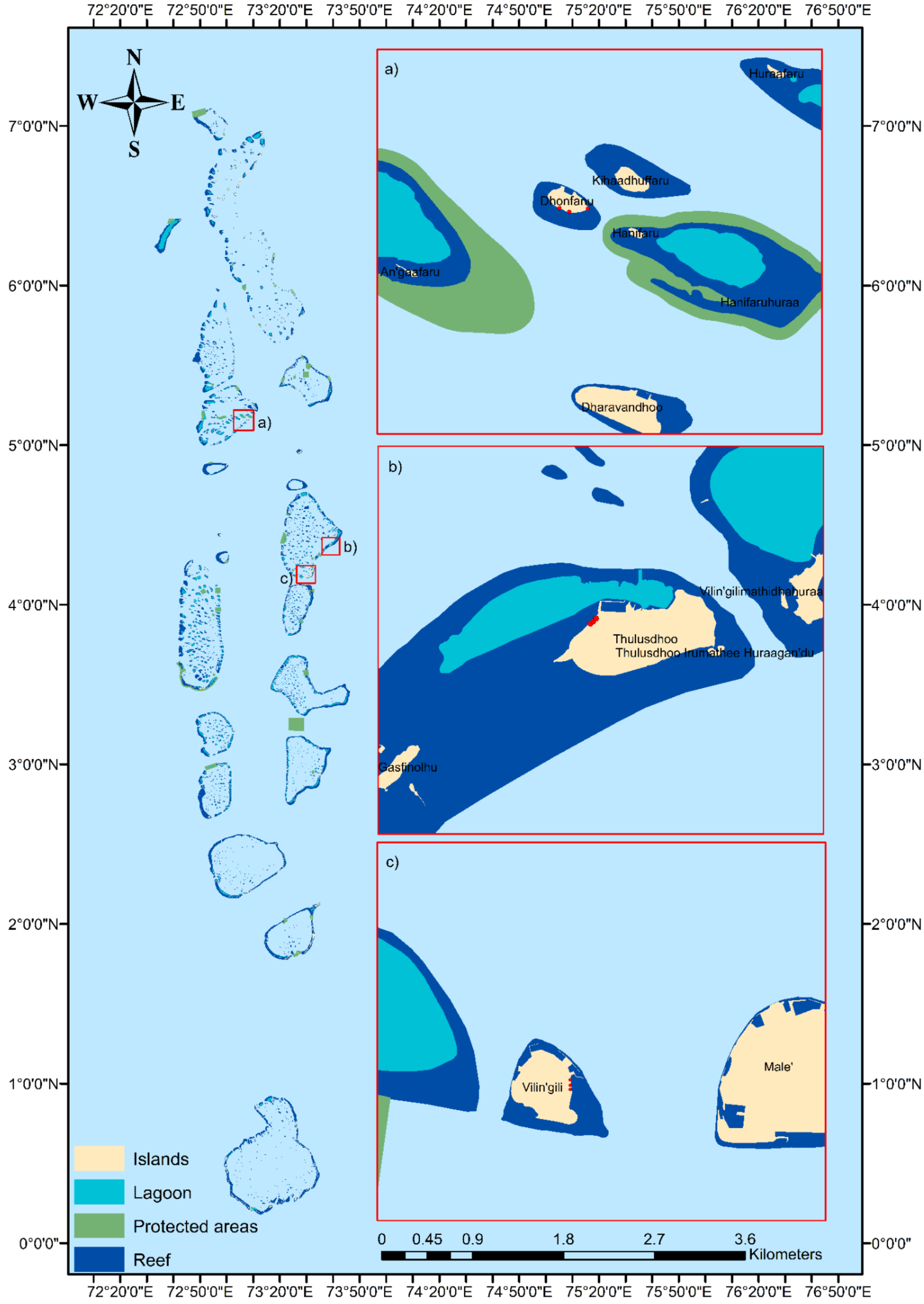

***Figure 6**. The location of the study with sampling sites in central Maldives **a)**Dhonfanu, **b)**Thulusdhoo and **c)**Villingili (created using datasets from Maldives Land and Survey Authority, 2022).*

2. Aims, Hypotheses and Objectives

2.1. Aims

To quantify microplastic pollution in the Maldives and to identify sources of plastic pollution by investigating the effects of land-use and ocean currents on plastic pollution in the Maldives.

2.2. Hypotheses (H) and Objectives (O)

Hypothesis 1 (H1) - There is a significant level of microplastic pollution on the Maldivian islands.

- H1:O1 - collect sand samples from different islands for microplastic analysis.
- H1:O2 - analyse and quantify the microplastic abundance in different sand samples.

Hypothesis 2 (H2) – Macro and microplastic concentrations, sizes and shapes will differ significantly between islands of different land-use intensities, with industrial islands having the highest and rural islands having the lowest pollution levels.

- H2:O1 – Observe macroplastic pollution and collect sediment samples from different islands for microplastic analysis.
- H2:O2 – Carry out Kruskal-Wallis statistical tests to find if there is a significant difference in plastic concentrations and the size and shape of microplastics between the islands.
- H2:O3 – Identify the main land-use type contributing to plastic pollution, if there is a difference.

Hypothesis 3 (H3) – Ocean currents transport plastic between different islands in the Maldives.

- H3:O1 – Observe macroplastic pollution at the sites during fieldwork and log by taking pictures and collect sediment samples from the different islands for microplastic analysis.
- H3:O2 – Analyse the size and shape of microplastics found in the samples to identify if the pollution was likely to be sourced from the island or transported with ocean currents according to its size and shape.
- H3:O3 – Map the speed and direction of ocean currents to identify if the ocean currents can impact microplastic abundance in islands with low land-use intensity.

3. Methods

A combination of field and laboratory-based methods was utilised in this study to allow observation of macroplastics, sediment sample collection and extraction, identification, and quantification of microplastics based on their shape, size, and fluorescence under the microscope. The methods used in this study are summarised in Figure 7.

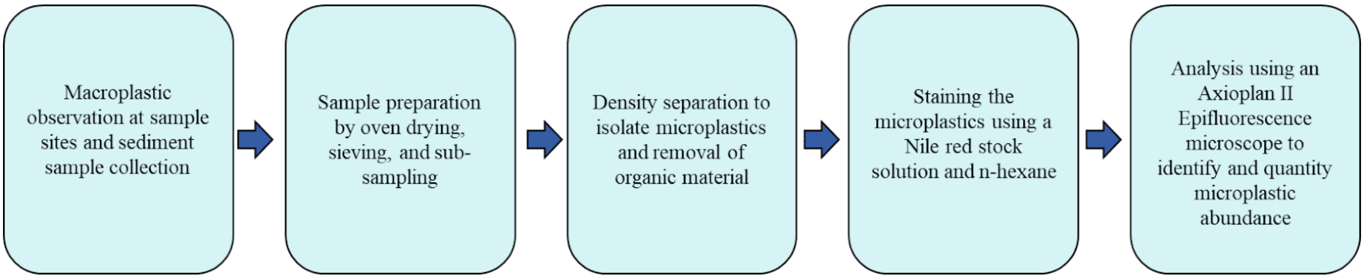

Figure 7. *Overview of methods carried out to identify and quantify microplastic abundance in the samples.*

3.1. Study site selection

Sediment samples were collected from 3 different islands in the Maldives (Figure 6) that had different land-uses to enable extraction, quantification of microplastics and to identify the effects of land-use on microplastic abundance and the main sources of pollution. All the selected islands are in central Maldives to prevent weather variances affecting the results.

3.1.1. Thulusdhoo

Thulusdhoo (Figure 8) was selected as an industrial land-use study site. Thulusdhoo has a population of 1483 people across 36.8 ha (The President's Office, 2022). The sample site was adjacent to the light industrial zone allocated for boat repair and near the Coca Cola factory located on the island (Ministry of National Planning and Infrastructure, 2019).

Figure 8. *Sample collection sites in Thulusdhoo (Esri, 2023).*

3.1.2. Villingili

Villingili (Figure 9), with a population of 2887 people in 31.7 ha, is located in the heavily populated and urbanised greater Male' area along with Male' and Hulhumale'. Male' and Hulhumale' has a combined population of 66489 people (The President's Office, 2022). Villingili has the last natural beach in the area, hence was selected as the urban study site.

Figure 9. *Sample collection sites at Villingili (Esri, 2023).*

3.1.3. Dhonfanu

Dhonfanu (Figure 10) was selected as the rural study site as it is not heavily developed, with scarce infrastructure, has a population of 556 people and is located between two marine protected areas; Hanifaru and An'gafaru areas (Figure 11), which have been protected since 2009 for their ecological significance (The President's Office, 2022).

Source: Esri, Maxar, Earthstar Geographics, and the GIS User Community

Figure 10. *Sample collection sites at Dhonfanu (Esri, 2023).*

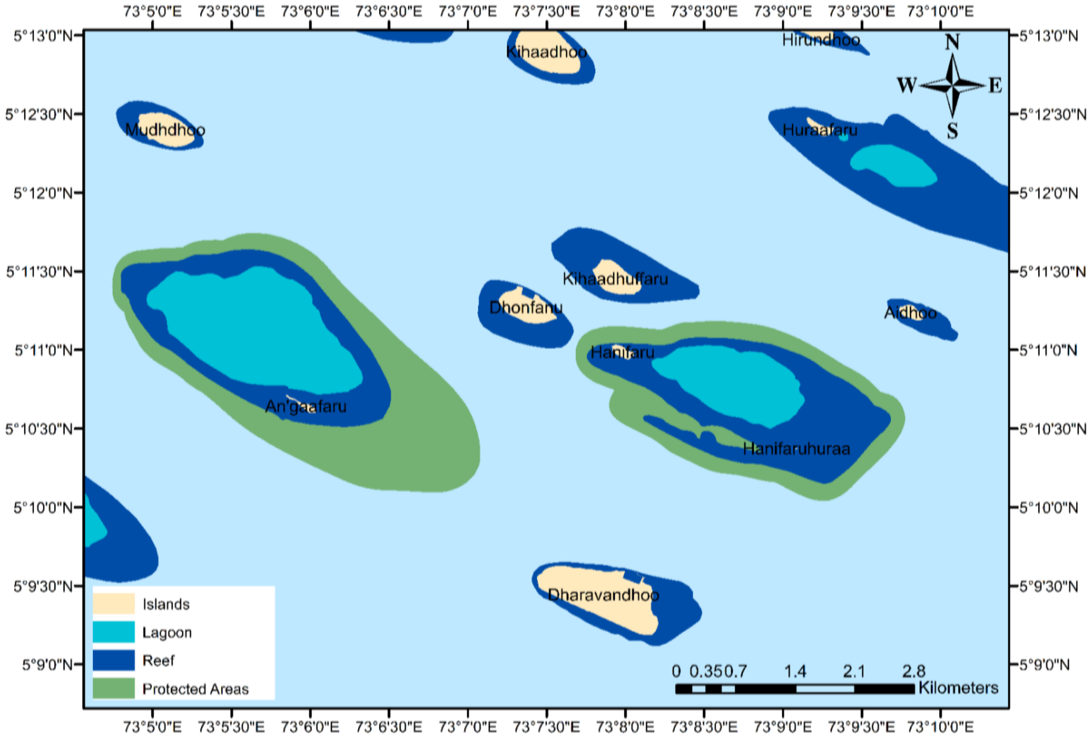

Figure 11. *Protected areas, An'gafaru and Hanifaru area, along with surrounding islands; Dharavandhoo (urban island) and Kihaadhuffaru (tourist island).*

3.2. Field method

Field methodology was carried out during late July and early August 2022 during the Southwest monsoon in the Maldives.

3.2.2. Plastic pollution observation

Macroplastic abundance at the sample sites were observed and logged with pictures to identify effects of land-use and ocean currents on plastic abundance at the sites.

3.2.3. Sediment sampling

100 g sand samples were collected from the surface in triplicates at 3 sites along the beach of each island. The samples were collected on the high tide line (Saliu *et al.*, 2018) right after the high tide to prevent effects of beach cleanings on the results (Lefebvre *et al.*, 2021). The sample bags were lined with aluminium foil and a metal scoop was used to collect samples to limit contamination of samples.

3.3. Laboratory method

The laboratory methods used were based on several methods to extract and analyse the microplastics in sand samples and carried out in a series of steps: sample preparation, density separation and filtration, removal of organic material, staining, and analysis of samples under the fluorescence microscope.

3.3.1. Sample preparation

Firstly, the samples were transferred into aluminium trays and oven dried overnight at 40°C, which was adequate to dry the samples completely. It was dried at 40°C as higher temperatures could affect the structural and physical integrity of the polymers by melting and degradation (Thomas *et al.*, 2020).

The sand samples were then sieved through a 5 mm sieve to remove all meso and macroplastics as well as larger rocks and shells.

10 g sub-samples were created from each of the triplicate samples using a riffle box. A riffle box sample splitter was used for sub-sampling as it has a greater accuracy and efficiency compared to other sub-sampling methods such as coning or quartering. Furthermore, sub-samples produced using a riffle box are also more homogeneous and represent the parent sample more closely than when other techniques are used (Campos-M & Campos-C, 2017). The 10 g sub-samples were then transferred to 50 ml plastic centrifuge tubes which can introduce more plastics into the samples from sand abrasion against the tubes.

3.3.2. Density separation and filtration

Density separation is used to isolate microplastics from heavier sediments to enable quantification of microplastics (Hurley *et al.*, 2018). 40 ml of 240 g/l NaCl solution was added to the centrifuge tubes containing the samples for density separation and was placed on the orbital shaker at 200 rotations per minute (RPM) for an hour.

The density of the NaCl solution used was 1.154 g/cm^3. The most common plastic polymers found in marine environments are polyethylene (PE) which has a density of 0.89 - 0.98 g/cm^3, PP with a density of 0.85 - 0.92 g/cm^3 and PS which is 1.04 - 1.06 g/cm^3 (Enders *et al.*, 2015; Filgueiras *et al.*, 2019), which are all less dense than the salt solution used allowing separation of these plastics from the sediments. However, there are some polymers such as PET and PVC that have a density of 1.45 g/cm^3 and 1.58 g/cm^3 respectively, which is denser than the NaCl solution used, limiting the recovery of these polymers (Cutroneo *et al.*, 2021). Utilisation of $ZnCl_2$ and NaI, although environmentally hazardous, will enable separation of these polymers. However, it was not used as NaI reacts with cellulose nitrate membrane filters, turning it black and making it difficult for analysis (Cutroneo *et al.*, 2021; Prata *et al.*, 2019a).

The samples were then centrifuged at 2000 relative centrifugal force (RCF) for 10 minutes allowing microplastics which are lighter to float and the remaining solids to settle at the bottom of the tube, enabling the supernatant containing the microplastics to be decanted without sediments (Hurley *et al.*, 2018).

Afterwards, the samples were filtered using a vacuum filter unit with a 0.45 μm Whatman Cellulose Nitrate membrane filter. The filter unit and centrifuge tubes were rinsed with deionised water to make sure that all the microplastics were on the filter paper. The filter paper was then carefully transferred to a new centrifuge tube.

3.3.3. Removal of organic material

Wet peroxide oxidation procedure was carried out to digest and remove natural organic material in the samples that can interfere and obstruct microscope analysis of microplastics (Razeghi *et al.,* 2021) and to prevent natural organic material from being misidentified as plastics (Hurley *et al.*, 2018). 25 ml of Hydrogen Peroxide (H_2O_2) was added to the samples in a fume cupboard and placed in an orbital shaker at 200 RPM for 24 hours. H_2O_2 (30% w/v) is an oxidising agent that enables organic matter digestion without affecting the integrity of microplastic polymers unlike acidic and alkaline digestion (Prata *et al.,* 2019a). It is carried out in a fume cupboard as H_2O_2 can be severely corrosive to skin, eyes, and respiratory tract.

After 24 hours, the samples were filtered again and the previous filter paper along with the filter unit was thoroughly rinsed with deionised water to ensure that all the microplastics were captured. The filter paper was then transferred to a 15 ml centrifuge tube for staining.

3.3.4. Staining

A 50 mg/l Nile red stock solution was prepared by dissolving 2.5 mg of Nile red in 50 ml of acetone. 700 µl of the Nile red stock solution along with 7 ml of n-hexane was added to the sample using a pipette giving a working concentration of 5 mg/l. The sample was left to stain overnight in the dark. Nile red is a fluorescent dye that fluoresces in hydrophobic environments (Shim *et al.*, 2016). Nile red is used instead of other dyes available for microplastic staining as it is more favourable due to it being highly absorptive to plastics and having a high fluorescence intensity for a broad range of polymers with a short incubation period (Shim *et al.,* 2016; Shruti *et al.,* 2022; Prata *et al.,* 2019b). The stock solution was prepared in acetone to increase solubility of Nile red in n-hexane (Shim *et al.,* 2016). Moreover, a longer incubation time was not used to prevent the dye from staining the filters which can result in background fluorescence that can interfere with the analysis (Shruti *et al.,* 2022).

The sample was filtered again in the fume cupboard using a filter unit and a Whatman Cellulose Nitrate membrane gridded filter paper. A majority of the Hexane in the sample tube was decanted into a waste beaker using a pasteur pipette. Additionally, the filter paper was thoroughly rinsed to ensure that all the microplastics were retained.

3.3.5. Microscopy

The final filter paper was transferred onto a microscope slide. A gridded filter paper was used to make the microscope analysis more efficient, ensure that all the microplastics were counted and to prevent double counting. A second microscope slide was placed on top of the filter paper to prevent the filter paper from wilting as it dries and interfering with microscope analysis. The microscope analysis was carried out using the Zeiss Axioplan II Epifluorescence microscope and in a dark room to prevent light from hindering analysis. The filter paper was analysed under three different light filters (Table 1), FITC (Fluorescein isothiocyanate) narrow, DAPI (4’,6-diamidino-2-phenylindole) and Cy3 (Cyanine-3), and the microplastics were categorised into the different sizes, shapes, and fluorescence colour. The samples were also analysed under the light without filters (Figure 12.d) to ensure that it was not organic material.

Due to the Nile red stain, different microplastics, depending on the polymer, fluoresced under different filters (Table 1) enabling a preliminary identification of the most common polymers found, to identify the specific sources of pollution; however, further research is required for a more accurate identification.

Table 1. *Common polymer types and their fluorescence under FITC narrow, DAPI and Cy3 filters used in the analysis, along with excitation and emission wavelengths for the fluorescence light filters (Adapted from Carl Zeiss, 2023; Shim et al., 2016 and Shruti et al., 2022). The coloured blocks indicate fluorescence under the filter and white indicates no fluorescence.*

Polymer type	**Fluorescence filter**		
	FITC narrow (excitation: 450-495 nm, emission: 515-565 nm)	DAPI (excitation: 365 nm, emission: 420 nm)	Cy3 (excitation: 546 nm, emission: 575-640 nm)
HDPE	🟩		🟨
LDPE	🟩		🟨
PP	🟩		🟨
PC	🟩		
PU	🟩		
EPS/PS	🟩		🟨
PVC	🟩 Dim		
PA		🟦	
PET		🟦	
PES		🟦 Dim	

The microplastics glowed in blue under DAPI, green under FITC narrow and yellow under Cy3 (Figure 12). Some of the microplastic particles fluoresce under multiple filters, they were categorised into the filter which they were brightest under.

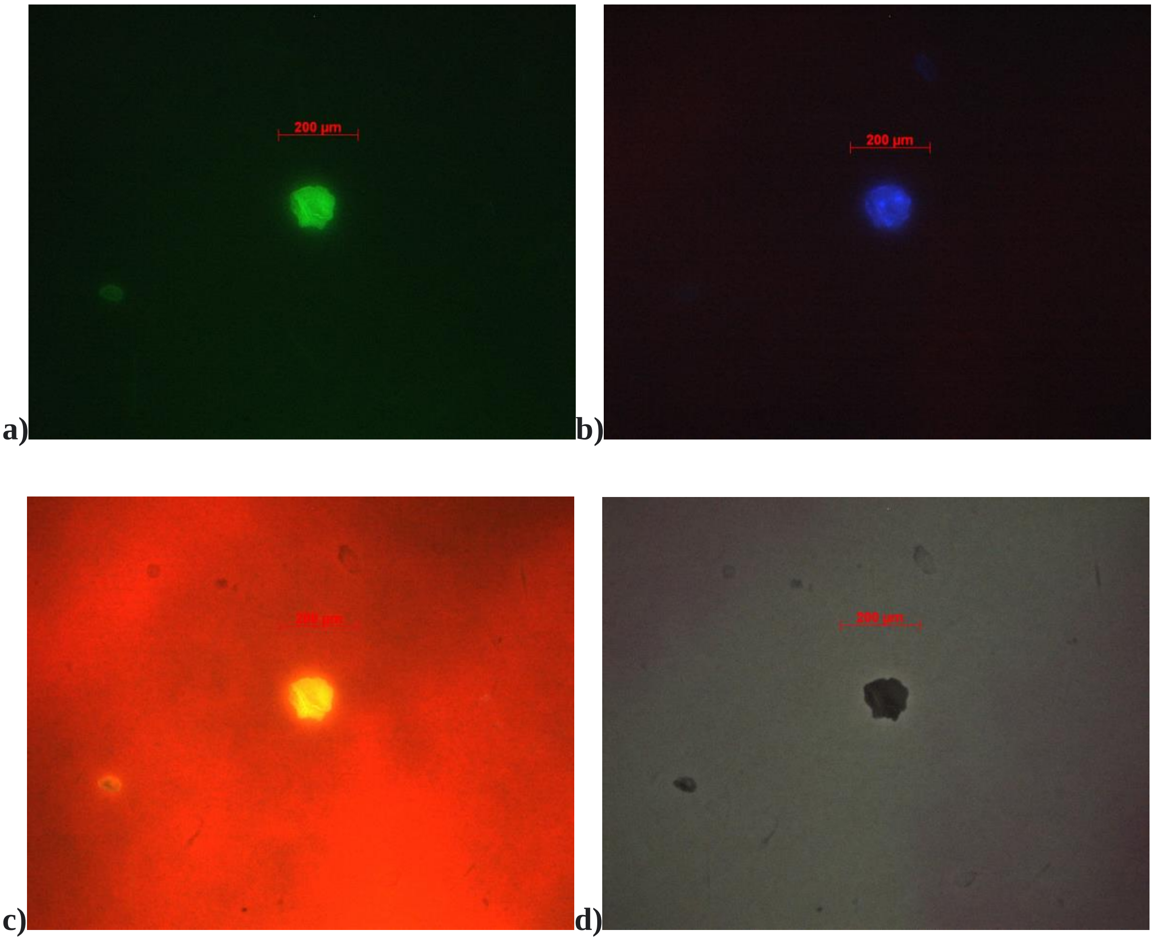

Figure 12. *plastic particle under the microscope **a)**FITC narrow, **b)**DAPI, **c)**Cy3 and **d)**no filter.*

The microplastic particles were categorised into 4 different sizes, large (>500 µm), medium (100 - 500 µm), small (20 - 100 µm) and extra small (<20 µm). Identifying the different sizes of plastics present on the different islands will help identify the sources of microplastics and how ocean currents influence pollution, as smaller microplastics are more likely to have gone under more degradation while being transported by currents, and larger particles are more likely to have been littered from the island. The size of microplastics affects bioavailability and its impact on the ecosystem, with smaller particles being more easily ingested (Peterson & Hubbart, 2021).

The microplastics were also categorised into different shapes; rounded fragments, films and fibres. The shape of microplastics, along with the size further contributes to the identification of sources of pollution.

3.3.6. Contamination

Film-like artefacts that fluoresced pink-blue under the DAPI filter were identified (Figure 13), a new batch of Nile red stock solution was made as an attempt to identify and reduce contamination. This reduced contamination; however, the artefacts were still present. Moreover, a different filter paper was used to see if the filter papers were the source of contamination, though, this did not make a difference. Rinsing the pipette tips used for staining with deionised water eliminated contamination.

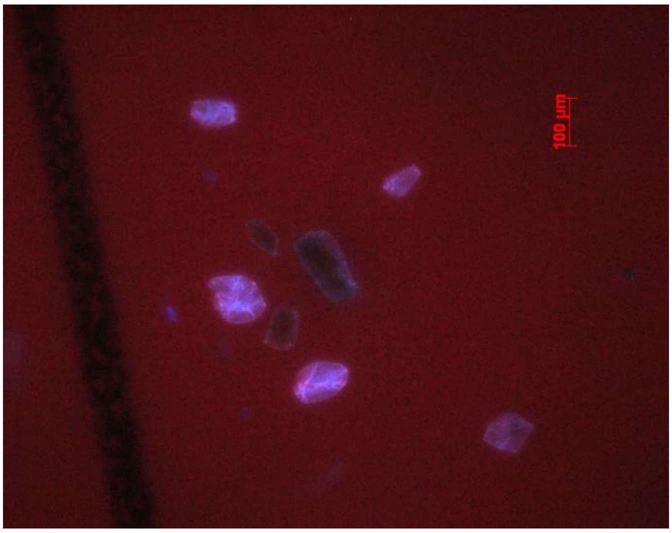

Figure 13. *Film-like artefacts found in some of the samples.*

3.3.7. Blank samples

Procedural blank samples were conducted to identify the levels of plastic introduced during laboratory methods (Dawson *et al.,* 2023). All the laboratory steps were repeated with the blank samples without sediment. Microplastic abundance in the blank samples were quantified and compared to the sediment samples to identify contamination levels and error in the laboratory methods. The contamination levels identified using the blanks were not subtracted from the data when being presented and analysed to increase the transparency of research limitations (Akoueson *et al.,* 2020).

3.4. Ocean current mapping

Ocean reanalysis data was used to map the ocean currents for the sample collection days using ArcMap (version 10.7.1) to identify possible effects of ocean currents on microplastic distribution and abundance on the islands. A Surface and Merged Ocean Currents (SMOC) dataset (Global Ocean 1/12° physics analysis and forecast) by the Copernicus Marine Environmental Services (CMEMS), (2022a) that combines surface currents, tides, stoke drift and other components such as sea surface temperature, and sea level anomalies that influences the surface velocity, and thus the total ocean current was used. The SMOC dataset enables drift and lagrangian stimulation and hence, identification of the transportation of buoyant microplastics by ocean currents. The dataset used had a horizontal resolution of 1/12° and an hourly frequency output; the high spatio-temporal resolution allows identification of mesoscale movements (CMEMS, 2022b).

3.5. Statistical analysis

Statistical data analysis was carried out using Rstudio. Rstudio was used to test the normality of the microplastic abundance data and to carry out the appropriate statistical test.

Since the microplastic data was not normally distributed, a Kruskal-Wallis test along with Dunn’s multiple comparison test was carried out to identify if there is a significant level of microplastic pollution on the different islands in the Maldives compared to the blank samples which showed contamination during laboratory methods.

A Kruskal-Wallis test was done between the microplastic abundance on the Rural, Urban and Industrial islands to identify if there is a significant difference in microplastic abundance with different land-use. Furthermore, a multiple comparison Dunn’s test was used to further analyse the difference with land-use type.

A Pearson’s chi-squared test was used to identify if there was a significant trend in the shapes and sizes of microplastic found on the islands with different land-use types.

A Kruskal-Wallis test, along with a multiple comparison Dunn’s test was also carried out to analyse if there is a significant difference in the shapes and sizes of microplastics found in Dhonfanu, to determine the impact of ocean currents on microplastic abundance.

3.6. Limitations

The organic material was not completely removed in some samples after the 24-hour hydrogen peroxide organic material digestion (Figure 14). To limit misidentification of organic material as microplastics that could lead to an overestimation of microplastic abundance, the samples were also analysed without a light filter to identify the organic material from its colour and structures. In future research, digestion could be carried out for a longer period of time to completely remove the organic material or a combination of hydrogen peroxide with an Iron catalyst can be used to make the removal more efficient (Razeghi *et al.,* 2021).

Figure 14. *Organic material, identified by its body and leg-like structures found in samples collected from site 1 in Villingili.*

Moreover, another solution such as $ZnCl_2$ or NaI, with the adequate measures to prevent harm to the environment, can be used to increase retrieval of plastics such as PVC and PET that could be an important pollutant and help identify the main sources of plastic pollution.

Identification of polymers visually can be inaccurate and lead to underestimation and overestimation of microplastic abundance in the samples (Shruti *et al.,* 2022). Both Fourier Transform infrared (FTIR) or Raman spectroscopy can be used to chemically identify the type of polymers and qualitatively confirm the polymer, as well as increase accuracy of microplastic quantification (Shim *et al.*, 2016; Shruti *et al.*, 2022). However, this technique was not used for identification and quantification of microplastics in this study.

4. Results and observations

4.1. Hypothesis 1. Microplastic pollution levels in Maldivian islands

Figure 15 shows that there is, compared to other countries in the region (Table 3), a high abundance of microplastics found on all the three islands. There was a mean microplastic abundance of 939.3 ± 85.8 microplastics per kg on Thulusdhoo, 600.8 ± 68.0 per kg of sand on Villingili and 506.8 ± 48.6 microplastics per kg on Dhonfanu (Figure 15). The blank samples done to identify contamination during lab processes had a mean microplastic count of 292.0 ± 29.1 particles per kg.

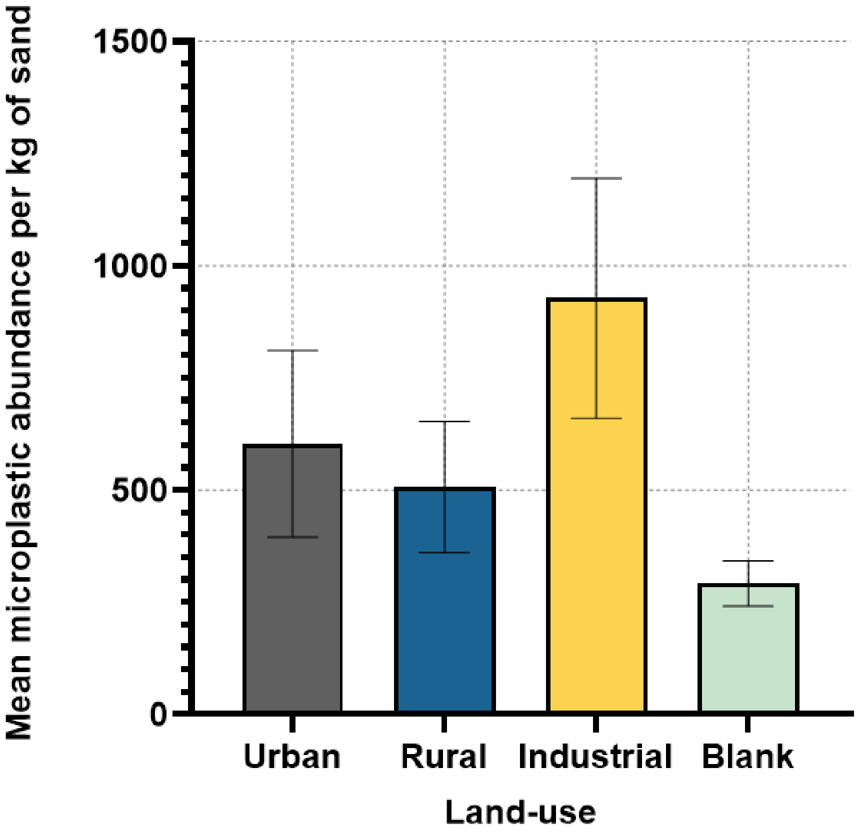

Figure 15. *Abundance of microplastics at Thulusdhoo, Villingili and Dhonfanu and blank samples, with error bars showing the variance in microplastic abundance/kg of sediment in the replicates.*

The Kruskal-Wallis test and multiple comparison test carried out between the microplastic counts at the sample sites and the blank samples (Kruskal-Wallis test: H = 17.169, d.f. = 3, p-value < 0.001) confirm that the microplastic abundance at the sample sites were significantly different to the blank samples since the p-value was <0.05 in both the Kruskal-Wallis and the multiple comparison Dunn's test, indicating that there was significant levels of pollution at the islands.

4.2. Hypothesis 2. Impact of land-use on macro and mesoplastic pollution and microplastic abundance and shape and size of microplastics found.

4.2.1. Macro and mesoplastic pollution

4.2.1.1. Industrial (Thulusdhoo)

Figure 16.a. shows that the sample site at Thulusdhoo was very polluted, with 5 - 10 pieces of visible macroplastic present at each site on the island and 10 mesoplastic pieces (Figure 16.b.) within 6 of the samples found while sample preparation.

a)

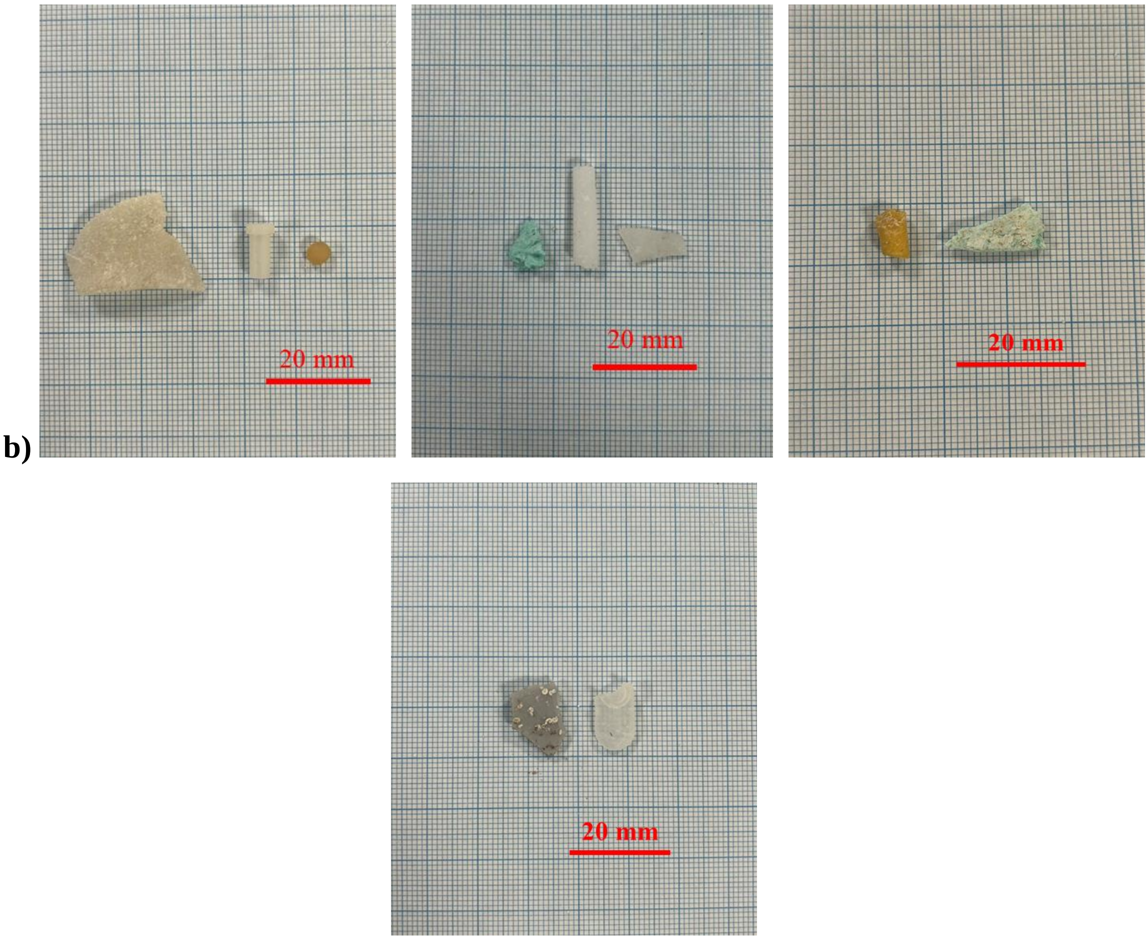

Figure 16. a) Macroplastics such as plastic bottles and packaging seen at the sample site, **b)** Mesoplastics found in the samples collected from site 2 and 3 on Thulusdhoo.

4.2.1.2. Urban (Villingili)

Figure 17 shows that the sample site at Villingili had less than 5 pieces of visible macroplastics at each site on the island and mesoplastics present in one of the samples collected at the site.

b)

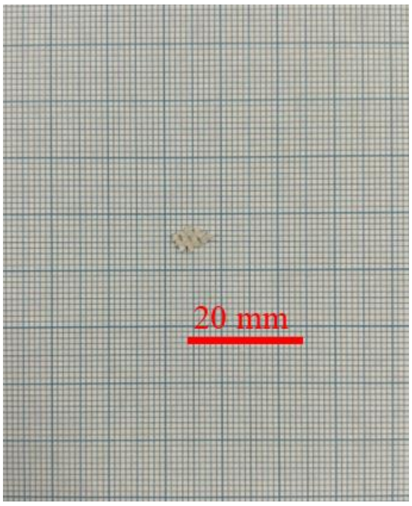

Figure 17. a) Macroplastics such as plastic wrappers seen at the sample site**, b)** Mesoplastic found in the sample collected from Villingili site 2.

4.2.2. Microplastic abundance

Figure 18 shows that the mean microplastic abundance differed between islands of different land-use, with the greatest mean abundance at the Industrial island (939.3 microplastics per kg) and lowest at the Rural island (506.8 microplastics per kg) and the Urban island having a mean abundance of 600.8 per kg of sand.

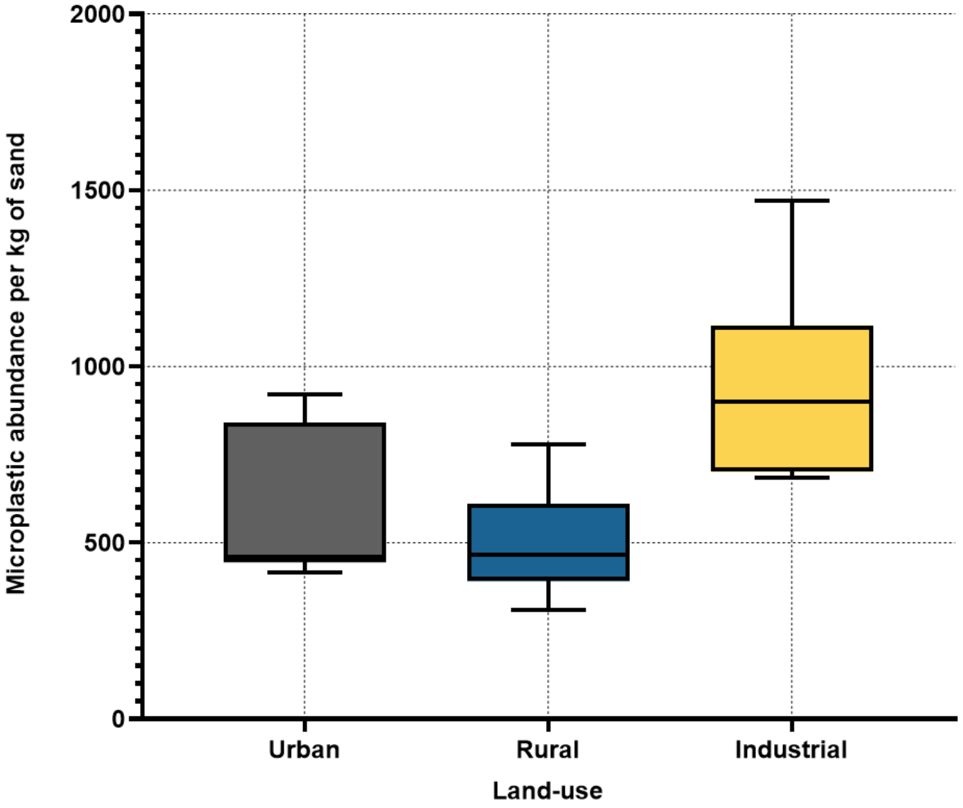

Figure 18. *Mean microplastic abundance per kg of sand on islands of different land-use types. Whiskers showing minimum and maximum values.*

There is a significant difference of microplastic abundance between islands of different land-use (Kruskal-Wallis test: H = 12.07, d.f. = 2, p-value < 0.05). The Multiple comparison test carried out to further analyse the difference shows that there is a significant difference between Urban and Industrial (Dunn's p = 0.0378) and Rural and Industrial (Dunn's p = 0.0025); however, no significant difference between Urban and Rural islands (Dunn's p = 1.00).

4.2.3. Microplastic shape

Microscope analysis of the samples showed that there were different shapes of microplastics found in the samples as seen in Figure 19. Fibres, although seen under both DAPI and FITC narrow, were predominant under the DAPI filter and rounded fragments and films were seen under all three filters, however, was the most prevalent under the FITC narrow.

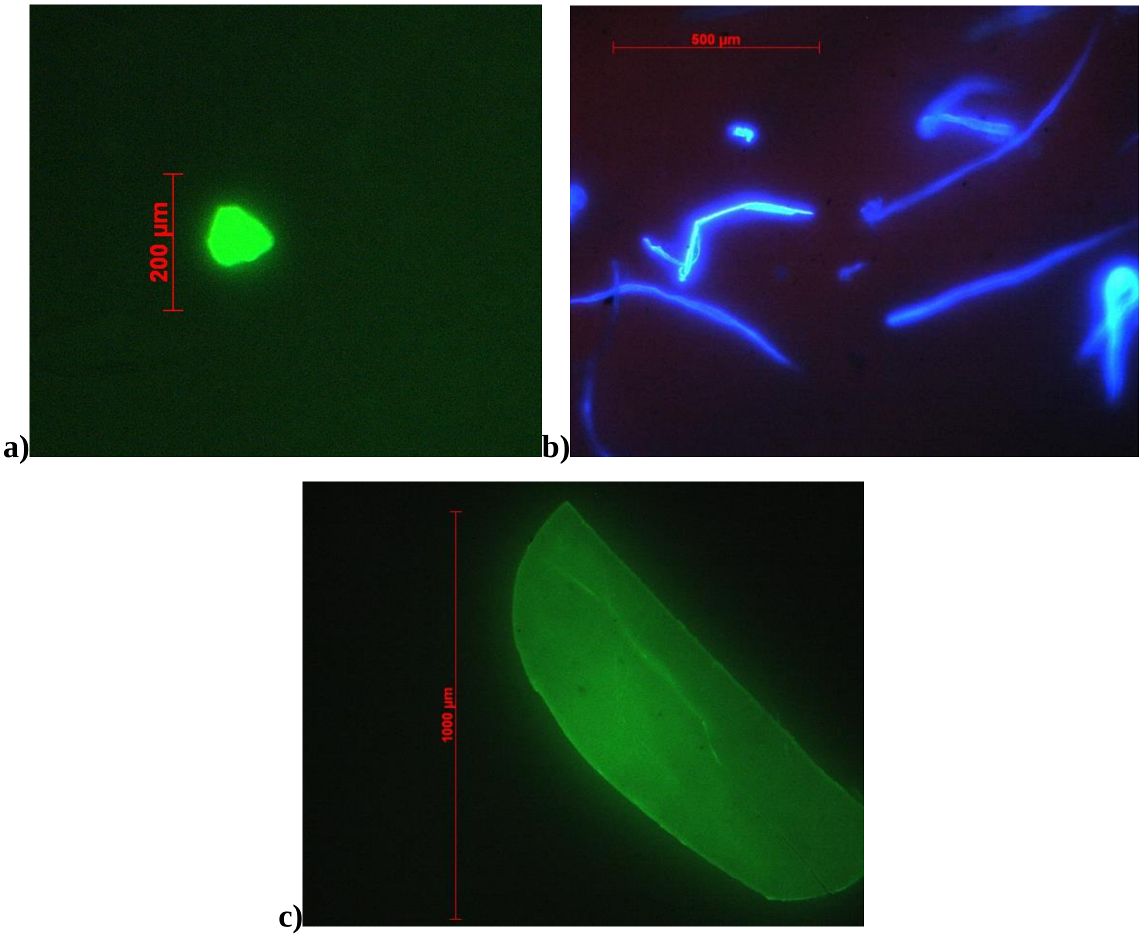

Figure 19. *Different shapes of microplastics seen under the microscope* ***a)****rounded fragment,* ***b)****fibre and* ***c)****film.*

Figure 20 shows the percentage of rounded fragments, film and fibre shaped microplastics found on each of the islands.

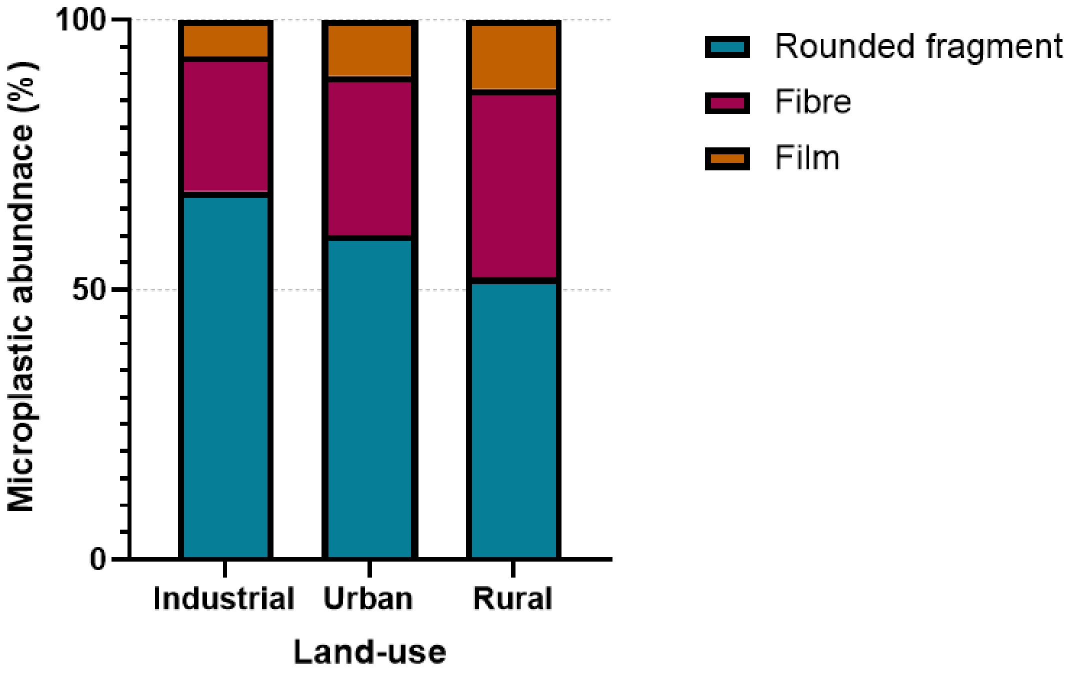

Figure 20. *Percentage of each microplastic shapes found at the different islands, with the Industrial island with 68% rounded fragments, 25% fibre and 6.8% film; the Urban island had 60% rounded fragments, 29% fibres and 10% film; and the Rural island 52% rounded, 25% fibres and 13% film.*

The highest total levels of rounded fragment particles were found on the Industrial island (5762 particles/kg of sediment) and lowest on the Rural island (2381 particles/kg of sediment). The highest total levels of fibres were on the Industrial island (2167 particles/kg of sediment) and the Rural and Urban islands had similar levels of fibres (1596 and 1593 particles/kg of sediment respectively). The highest total levels of films were found in the samples from the Urban island (749 particles/kg of sediment) and lowest at the Industrial island (574 particles/kg of sediment). Rounded fragments were the most abundant at all sites and the film microplastics were least abundant at all the beaches (Table 2). Pearson's Chi-squared test confirms a pattern in the shapes of microplastic found in samples from the different islands ($X^2 = 399.19$, d.f. = 4, p-value < 0.001).

Table 2. *Total microplastic abundance of different shapes at the different beaches with different land-use type.*

Shape	**Total microplastic abundance/ kg of sand**		
	Industrial	**Urban**	**Rural**
Fragment	5762	3251	2381
Fibre	2167	1593	1596
Film	574	749	585

4.2.4. Microplastic size

Microplastics of different sizes were observed in the samples during microscope analysis and was categorised into the extra small (<20 µm), small (20-100 µm), medium (100-500 µm) and large (>500 µm) microplastics, as seen in figure 20.

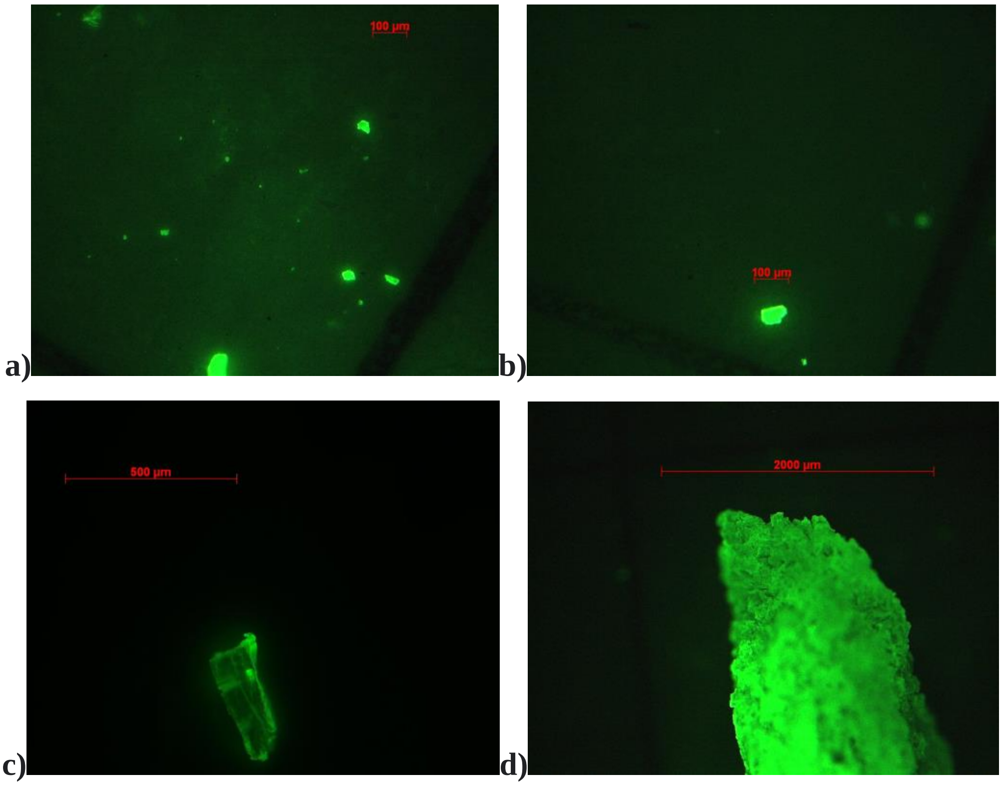

Figure 20. *Microplastic particles of different sizes under the microscope **a)**extra small, **b)**small, **c)**medium and **d)**large*

Figure 21 shows the percentage of extra small, small, medium and large microplastic particles found on the different islands.

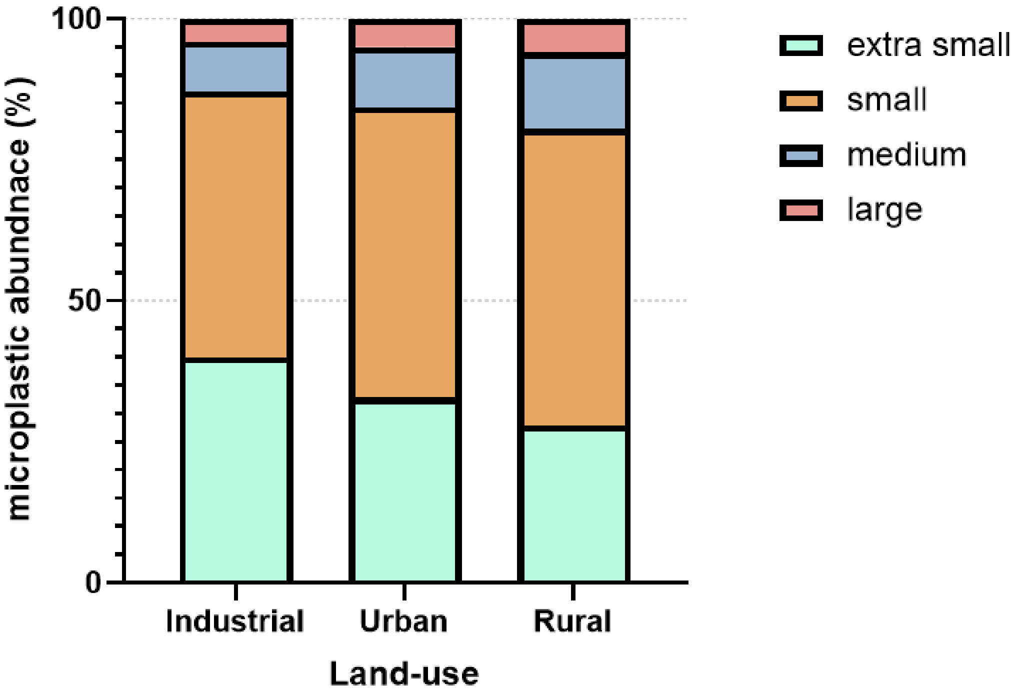

Figure 21. *Percentage of each microplastic size found on the different islands. The Industrial island had 39.9% extra small, 47% small, 8.8% medium and 4.2% large particles. The Urban island had 32.8% extra small, 51.5% small, 10.6% medium and 5.01% large particles; and the Rural island 27.8% extra small, 51.7% small, 13.6% medium and 5.96% large particles.*

The highest total amount of large microplastics were found on the Industrial island (352 microplastics/kg of sediment) and both the Urban and Rural islands had similar levels of large particles (270 and 272 microplastic particles/kg of sediment respectively). The total extra small particles found in samples collected from an island were also the greatest at the Industrial island (3377 microplastics/kg of sediment), and lowest at the Rural island with 1269 extra small microplastic particles/kg of sediment. The same trend was seen in medium and small sized microplastics with highest at the Industrial and lowest at the Rural island. Large microplastics were the least abundant and small particles were the most abundant at all beaches. This trend in size of microplastics found on the different islands with varying land-use was confirmed by the Pearson's Chi-squared test ($X^2 = 260.16$, d.f. = 9, p-value < 0.001).

4.3. Hypothesis 3. Impact of ocean currents on microplastic abundance

4.3.1. Macroplastic pollution on the Rural island, Dhonfanu

Figure 22 shows that there was no visible macroplastic pollution at the sample site at Dhonfanu

Figure 22. Macroplastic pollution at the sample site

4.3.2. Microplastic size and shape on Dhonfanu

As seen in Figure 23, there is a high proportion of small (52.65%) and extra small (27.82%) sized particles and rounded fragment microplastic particles (52.2%) compared to other sizes and shapes found in the samples collected from Dhonfanu. Kruskal-Wallis test confirms that there is a significant difference in shapes of microplastics found in Dhonfanu (Kruskal-Wallis test: H = 17.665, d.f. = 2, p-value < 0.001), with the Dunn's test confirming the difference between all shape groups (P < 0.01). Statistical test carried out confirms a significant difference in microplastic abundance in each size group in Dhonfanu (Kruskal-Wallis test: H = 28.085, d.f. = 3, p-value < 0.001), with the Dunn’s test confirming significant difference between each size group (p < 0.001).

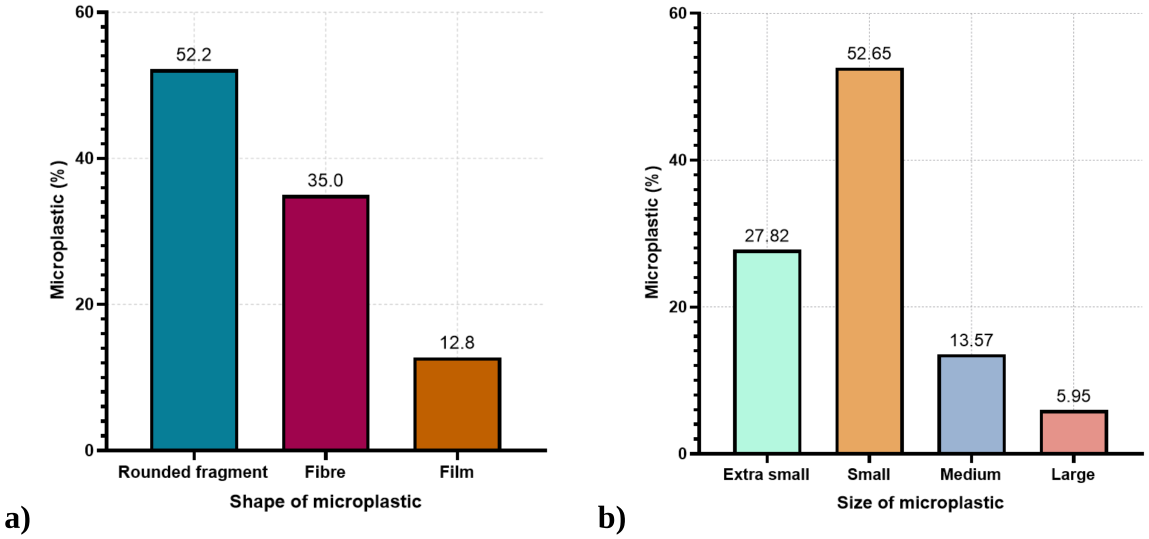

***Figure 23. a)** percentage of different shapes of microplastics* **b)** *percentage of different sizes of microplastics found in samples collected from Dhonfanu*

4.3.3. Ocean current direction and speed

Figure 24 shows that the ocean currents were northwards towards Dhonfanu. Dharavandhoo (Figure 11), a more developed, populated island with a domestic airport is located approximately 2.8 km to the south of Dhonfanu, allowing transportation of plastics to Dhonfanu from Dharavandhoo. Likewise, there is a tourist island (Figure 11) within less than 1 km from the Rural island, which could also contribute to microplastic pollution.

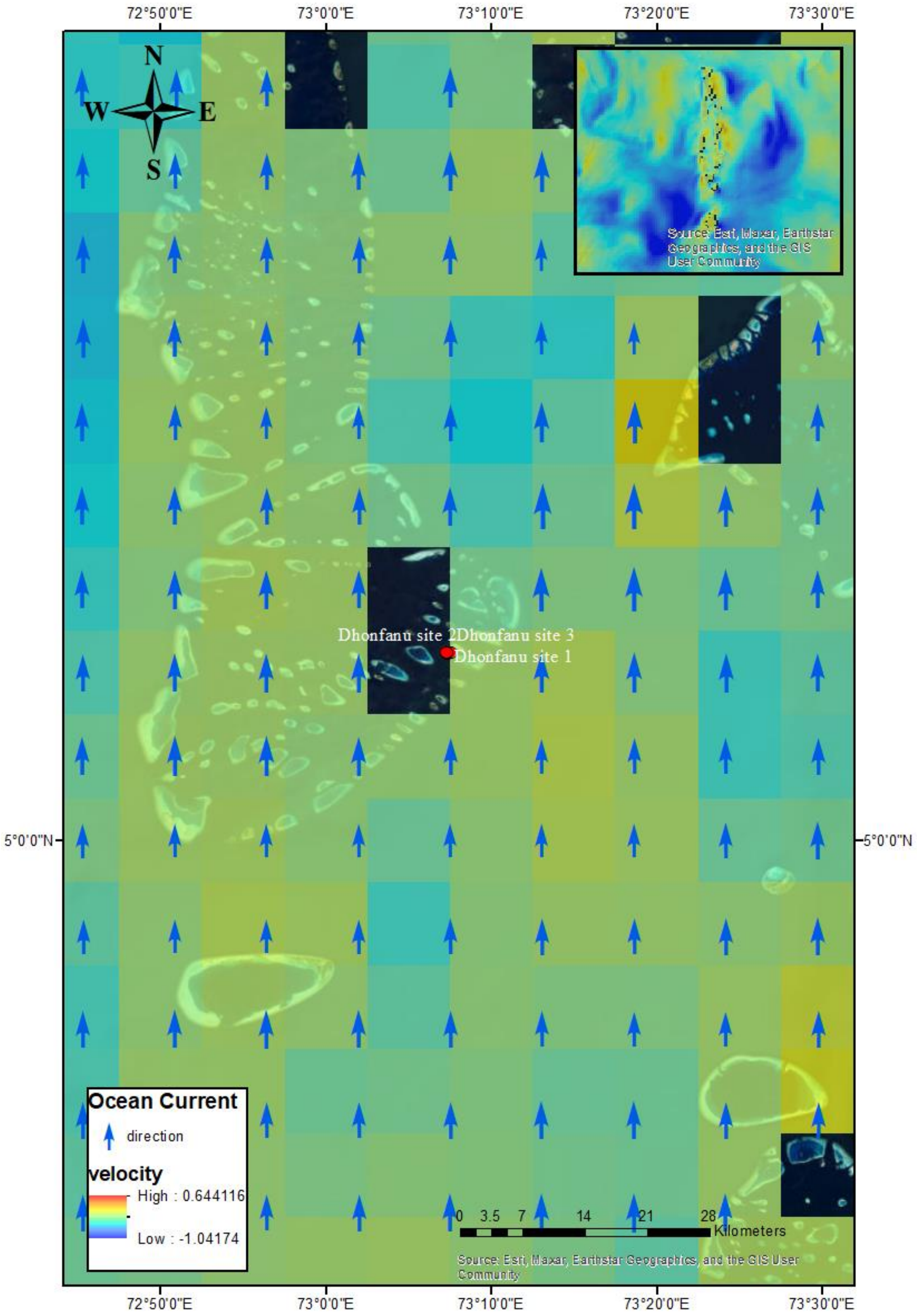

Figure 24. *Ocean current direction and speed the day (21st July 2022) samples were collected from the Rural island, Dhonfanu.*

4.4. Further findings

4.4.1. Microplastic polymer types

Microplastic fluorescence under the microscope can provide an estimation of the plastic polymer types found on the different islands, providing an idea of more specific sources of pollution. Spectroscopy is required for a more accurate identification of plastic polymers; however, this data provides a baseline for further research. Figure 25 shows the mean abundance of microplastics that fluoresce under the DAPI, FITC narrow and Cy3 filter.

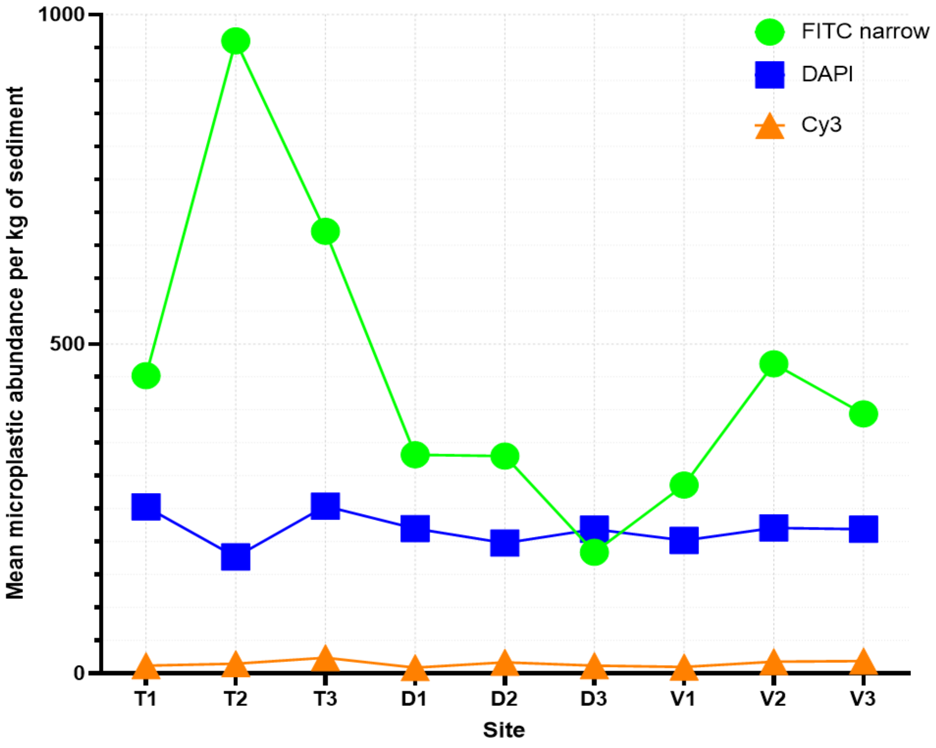

Figure 25. *Mean microplastic abundance at the different sample sites that fluoresce under each light filter.*

Most number of microplastics fluoresce under the FITC narrow filter, indicating that the most abundant types of polymers on these islands are most likely to be PE, PP, PC, PU, EPS, and PVC as seen in Table 1. The least number of microplastics fluoresce under just Cy3, however, since most of the particles that fluoresce under Cy3, fluoresce brighter under FITC narrow, and were classified under FITC narrow. PA, PET, and PES are most likely to be the least abundant plastic polymer pollutants as they glow only under DAPI which is lower than FITC at most sites.

5. Discussion

5.1. Hypothesis 1. Microplastic pollution levels in Maldivian islands

There was a significant amount of microplastic pollution on all the islands studied in this research when compared with microplastic abundance in the procedural blanks (292.0 ± 29.1 particles per kg in average) carried out to identify contamination during the laboratory methods, therefore, the first hypothesis can be accepted.

A mean microplastic abundance of 939.3 ± 85.8 microplastics/kg of sediment was found in Thulusdhoo, 600.8 ± 68.0 microplastics/kg of sand in Villingili and 506.8 ± 48.6 microplastics/kg in Dhonfanu. These results are consistent with previous studies carried out in the Maldives such as the study carried out in Naifaru by Patti *et al.* (2020) that showed microplastic pollution at all sites studied with a concentration of 55 - 1127.5 microplastics/kg of sediment. Moreover, Saliu *et al.* (2019) also stated that the inhabited islands studied in F. Atoll had a microplastic abundance of between 197 - 822 particles/kg of sediment. A study carried out on an uninhabited remote island in the Maldives, Lh. Vavvaru had a microplastic abundance of 1029 ± 1134 particles/m^2 at the accumulation zone of the beach (Imhof *et al.,* 2017). However, the difference in units of microplastic abundance measurements between the studies prevents comparison.

Microplastic abundance at Thulusdhoo, Villingili and Dhonfanu was greater than other coastal regions in the Indian Ocean and other regions. As seen in Table 3, these Maldivian islands had a higher microplastic abundance than the Andaman and Nicobar Islands which is known for their natural beauty and high biodiversity levels, located in the south-eastern Bay of Bengal (Mohan *et al.,* 2022) and coastal areas of Tamil Nadu, India, which is highly populated and urbanised (Sathish *et al.,* 2019). A lower plastic pollution was also found on the Lesser Antilles in the Caribbean Sea (Table 3), which has a population of approximately 70000 inhabitants and is also a popular tourist destination, with up to 2.5 million visitors in 2014 in St. Martins (Bosker *et al.,* 2018). As seen in Table 3, the mean microplastic abundance was lower at both the Baja California peninsula, Mexico (Piñon-Colin *et al.,* 2018) and Mar Menor, Spain (Bayo *et al.,* 2019) with urban and rural or natural sample sites compared to all three islands included in this study.

Table 3. *Microplastic Abundance at different coastal areas.*

Location	Microplastic abundance/ kg of sediment	Study
Thulusdhoo	939.3 ± 85.8	This study
Villingili	600.8 ± 68.0	This study
Dhonfanu	506.8 ± 48.6	This study
Naifaru	55 - 1127.5	Patti *et al.*, 2020
F. Atoll islands (Dharan'boodhoo, Magoodhoo, Bileiydhoo, Filitheyo)	197 - 822	Saliu *et al.*, 2019
Andaman and Nicobar Islands	72.5 - 475	Mohan *et al.*, 2022
Tamil Nadu, India	3 - 611	Sathish *et al.*, 2019
Lesser Antilles, Caribbean	124 - 341	Bosker *et al.*, 2018
Baja California Peninsula, Mexico	135 ± 92	Piñon-Colin *et al.*, 2018
Mar Menor, Spain	8.2 - 166.3	Bayo *et al.*, 2019

The prominent levels of microplastic abundance on these Maldivian islands can be due to high levels of single-use plastic usage in the Maldives, with approximately 57 million plastic bottles of water being consumed per year by households (MOPA, 2021). Deliberate littering or mismanaged waste and several activities such as fishing, aquaculture, tourism, boat building, and shipping can introduce plastics into the environment (Lebreton *et al.*, 2017). Moreover, reclamation of land, which is done frequently in the Maldives with 64.6% of the inhabited islands having undergone reclamation between 2006-2016 may also contribute to the high microplastic levels (Duvat & Magnan, 2019). Sand mining for reclamation can reintroduce microplastics from marine depositional zones that act as sinks, back into the marine environment and reclaimed areas (Patti *et al.*, 2020; Woodall *et al.*, 2014). Additionally, due to the location of Maldives, they receive a large percentage of ocean plastics from other countries in the region as the ocean currents carrying plastics between Bay of

Bengal and the Arabian Sea flow past the Maldives in reversing direction throughout the year (Pattiaratchi *et al.,* 2022).

The impacts of land-use and ocean currents on microplastic pollution levels on the different islands are discussed in the following sections.

5.2. Hypothesis 2. Impact of land-use on macro and mesoplastic pollution and microplastic abundance and shape and size of microplastics found.

5.2.1. Microplastic abundance

The results show that the mean abundance of microplastics on the Industrial island (939.3 ± 85.8 particles/kg of sediment) was significantly higher compared to the Urban island as well as the Rural islands, where microplastic abundance was lowest, confirming hypothesis 2. Although the Urban island (600.8 ± 68.0 particles/kg of sand) had a higher average microplastic abundance compared to the Rural island (506.8 ± 48.6 particles/kg), the difference was not statistically significant. The macro and mesoplastic particles logged at the sites also follow this trend, with the highest number observed on the Industrial island, then the Urban island and no macro or mesoplastics seen at the site on the Rural island.

The abundance of microplastics on the Industrial island being significantly higher than the Rural and Urban islands can be due to the high amounts of plastic use on the island, in both the boat building factory adjacent to the sample site and in plastic bottle production at the Coca-Cola factory located on the island. Along with large fragments of plastics, nurdles, which are microplastic pellets commonly used in plastic bottle production (Tunnell *et al.,* 2020), although rarely, were observed at the sites on the Industrial island (Figure 26) suggesting that the plastics used in the Coca-Cola factory were introduced to the environment through mismanaged waste or during transportation (Lebreton *et al.,* 2017) and contributed to the higher microplastic abundance at the Industrial island compared to the other two islands (Su *et al.,* 2020). Additionally, it also indicates that land-use influences plastic pollution abundance.

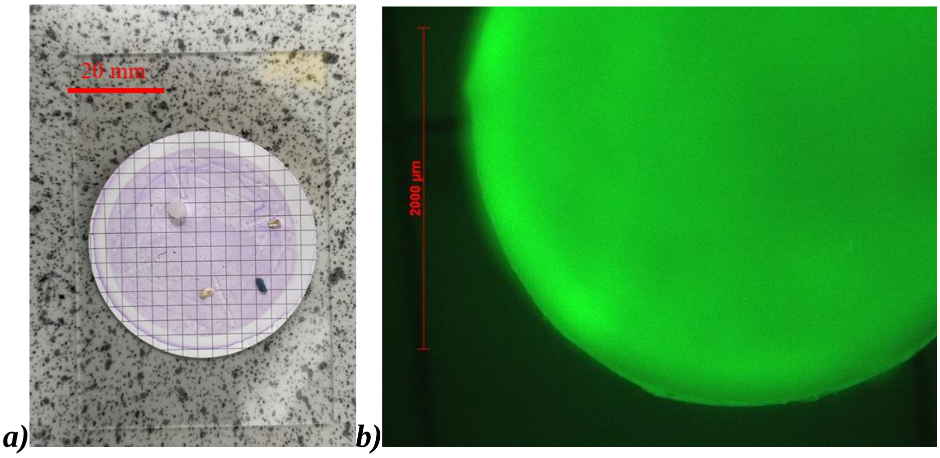

Figure 26. *Microplastic nurdle in sample collected from site 1 at the Industrial island (Thulusdhoo),* ***a)****on the filter paper ready for microscope analysis* ***b)****under the microscope*

The high levels of littered macro and mesoplastics such as water and other beverage bottles (Figure 16) can also contribute to the high microplastic abundance (Jeyasanta *et al.*, 2020) as it breaks down due to exposure to sunlight to produce secondary microplastics (Thushari & Senevirathna, 2020). As the results show, a higher number of large microplastics were found on the Industrial island compared to the other two islands, indicating that the Industrial island had more microplastics that underwent less disintegration by UV light or abrasion from ocean currents, proposing that they were sourced from the island and that the land-use impacted the plastic abundance.

The Urban island had more macro, meso, and microplastics present at the site compared to the Rural island and can be explained by the greater anthropogenic pressures on the island. However, as seen in the results there is no statistically significant difference in microplastics between these two islands.

The findings for the difference in microplastic abundance on the Urban and Rural islands were consistent with the study carried out by Piñon-Colin *et al.* (2019) in the Baja California peninsula in Mexico, where the mean microplastic abundance on the urban beach (162 ± 150 microplastics/kg of sand) was higher compared to the rural areas (115 ± 30 microplastics/kg of sand), which, however, was not statistically significantly different.

The insignificant difference in microplastic abundance between the Rural and Urban islands can be a result of other factors such as ocean currents and winds influencing microplastic distribution. The dominance of small and extra small fragments with rounded edges in the samples collected from the Rural island (as seen in Figure 23) and the absence of meso and macroplastics at the site (Figure 22) indicates that the microplastics present underwent environmental weathering and were transported to the island from other nearby islands or from longer distances through ocean currents and winds instead of being sourced from the island. This is further supported by studies done by Dehm *et al.,* (2020), as it suggests that microplastic sizes <0.5 mm will be higher unless there is a regular source of new, large microplastics present at the site. Microplastic particles can be transported to the Rural island from the tourist island as tourism contributes to microplastic pollution levels on beaches (Garcés-Ordóñez *et al.,* 2020) and from the Urban island, less than 3 km away which has a greater population and hence higher anthropogenic pressures such as littering.

Therefore, land-use plays an important role in plastic pollution on islands, and industrial land-use contributes the highest amount of plastic pollution. However, other factors such as transportation of microplastics by ocean currents and winds can also influence the microplastic abundance on the islands. The impact of ocean currents on microplastic abundance is further discussed in the following section.

5.2.2. Microplastic shape

Microplastic films are most likely to originate by fragmentation of single-use plastic bags, plastic packaging and LDPE used in sheet plastics (Amin *et al.,* 2020). Moreover, film or foil plastics are also a basic component of fabric used in bags and covers (Imhof *et al.,* 2017). 104 million plastic bags were imported to the Maldives just in 2018 (UNICEF Maldives, 2019). As seen in the results, the highest total number of microplastic films were in the Urban island samples (749 particles/ kg of sand), this can be explained by the high levels of plastic usage in the Maldives, specifically at domestic levels on the island and other urban islands with high populations for shopping and bin liners as well as plastic food packaging and wrapping.

Fibre microplastics are likely to have originated from synthetic materials used in rope assembling, commonly used on boats (Saliu *et al.,* 2019). Fibre microplastics can also come from fragmentation of fishing nets and synthetic cloth. The highest abundance of fibre microplastics were found in the Industrial island (2167 particles/kg of sediment); this could be a result of high levels of ropes and synthetic cloths used near the boat building zone near the site. Moreover, fibres can also be introduced from the clothing of people at the sites.

Fragments are sourced from degradation of larger intact plastics such as plastic bottles or bigger plastic fragments (Amin *et al.,* 2020). Rounded fragment plastics were highest at the Industrial island (5762 particles/kg of sediment), this may be due to higher levels of plastic littered from the island. The size and condition of the fragments indicate if they were transported from a large distance or littered at the site; with weathered and broken-down plastics having grooves, pits, and fractures on the surface and rounded edges (Corcoran, 2022; Imhof *et al.,* 2017). The sizes of microplastics found at the different sites and possible justifications for the reason behind the size of plastic found are further discussed in the following sections.

The number of rounded fragments were highest at all sites and film microplastics were the least abundant at all sites as seen in Table 2. Fragments may be the most abundant shape of microplastics at all sites as plastic bottles are a large polluter in the Maldives, with up to 57 million plastic bottles of water consumed per year by households in the Maldives (MOPA, 2021) and is one of the main contributors to fragmented microplastics, along with styrofoam food packaging (Amin *et al.,* 2020). The lower abundance of films compared to the other shapes may have been a result of the recent ban of plastic bags and packaging in the Maldives in June 2022 (Ministry of Environment, Climate Change and Technology, 2023) which are the source of film microplastics. Moreover, the low abundance of film microplastics compared to fragments and fibres may also be due to films being more susceptible to degradation as it is thin and has a higher surface area, hence making it more difficult to identify (Corcoran, 2022).

5.2.3. Microplastic size

The highest total number of microplastics for all sizes; large, medium, extra small and small was found at the Industrial island (352, 743, 3982, 3377 particles/kg of sand respectively) and the lowest for all sizes was found at the Rural island (272, 619, 2402, 1269 particles/kg of sand respectively). The higher number of microplastics of all sizes at the Industrial island is due to the greater anthropogenic pressures and sources of plastic littered at the site, which break down over time to produce high numbers of microplastics of all sizes (Thushari & Senevirathna, 2020); compared to the Rural island where less plastics were introduced at the site. Large microplastics were the least abundant and the small particles were most abundant at all sites and extra small particles were less abundant than small particles. According to Song *et al.*, (2015) abundance of microplastics detected increased with the decline in size, this was observed in this study as well with small microplastics being the most abundant, this may be due to the formation of more small particles by the degradation of larger microplastics due to exposure to sun and abrasion with sediments at the tides line. The less abundant results for extra small microplastics may have been due to underestimation of the abundance as they are more difficult to identify (Song *et al.,* 2015). Larger particles were less abundant at all the sites as they may have been in the environment, exposed to degradation conditions and been broken down over time to produce more smaller microplastics.

5.3. Hypothesis 3. Impact of ocean currents on microplastic abundance

As seen in the results section, there was no macro or mesoplastics on the Rural island sites, however, the microplastic abundance in the samples collected from the Rural island (506.8 ± 48.6 microplastics per kg of sand) was not significantly different to that of the Urban island (600.8 ± 68.0 per kg of sand). There are several other factors such as ocean currents which play a dominant role in transportation of the buoyant plastic particles that influence abundance. The ocean currents are caused by a complex interaction between different mechanisms, such as, tides, winds, waves, density gravity, Coriolis force that leads to Stoke drifts and Ekman and Geostrophic currents (Pattiaratchi *et al.,* 2022) which influences microplastic abundance. The shape, size and conditions of the plastic particles can show if they were from the island or underwent high levels of disintegration, and thus transportation (Imhof *et al.,* 2017).

The Rural island, Dhonfanu had a statistically significant higher proportion of small (52.65%) and extra small sized (27.82%) microplastic particles, as well as fragments that had rounded edges and smoothened sides (52.2%), compared to other sizes and shapes, indicating that the particles were deteriorated by UV light and abrasion with each other and ocean waves. High levels of broken-down particles shows that the particles were transported from other locations (Imhof *et al.,* 2017).

The ocean current direction on the day of sample collection (Figure 24) was northwards towards Dhonfanu from an urban island with a high anthropogenic influence, Dharavandhoo located within less than 3 km, suggesting that plastic pollution from Dharavandhoo can be transported to Dhonfanu. This can be further supported by the case study on the X-Press Pearl nurdle spill off of Sri Lanka, where 78 tonnes of plastic nurdles were released into the ocean due to an explosion and fire that occurred onboard, which started between the 22nd and the 25th of May 2021 and continued for 13 days while it was anchored ~9.5 km from the coast of

Colombo (Pattiaratchi *et al.,* 2022). On May 25th, a vast number of nurdles washed up on beaches closest and directly east to where it was anchored, subsequently, nurdles were also observed along the west coast of Sri Lanka. The ocean surface currents along with a particle tracking model showed that by the 29th of May, the particles detached from the coast and were carried offshore (Pattiaratchi *et al.,* 2022). This indicates that microplastics can be transported by ocean currents and winds to large distances within a short amount of time. Furthermore, research done by Onink *et al.,* (2021) also show that microplastics can be transported by ocean currents to large distances and only a day is required for microplastic particles to travel up to 10 km.

In addition to microplastic pollution from Dharavandhoo, it can also be from other islands such as the tourist island nearby, as well as from other countries, introduced through rivers and directly from activities such as fishing and shipping, that accumulated in the ocean over time and transported with ocean currents (Pattiaratchi *et al.,* 2022).

Therefore, the insignificant difference between the Rural island with limited inland human activities and plastic pollution sources and the Urban island which have high levels of plastic littered from the island, as mentioned in hypothesis 3, may be a result of the impact of ocean currents transporting microplastics from nearby islands and plastics that have accumulated in the ocean over time, accepting the hypothesis.

5.4. Plastic polymers

Identifying the microplastic polymers can help determine the more specific, main sources of pollution. Some common plastic polymers used in everyday products and found in marine and coastal environments include PP, HDPE, LDPE, PS, PES, PET, PA, PU and PVC (Andrady, 2017; Castelvetro *et al.,* 2021; Gewert *et al.,* 2015) and different polymers can be used for making different products that are used in different sectors such as medicine, construction, and everyday household items (Table 4). Therefore, identifying the polymers of microplastics found on the Maldivian beaches studied can help identify the specific sector or activities that contributed most towards pollution.

Table 4. *Plastic polymers commonly found in the environment and examples of products made from it. Adapted from Bergmann et al., (2015), Geyer et al., (2020) and Rodrigues et al., (2019).*

Polymer	Use
PE (HDPE & LDPE)	Bottles, plastic bottle caps, plastic bags, packaging, containers, cables, boats
PP	Water bottle caps, straws, food packaging, rope, cotton swab
PC	Bottles, clothing, medical equipment
PU	Foam products such as mattresses, pillows, and insulation
EPS/PS	Styrofoam, plastic cups
PVC	Cable insulation, pipes, hoses, windows, and door frames
PA	Fishing nets and lines
PET	Fabric, water bottle, cleaning product packaging
PES	Clothing and fabrics, cleaning products used in boat building and machinery

As mentioned in the results, since the highest number of particles fluorescence under FITC narrow, it can be approximated that the PE, PP, PC, PU, EPS, and PVC were the most common and hence, items such as packaging, single use beverage bottles and utensils, foam products such as takeaway containers and pipes are most likely to be the main specific sources of microplastic pollution in the Maldives. Low levels of particles under DAPI, may be due to the inefficiency of the use of NaCl solution to isolate PET particles that fluoresce under DAPI. Due to the inaccuracies in using this method to identify polymers, it cannot be said for certain which products were the main sources of microplastics, rather, these results can be used as a basis for further research to identify main sources for microplastics on these islands.

6. Conclusion

Despite the large number of negative impacts of plastic pollution; micro, meso and macro, on both the ecosystem, specifically marine environment and biodiversity and economy in countries such as the Maldives, there is a lack in research done on finding sources and how land use and ocean currents affect abundance and distribution of meso, macro, and microplastics.

This study shows that the islands studied in the Maldives; Thulusdhoo, Villingili, and Dhonfanu all had significant amounts of microplastics pollution levels, and were greater compared to other coastal regions, both in the Indian Ocean and other regions of the world. Observations of macro and mesoplastic pollution at the sample collection sites in addition to microplastic quantification in the samples at the chosen islands with different land use intensities; Industrial, Urban and Rural, showed that the land use impacted plastic pollution as the Industrial island had a statistically significantly higher microplastic pollution followed by microplastic abundance on the Urban and Rural islands. However, other factors such as ocean currents can also influence microplastic abundance. As such, the microplastic pollution at the Urban and Rural islands were not statistically significantly different; however, the size and shape of microplastics found on these along with the ocean current direction model showed that this could be a result of transportation of plastics by ocean currents to the Rural island.

7. Direction for future research

Future work should address other factors affecting microplastic abundance and distribution such as rainfall, which can be covered by carrying out the research over a longer period of time during different monsoon seasons, as well as on different islands at a larger spatial scale. Additionally, FTIR or Raman spectroscopy should be done to increase the accuracy of the microplastic quantification and prevent under or overestimation; and in addition, to confirm the plastic polymers found and hence identify the specific sources of pollution to frame a solution to reduce and prevent plastic pollution in t he Maldives.

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