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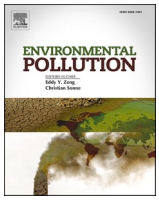

Microplastic trapping efficiency and hydrodynamics in model coral reefs: A physical experimental investigation☆

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ABSTRACT

Coastal ecosystems, such as coral reefs, are vulnerable to microplastic pollution input from proximal riverine and shoreline sources. However, deposition, retention, and transport processes are largely unevaluated, especially in relation to hydrodynamics. For the first time, we experimentally investigate the retention of biofilmed microplastic by branching 3D printed corals (staghorn coral *Acropora* genus) under various unidirectional flows (U = {0.15, 0.20, 0.25, 0.30} ms^{-1}) and canopy densities (15 and 48 corals m^{-2}). These variables are found to drive trapping efficiency, with 79–98% of microplastics retained in coral canopies across the experimental duration at high flow velocities (U = 0.25–0.30 ms^{-1}), compared to 10–13% for the bare bed, with denser canopies retaining only 15% more microplastics than the sparse canopy at highest flow conditions (U = 0.30 ms^{-1}). Three fundamental trapping mechanisms were identified: (a) particle interception, (b) settlement on branches or within coral, and (c) accumulation in the downstream wake region of the coral. Corresponding hydrodynamics reveal that microplastic retention and spatial distribution is modulated by the energy-dissipative effects of corals due to flow-structure interactions reducing in-canopy velocities and generating localised turbulence. The wider ecological implications for coral systems are discussed in light of the findings, particularly in terms of concentrations and locations of plastic accumulation.

1. Introduction

There remain several uncertainties in relation to the transport and ultimate fate of microplastics in the aquatic environments due to discrepancies between modelled and observed data, with the "missing plastic" phenomenon unresolved. However, the trapping of microplastics (<5 mm diameter) in aquatic ecosystems has recently been documented in coral reefs, seagrasses, saltmarshes, and mangroves (Cozzolino et al., 2020; Li et al., 2018; Ogbuagu et al., 2022; Unsworth et al., 2021), with these environments having the potential to act as microplastic sinks. These habitats are the foundation of biodiverse and productive ecosystems, providing shelter, nursery grounds, and nutrients for a diverse range of species, along with ecosystem services for hundreds of millions of people (Barbier et al., 2011; El-Naggar, 2020; Woodhead et al., 2019). Yet, these environments may also provide subsequent transfer of microplastics through the food web (Auta et al., 2017). Submerged seagrasses and corals produce expansive bed-covering 'canopies' that modulate particulate transport and retention processes (Gacia et al., 1999). Despite this, the knowledge of microplastic transport and deposition processes within these canopies is limited, as are the underlying hydrodynamic drivers (Soares et al., 2023).

Scleractinian coral, such as *Acropora* genus, have been identified as a potential sink for microplastic pollution (Reichert et al., 2021). *Acropora* form structurally complex canopies that are one of the most biodiverse ecosystems globally, with 25% of all ocean species being found on reefs (El-Nagger, 2020). However, reefs are at risk from many anthropogenic drivers, including rising sea temperatures, which may be accentuated by

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pollutants such as microplastics (Hughes et al., 2017; John et al., 2022). Reefs are particularly at risk of microplastic pollution due to their coastal location and the mainly terrestrial origin of marine plastic waste, with shallow reefs being particularly in danger at low tide as microplastics are more likely to settle within the canopy (Lebreton et al., 2017; Reichert et al., 2018; Forsberg et al., 2020). The entrapment of microplastics by coral reefs may increase the likelihood of ingestion, causing negative impacts including reduced photosynthetic capability and growth, bleaching, and feeding impairment (Corinaldesi et al., 2021; Mendrik et al., 2021; Reichert et al., 2019). These long-term impacts could be widespread, influencing the numerous species that rely on reefs for survival and wider ecological communities dependent on corals for ecosystem services. Therefore, there is a need to systematically study the transport and trapping dynamics of microplastics in reefs given the likely exposure and associated risks with microplastic accumulation.

A limited number of studies have started investigating the drivers of plastic trapping in various aquatic canopies (Cozzolino et al., 2022; de los Santos et al., 2021; de Smit et al., 2021) but our understanding of the mechanisms and controls on microplastic trapping remains incomplete, especially for corals. Microplastic transport processes depends on particle size, shape, relative density, biofilm formation, and interaction with other suspended materials (Mendrik et al., 2023; Waldschläger et al., 2022). Furthermore, recent studies have shown that different coral species, morphologies and polyp sizes ingest and accumulate varying levels of microplastics (Martin et al., 2019a,b; Zhou et al., 2022). Depositional spatial distribution is also known to be influenced by hydrodynamic conditions which are modulated by canopy morphology, and therefore a combination of bio-physical factors will determine particle fate and entrapment (de los Santos et al., 2021; Zhang, 2017). Studies have shown that particle capture is elevated with increases in habitat complexity, higher turbulence, and erosive processes allowing more seeds to be trapped by seagrass and bivalves (Meysick et al., 2019); which is strongly influenced by canopy density. Flume experiments showed that seagrass can retain floating plastic at several flow velocities and trap negatively buoyant microplastics due to erosive processes forming scour around the stem shoots (de los Santos et al., 2021). The canopy influence on hydrodynamics identified in these studies may also occur within coral canopies and modulate the microplastic trapping, yet this remains unquantified. Individual coral and macroalgae have been tested for their ability to accumulate microplastics using a field flume, with corals capturing the highest number of particles in their canopy structure (de Smit et al., 2021); yet the hydrodynamic processes controlling particle retention was not tested and thus the controls are undetermined.

The fundamental flow and turbulence characteristics within coral reefs have been presented in several publications (Davis et al., 2021; Monismith, 2007; Pomeroy et al., 2023); however the hydrodynamics remain only partially quantified due to vast natural variability. Flow velocities reduce with distance downstream of a canopy and this flow adjustment length is influenced by canopy density (Belcher et al., 2003; Chen et al., 2013). Within a canopy, flow can be accelerated or attenuated, creating flow velocity gradients and turbulence which modulates the transport and residency time of sediment particles (Abdolahpour et al., 2020; Lefebvre et al., 2010; Ortiz et al., 2013; Tinoco and Coco, 2016). A reduction in bottom shear stress can hamper sediment resuspension and trap particles into the bed (Bos et al., 2007; Gacia and Duarte, 2001). Therefore, these habitats may facilitate microplastic trapping and accumulation (de Smit et al., 2021). These flow characteristics and canopy properties are proposed to be fundamental controls on microplastic transport and trapping in canopies yet are largely unevaluated. Here, we explore the role of complex coral structures on the transport and trapping of microplastics in relation to the underlying hydrodynamics using physical modelling under various flow conditions and coral densities.

The aim of this study is to determine the microplastic trapping mechanisms and efficiency of coral structures, and the relation to the associated hydrodynamics. Specifically, this paper addresses the following questions (i) How are microplastics passively trapped in coral canopies? (ii) What is the influence of coral density and bulk flow velocity on the spatial distribution and trapping efficiency of microplastic? (iii) To what extent does canopy-scale hydrodynamics modulate microplastic trapping?

2. Materials and methods

2.1. Microplastic particles

Secondary microplastic particles in the form of fragments of recycled, ground melamine plastic, density 1.6 g/cm^3, formed the test polymer (sourced from: Emriver Modeling Media,). The polymer tested here are fragment shaped to represent natural degradation, and negatively buoyant as per most microplastics found in coral reefs (Huang et al., 2023; Miller et al., 2023; Patterson et al., 2022) in addition to being a recognised plastic pollutant (Ashrafy et al., 2023). Fragments were sieved to fractions of a range of 1–5 mm, ensuring fragmentation of plastic and heterogeneous shapes and sizes that replicates the environmental degradation in aquatic environments (Rummel et al., 2017). The test microplastic fragments were colonised with biofilms following Mendrik et al. (2023). Benthic sediment and overlying water was collected from the Humber River, Hull, UK. Fifty grams of sediment and 200 ml of river water was placed in flasks with microplastics in a shaking incubator for 10 days at 37 °C, 200 rpm. The flasks were then left at room temperature for 2 weeks. Fragments were soaked overnight in water of the same salinity and temperature as the experimental environment to ensure no electrostatic discharge from particles, which could alter transport behaviour. The inclusion of biofilms ensured representation of plastics found in the environment, and to account for associated modifications to particle trajectory due to changes in buoyancy (Hoellein et al., 2019; Mendrik et al., 2023), which has considerable implications from a hydrodynamic and transport perspective (Lagarde et al., 2016; Rummel et al., 2017).

2.2. Surrogate canopies

Coral colonies were replicated using prototype model of a staghorn coral *Acropora* genus (Cults3D, 2020). The prototype 3D-model was manually created using images of staghorn coral as a reference using 3D sculpting software (Zbrush). Staghorn corals are branching, stony corals with branch sizes from a few centimetres to over 2 m, encompassing approximately 160 species and around one-fifth of extant reef-building corals globally (IUCN, 2009). 3D-printed models were produced from the prototype printed in recycled polylactic acid (PLA) with a base diameter d_s = 0.10 m and height h_c = 0.15 m, with 11 branches of various lengths and diameters, including micron scale surface roughness, providing an exposed surface area of 0.01833 m^2 (Fig. 1, supplementary material). The models were produced using an Ultimaker S5 3D and Artillery Sidewinder X1 printers, using Filamentive recycled PLA (rPLA) filament with a maximum diameter of 2.85 mm and printed at the original file scale. Two coral canopy densities were simulated to encompass various reef formations, defined as *sparse* (15 corals m^{-2}) and *dense* (48 corals m^{-2}) (Fig. 1b). Individual canopy elements of coral were populated on a baseboard (10 mm thick) in a systematic staggered geometry to produce a full canopy spanning the entire flume width of 0.50 m of length 1.85 m located in the flume centre (Fig. 1a). The canopy length exceeded 10 h_c to encompass a developing flow regime downstream of the leading edge. A thin layer of fine silica sand (d_{50} = 120 μm) was fixed to the top surface of the baseboard to provide surface roughness comparable to natural environments. This baseboard was also used within a control experimental run to represent a bare bed devoid of coral canopies.

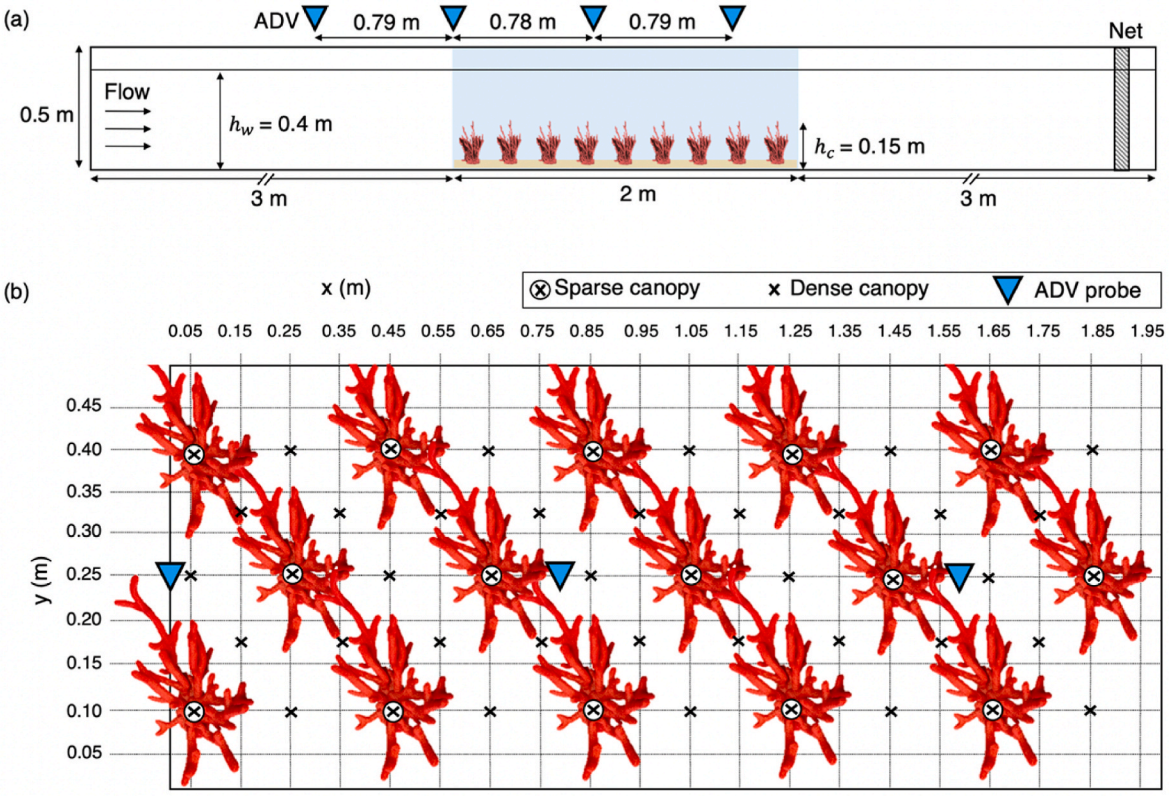

Fig. 1. The experimental setup: a) flume side view schematic, and b) sparse and dense corals arrangements, and acoustic Doppler velocimeters (ADV) probe locations.

2.3. Experimental setup and scenarios

Physical model experiments were conducted using a flume of length 8.00 m, width 0.50 m, and depth 0.50 m at the University of Hull, UK (Fig. 1 a. The coordinate system x, y, z has origins at the upstream canopy edge, the outer channel wall, and the baseboard top. Experiments were operated under unidirectional flow with a standing water depth of (h_w) 0.40 m, producing a submergence ratio (h_c/h_w) of 0.38, consistent with the natural environment (de los Santos et al., 2016).

Microplastic retention within each canopy was measured at four bulk incoming velocity conditions, U = 0.15, 0.20, 0.25, 0.30 ms^{-1}, relating to velocities typically found in shallow coral reefs (Johansen, 2014). The corresponding Reynolds numbers ($Re = Uh_w/\nu$) ranged between 6.0 × 10^4 and 1.2 × 10^5; whereby ν is the water kinematic viscosity (≈1.0 × 10^{-6} m^2 s^{-1}).

A set weight (80 g) of microplastic fragments was tested per canopy density (sparse, dense, and bare bed) at four flow velocities, resulting in 12 scenarios. Before each simulation, the flume was operated for 2 min to allow flow stabilisation. Plastic fragments were released at a constant rate for 10 min via a siphon submerged 0.05 m below the water surface. The distance of release was determined based on the flow speed to ensure microplastics were in suspension when they entered the front of the canopy. Upon introduction of all microplastics, the flume was run for 1-h, enabling assessment of transport rates and processes during this time. A downstream net captured any microplastics not trapped in the canopy (Fig. 1a). While previous research has detailed ingestion of microplastic by corals over longer timeframes (Mouchi et al., 2019; Rades et al., 2022; Reichert et al., 2021), this study demonstrates microplastic trapping at a canopy-scale and demonstrates trapping can occur over a much shorter time frames.

2.4. Data acquisition and processing

Microplastic distribution was recorded by overhead cameras at x = 0.07 m, 0.90 m, and 1.70 m, and side images at x = 0.12 m and 1.10 m. Images were manually digitised to determine the spatial distributions. Following each run, the microplastics downstream of the canopy were dried, and weighed quantify microplastic retention percentage within the canopy. All retained microplastics were removed after each run.

Bulk incoming flow velocities, U ($U = Q/A$), were calculated based on the incoming flow depths, discharge (Q), and channel cross sectional area (A). Instantaneous streamwise (u) and vertical (w) flow velocities were acquired using acoustic Doppler velocimetry (ADV; Nortek Vectrino) at a sampling rate of 50 Hz for 5 min at x = −0.78 m, 0.00 m, 0.79 m, and 1.57 m (Fig. 1a) for twelve vertical positions with profile centres between z/h_c = 0.06 and 1.99. To minimise noise, only the data from each profile centre is presented in the results. ADV beam data with a signal-to-noise ratio below 30 discarded from further analysis. The time-averaged streamwise ($\overline{u}$) and vertical velocities ($\overline{w}$) are defined as the mean of instantaneous velocities acquired at each elevation, whereby streamwise turbulent velocity fluctuations, $u' = u - \overline{u}$. Velocities were acquired separately from the microplastic data acquisition to avoid disruption to the flow. Several branches were removed from the dense canopy to enable data acquisition close to the bed, with minimal disruption to flow dynamics.

3. Results

3.1. Microplastic retention

Herein, *microplastic retention* represents the amount (percentage) of microplastics remaining within a canopy after the 1-h experimental duration, and *trapping efficiency* refers to comparison of microplastic retention between scenarios, whereby a higher trapping efficiency

corresponds to greater magnitude of microplastic retention. Microplastic retention within the canopy varied depending on the canopy density and incoming flow velocity (Fig. 2). For the bare bed conditions, the majority of microplastics were retained at low velocities: 99.2% at $U = 0.15$ m s^{-1} and 81.7% at $U = 0.20$ m s^{-1}. Trapping efficiency notably reduced at higher velocities, with retention of 13.0% at $U = 0.25$ m s^{-1} and 10.4% at $U = 0.30$ m s^{-1} (Fig. 2a). For the sparse and dense coral canopies, the microplastic retention was comparative across bulk velocities. At low velocities ($U = 0.15$ and 0.20 m s^{-1}), trapping efficiency was very similar and substantial for both sparse and dense canopies, with 99.3–99.9% retained (Fig. 2b and c), whereby the dense canopy only retained between 0.1% and 0.4% more. Trapping efficiency decreased slightly at $U = 0.25$ m s^{-1} with 92.3% of microplastics being captured for the sparse canopy and 97.7% for dense (5.4% more than sparse). At $U = 0.30$ m s^{-1} the trapping efficiency decreased further, with the sparse canopy trapping 79.3% and 94.4% within the dense coral condition (15.1% more than sparse).

3.2. Microplastic spatial distribution

The microplastic spatial distribution and deposit patterns at the end of each run provides further insight into the percentage retained. Fig. 3 (c, d) shows microplastic distribution at the end of each experiment, which are distinguished into regions of high accumulation and low accumulation. High areas of accumulation were assigned where microplastics deposits fully covered the bed (i.e. no bed was visible through the deposits) whereas low areas of accumulation areas expressed fragmentation in the microplastic deposits (i.e the bed was visible through deposits). The downstream distribution of microplastics increased with larger incoming bulk velocities (U), which is delayed for the dense canopy relative to the sparse.

For the sparse canopy (Fig. 3c), at $U = 0.15$ m s^{-1} the majority of microplastics were deposited within the first metre ($x < 1.00$ m), with a high accumulation occurring in the spanwise centre. Additional coverage of low accumulations occurred in the downstream regions of each individual coral. As bulk velocity increases to $U = 0.20$ m s^{-1}, the central high accumulation areas gradually extend into the second meter and become more fragmented in distribution. As bulk velocity increases to $U = 0.25$ and 0.30 m s^{-1}, the central high accumulation becomes more laterally dispersed to form high accumulation deposits downstream of each coral. Microplastics were also occasionally trapped on branches or within the coral structure itself, for example for $U = 0.15$ m s^{-1} at $x = 0.35$ m (Fig. 3a).

For the dense canopy (Fig. 3d), the majority of microplastics were located within the first metre of the canopy despite an increase in bulk velocity. At $U = 0.15$, 0.20, and 0.25 m s^{-1}, a large amount was retained between $x = 0.00$–0.75 m, whereas for $U = 0.30$ m s^{-1} the majority was dispersed between $x = 0.50$–1.25 m. This central area of high accumulation remains a unified body with bulk velocity increase, differing from observations in the sparse canopy. Upstream of this unified body, hotspots of microplastic deposits are present in the wake of each coral. Low accumulation deposits were observed downstream of the high accumulation regions at all velocities and end towards the end of the canopy at higher velocities, exceeding the canopy extent by $U = 0.25$ ms^{-1}. A considerable amount of microplastics were observed to be collecting on the branches and within the coral structures (Fig. 3b) and behind the corals for example at $x = 0.20$ m (Fig. 3d).

3.3. Microplastic transport

Microplastic retention was promoted by a higher canopy density and slower incoming bulk flow velocity (Fig. 4). Fig. 4a reveals that the percent of microplastic retention decreases relative to incoming bulk velocity for a given canopy density. A linear trendline provides an indication of the rate of change in microplastic retention relative to incoming bulk velocity, referred to as the *transport capacity*. Steeper trendlines indicate faster rates of microplastic transport and therefore greater transport capacity, which is shown for the sparse canopy compared to the dense canopy. The trendlines reveal that the transport capacity in the sparse canopy is 4 times greater than the dense canopy, but the transport capacity in the bare bed is 5 times greater than the spare canopy and 18 times more than the dense canopy. Although the processes are expected to express non-linearity if considered outside of the flow velocities tested.

The distribution of microplastic retention throughout the canopy at the end of each run is summarised in Fig. 4b, with the median x location of high accumulation (as per Fig. 3) occurring further downstream with increase bulk velocity. This is accompanied by an increased longitudinal spread in deposit distribution throughout the dense canopy. At any given bulk incoming velocity, the median location of deposition of high accumulation areas occurs 2.5 times further downstream in the sparse canopies than dense canopies. The use of bulk velocity in Fig. 4b does not account for flow development effects, hence canopy time-averaged hydrodynamics are presented in a subsequent section (3.4).

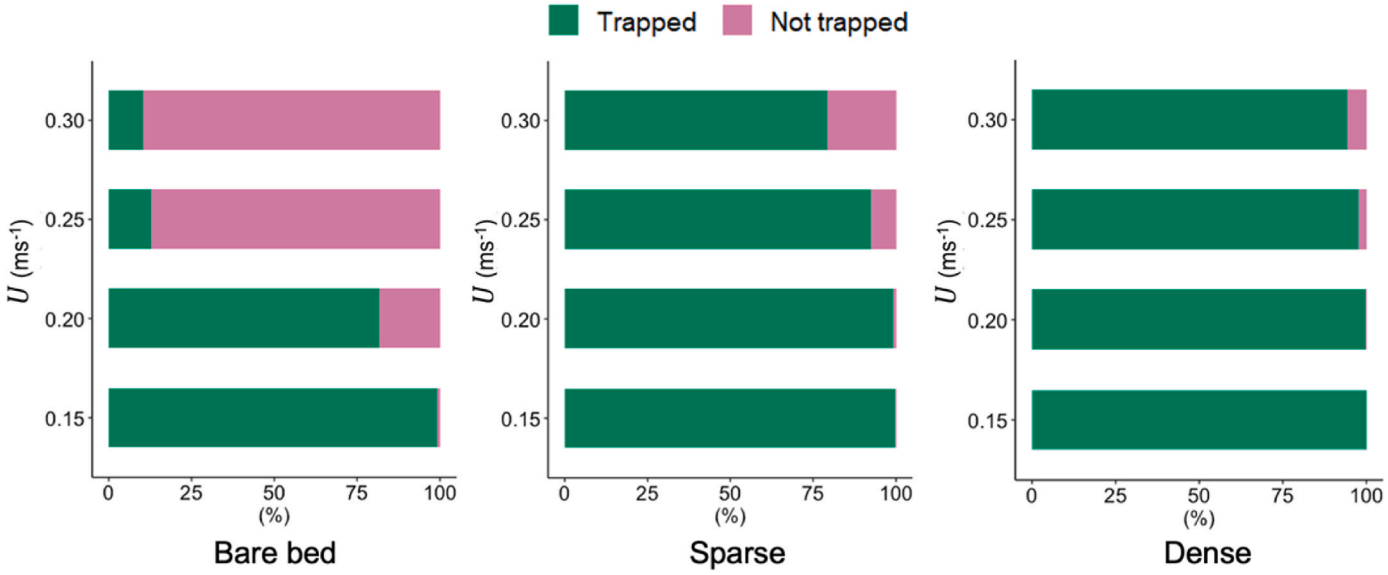

Fig. 2. Microplastic retention (%) after the 1-h test period at varying incoming bulk velocities for a) bare bed b) sparse coral and c) dense coral canopies.

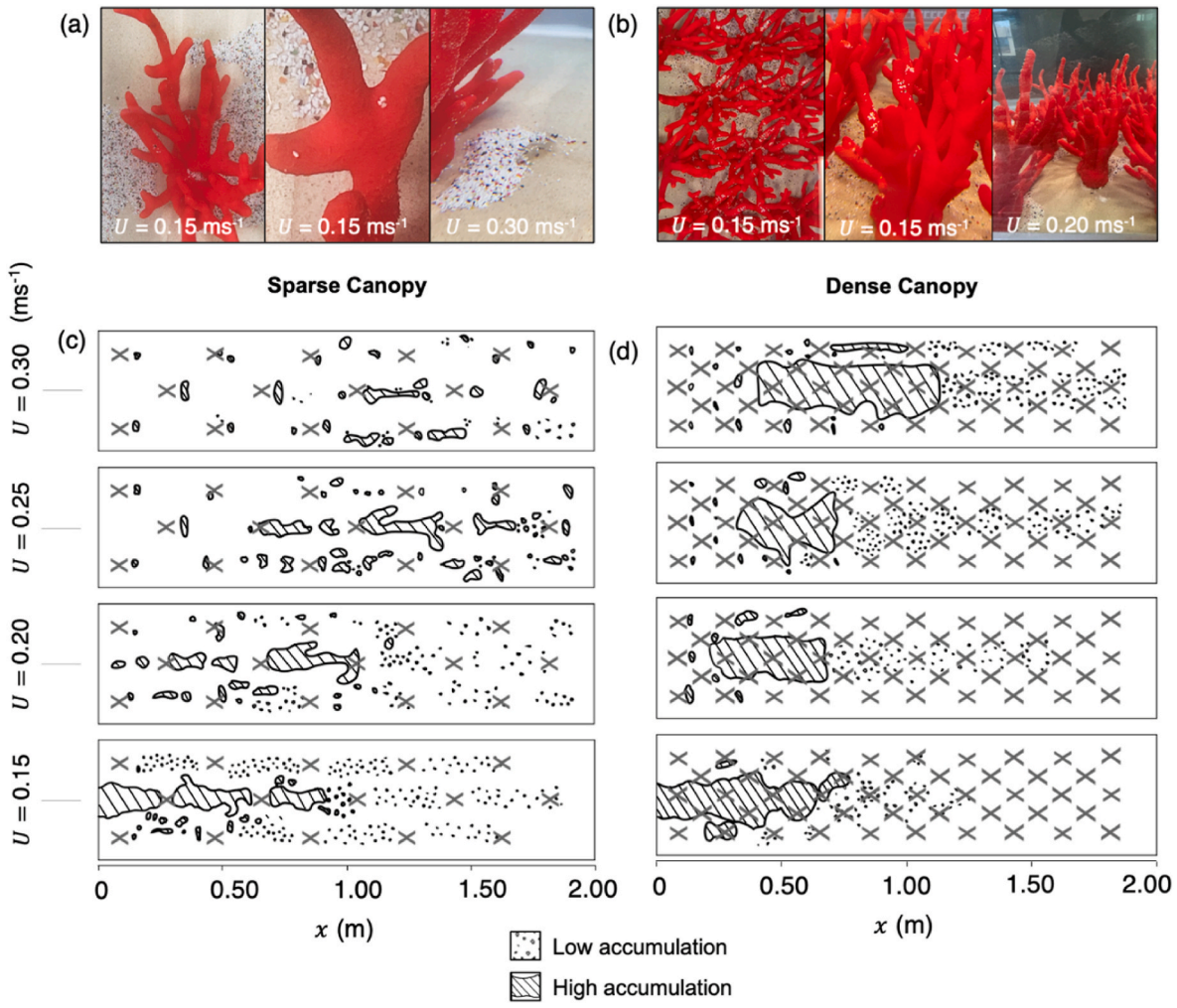

Fig. 3. (a,b) photograph examples of microplastic deposition in the (a) sparse and (b) dense canopies. (c,d) diagrams of the spatial distribution and accumulation of microplastics within (c) sparse and (d) dense coral canopies at varying bulk velocities. Each coral is represented by a cross. Produced from overhead photos at the end of each experimental run.

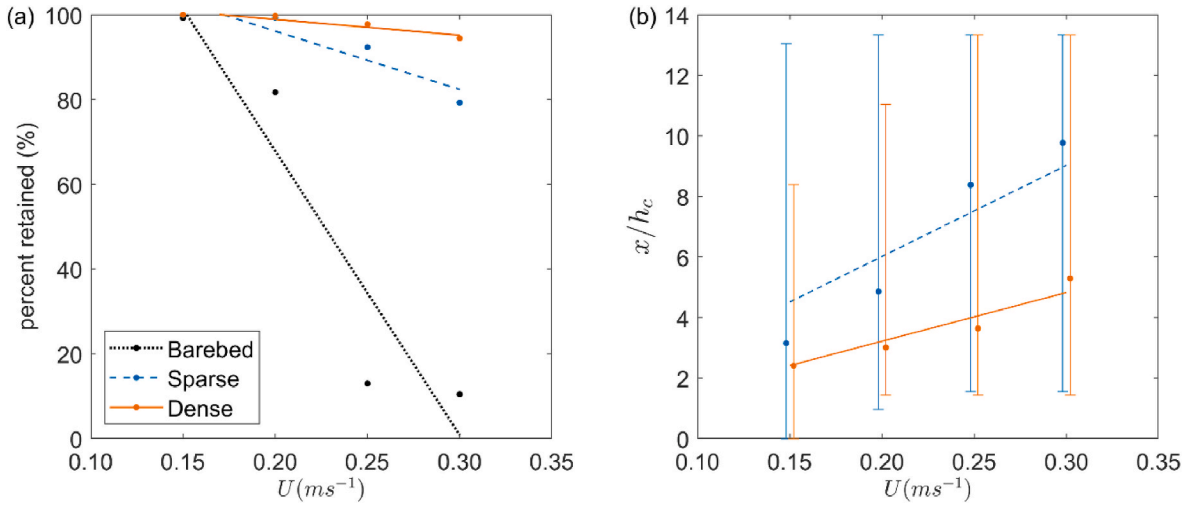

Fig. 4. (a) Microplastic retention (%) in canopy after each run relative to bulk incoming velocity and canopy density, (b) spatial downstream extent of microplastic accumulation within the canopy at the end of each run, dots mark median location of the high accumulation areas (normalised by canopy height) and error bars indicate extent of low accumulation deposits.

3.4. Time-averaged hydrodynamics

The hydrodynamics within and above the canopies are presented by the time-averaged streamwise velocity ($\overline{u}$) and dimensionless Reynolds shear stress ($-\overline{u'w'}$) profiles throughout the flume at all incoming velocities (Fig. 5). For comparison, the profile characteristics at a given horizontal and vertical location are comparable under differing incoming bulk flow conditions, yet increase in magnitude with bulk incoming velocity. Hence, evaluation of flow conditions at $U = 0.20$ m s^{-1} provide a representative case to explore the hydrodynamics throughout the canopies, and the corresponding bare bed profiles are included in Fig. 5.

Upstream of the canopy ($x = -0.78$ m) all streamwise velocity profiles are comparable indicating uniform incoming flow (Fig. 5 a,b). At the canopy front ($x = 0$ m) the $\overline{u}$ profiles follow a logarithmic profile, with the sparse canopy profile expressing a slight deviation from the bare bed, with a reduction in $\overline{u}$ for $z < 0.10$. Here, the dense canopy deviates notably, with a reduction in $\overline{u}$ below the canopy top ($z < 0.15$), with the greatest reduction occurring near the bed. The Reynolds shear stresses (representing the turbulent fluctuations in fluid momentum) in-front of the canopy are negligible due to the lack of fluid-structure (flow-coral) interactions (Fig. 5 c,d). Within the canopy, at $x = 0.79$ m the streamwise velocity profile for both coral canopies deviate considerably from the bare bed, with the formation of a classical inflection point in the profile and strong velocity gradients (Fig. 5 a,b). This corresponds with an increase in streamwise velocity above the canopy where a free stream layer is present ($z > 0.20$ m), the flow is notably reduced within the canopies, whereby the sparse canopy $\overline{u}$ tends to zero and becomes slightly negative ($z < 0.03$ m), while the dense conditions remain positive. This is accompanied by a strong distinct peak in $-\overline{u'w'}$ at the top of the dense canopy, alternatively this canopy top peak is not present in the sparse canopy, instead a lower magnitude broad peak occurs within the canopy between $z = 0.06$ and 0.12 m (Fig. 5b). At $x = 1.57$ m the magnitude of $-\overline{u'w'}$ peaks at the canopy top increase in magnitude, and a peak is introduced for the sparse canopy whose magnitude exceeds the dense canopy and extends into the canopy ($z < 0.15$ m).

The strong peak in $-\overline{u'w'}$ at the dense canopy top at $x = 0.79$ m and 1.59 m is present irrespective of incoming bulk velocity (Fig. 5c). For all bulk incoming flow velocities, the respective $-\overline{u'w'}$ far inside the canopy ($z < 0.10$) is of higher magnitude for the sparse canopy compared to the dense, which increases systematically with incoming bulk flow velocity at $x = 1.57$ m. Although the increase in $-\overline{u'w'}$ with $\overline{U}$ is shown to be non-linear.

4. Discussion

Here we investigated for the first time the microplastic trapping efficiency and mechanisms in coral canopies under experimental conditions using *Acropora* genus as a model species for 3D replicates. Our experiments demonstrated that coral canopies can ultimately act as sinks for microplastics, which is driven by relationship between the ecosystem properties and hydraulic (ecohydraulic) conditions. Microplastic trapping occurred at all flow velocities for sparse and dense coral canopies, with higher trapping efficiency than bed devoid of corals, especially at high flow velocities. Previous studies have observed no difference in microplastic retention between seagrass and unvegetated areas, while others report greater accumulation in meadows compared to bare beds, which may be explained by differences in canopy density and flow dynamics (Cozzolino et al., 2020; Huang et al., 2020).

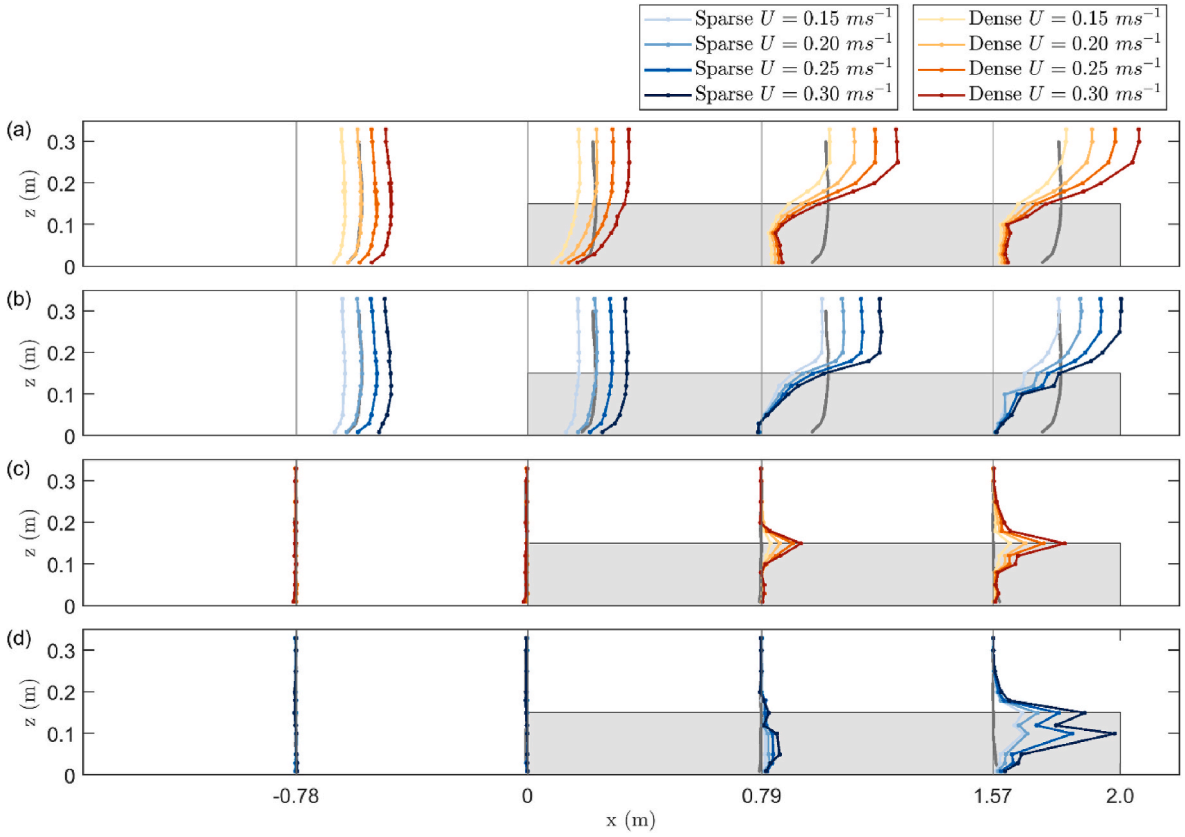

Fig. 5. (a–b) Time-averaged streamwise velocity ($\overline{u}$) profiles at for bare bed and canopies throughout the flume. (c–d) time-averaged dimensionless Reynolds shear stresses ($-\overline{u'w'}$). Thick grey profile indicates the bare bed at $U = 0.20$ ms^{-1}.

4.1. Microplastic trapping mechanisms

To answer research question (i) "How are microplastics passively trapped in coral canopies?", several trapping mechanisms are identified in coral structures: (a) particle interception by the coral and settling to the bed, with the coral acting as a barrier, (b) microplastics settling on to the coral branches or becoming trapped within the coral structure itself, and (c) accumulation in the downstream wake zone of individual corals (Fig. 6a,b,c). Fig. 6 d,e depicts the flow contours around the corals, supporting visual interpretation of the correspondence to the trapping mechanisms in Fig. 6 a-c.

We observed the passive removal of microplastics by corals, where the structure of the canopy resulted in microplastic trapping. Passive mechanisms have been observed previously, where adhesion of microplastics to the coral surface was identified to be the primary mechanism of coral trapping particles, compared to active removal through ingestion (Corona et al., 2020). In our study, corals acted as a barrier, initiating increased deposition of microplastic accumulation within seabed sediments. This has been confirmed by field studies, with sediments adjacent to reefs identified as major accumulation sites of microplastics (Jeyasanta et al., 2020; Näkki et al., 2017; Utami et al., 2021). In addition, microplastic accumulation in the downstream wake of corals (Fig. 6c) was observed in both the sparse and dense canopies. The microplastics were seen to be transported as bedload in the streamwise direction before becoming trapped in flow recirculation in the wake of the coral (Fig. 6e).

Furthermore, microplastics were observed to settle on the branches and within corals during all scenarios (Fig. 3 a, b and Fig. 6b), suggesting that a coral organism would interact directly with microplastics. Given corals screen large volumes of water through suspension feeding (Reidenbach et al., 2006), the behaviour of live coral in response to microplastics requires consideration when determining trapping efficiency and the combination of passive and active trapping mechanisms requires more investigation (section 4.4).

The trapping mechanisms presented were observed within both canopy densities and at all velocities tested, although differences were seen between canopies. The sparse canopy featured a greater spatial dispersal of microplastics with fewer collecting on the coral branches compared to the dense canopy, where microplastics tended to remain on coral structures with more high accumulation areas (Fig. 3). Accumulation in the downstream region of corals occurred for both coral canopies but was notably more concentrated at higher flow velocities (Fig. 3a). It is apparent that for the sparse canopy, individual corals were impacting the settling of microplastics independently, whereas for the dense canopy the impacts were due to interactions of multiple corals in close proximity. This is evidenced by the isolated deposits in the wakes of coral in the sparse canopies, in contrast to larger unified deposits in the dense canopies (Fig. 3). To fully evaluate the flow and microplastic interaction with coral branches, it is recommended that future research utilise particle tracking of the microplastics and advanced measurement of full flow fields.

While only one polymer type was tested in this study, the identified trapping mechanisms are believed to be applicable irrespective of polymer type given the hydrodynamics remain unchanged. Negative buoyancy promoted interaction and deposition on the bed, while more buoyant polymers are expected to be more commonly observed in the water column. Here, microplastics were trapped on the bed, stimulating future studies to consider the potential of microplastic burial and accumulation within bed sediments especially in aquatic canopies (de Smit et al., 2021), with the potential for resuspension requiring future assessment. The transport processes of different polymers are expected to introduce additional complexity and dynamics in the trapping

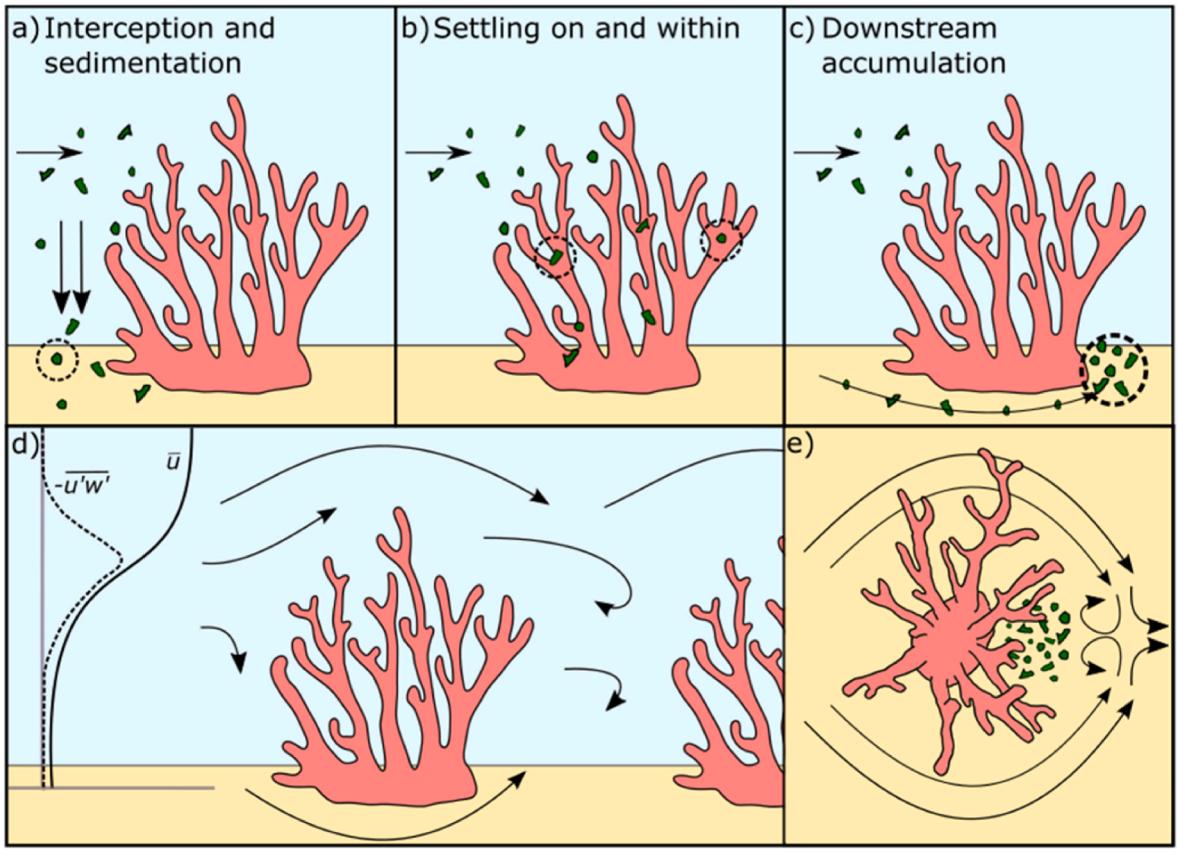

Fig. 6. (a–c) coral microplastic trapping mechanisms, and (d–e) the associated fundamental hydraulic profiles and flow contours (arrows) as supported by supplementary video 1.

mechanisms which will be modulated by the turbulence driven suspension. It is proposed that particles with greater buoyancy (lower specific density), such as polypropylene (PP) and polystyrene (PS), have higher potential for suspended transport, hence several conjectures associated with trapping can be presented: (i) microplastics may become trapped within coral wakes in suspension (not on the bed), (ii) transport of microplastics in the canopy mixing layer could settle on branches following movement into the canopy via sweep turbulent events and hence change the distribution of deposits, (iii) downstream trapping is expected to occur only when near-bed stresses are sufficiently low (this threshold is unknown). There is also the potential of vertical microplastic exchange in and out of the canopy. Assessment of this remains open for further investigation.

4.2. Microplastic trapping efficiency

For research question (ii) "What is the influence of coral density and bulk flow velocity on the spatial distribution and trapping efficiency of microplastic?", several differences in transport efficiency were identified. Trapping efficiency varied with canopy density and flow velocity (Fig. 2), whereby particle retention increased at lower flow velocities and higher density canopy. Although the relationship is non-linear, as the dense canopy captured 15% more microplastics than the sparse canopy at $U = 0.30$ ms^{-1} but only 0.1% more at $U = 0.15$ m s^{-1}. While only small differences in microplastics retained were observed between sparse and dense coral canopies, the variation in spatial distribution was notable (Fig. 3 c, d). Within the sparse canopy, microplastics typically accumulated throughout the entire canopy, while within the dense arrangement, high accumulation occurred within the first meter at all flow velocities. This reflects findings of microplastic retention by other marine canopies (seagrass) which also increase with lower velocities and higher shoot densities (de los Santos et al., 2021). Given the experimental duration of 1-h, a reef may increase the residence time or trapping efficiency of microplastics rather than fully capturing it and stopping its trajectory.

4.3. Hydrodynamic influence on microplastic trapping

Submerged canopies modify canopy hydrodynamics (Nepf, 2012), with flow velocities a principle driver of microplastic accumulation in seagrass meadows (de los Santos et al., 2021). Hence, hydrodynamics provide explanation of microplastic distributions and transport recorded within the coral canopies and are detailed below, answering research questions (iii) "To what extent does canopy-scale hydrodynamics modulate microplastic trapping?".

Identification and explanation of the spatial hydrodynamic features is required to support subsequent evaluation of the modulation of flow on microplastic trapping and transport. Streamwise velocities are linked to bulk mass movement, while the Reynolds shear stress represents the transport of momentum which signifies the mass transfer of fluid (Reidenbach et al., 2007). Flow adjustment was recorded for both canopies, whereby canopy streamwise velocity profiles deviate from the bare bed. Streamwise velocity decreases at the canopy front and within the canopies due to flow impedance by the canopy drag (Nepf, 2012), while incoming flow is forced up and over the canopy (Nepf and Vivoni, 2000). The dissipation of energy within the canopies corresponds with turbulence generation at the canopy-water interface, which is determined by the canopy properties (Nepf, 1999). The inflection point in the streamwise velocity profiles in at $x = 0.79$ m (Fig. 5a), and increase in Reynolds shear stress at the canopy top (Fig. 5b), represent a shear layer. This is indicative of a mixing layer containing large-scale vortices, flow instabilities, and elevated turbulence levels (Ghisalberti, 2002; Lefebvre et al., 2010). These processes are fundamental to sediment mobility, thus could be applied to microplastics (Lefebvre et al., 2010; Tinoco and Coco, 2016). Based on rigid canopy results of Houseago et al. (2022) at comparable Reynolds numbers, it is suggested the high Reynolds shear stresses at the canopy correlates to *sweep* quadrant analysis events. As such, the fluid at the canopy top is directed downwards and into the canopy, preventing any microplastics from exiting the canopy vertically, and thus streamwise transport dominates.

Given most microplastics had begun to settle on the bed upon entering the canopy, interaction with the developing mixing layer was limited and instead slowed down by the overall canopy induced bulk flow velocity reduction. As such, reduced in-canopy streamwise velocity and Reynolds shear stress within the dense canopy at $x = 0.79$ m provides explanation for the high accumulation of microplastics in the first meter of the canopy (Fig. 3 c, d), whereas microplastics are transported further downstream for respective sparse canopies. This can be supported by the slower rates of microplastic transport within the dense canopy, with our results demonstrating the sparse canopy is 4 times more efficient at transporting microplastics than the dense canopy. It is explanatory that microplastic transport distance corresponds with the canopy flow adjustment length, and the associated reduction in streamwise velocity with distance into a canopy (Belcher et al., 2003; Chen et al., 2013). The adjustment length is typically evaluated as relative to canopy height, such that mention of the first meter ($x = 1.00$ m) corresponds to $x/h_c = 6.5$; which is close to the developed flow region in dense canopies (see discussion in Hong et al., 2022), hence notable flow reductions from the canopy front. Given the adjustment length decreases with canopy density (Belcher et al., 2003; Chen et al., 2013), this provides an explanation for the greater median x distance of microplastic deposits within the sparse canopy. The longer adjustment length in the sparse canopy is further evidenced by the smaller magnitude peak in Reynolds shear stress at $x/h_c = 6.5$, indicating the shear layer is less developed. Direct measurement the flow adjustment lengths and distance of microplastic deposits within a canopy is required in future research, yet the known concepts and processes are explanatory and provide fundamental insights.

The spanwise distribution of microplastic accumulation within both canopies varied depending on density and velocity. For the sparse canopy, accumulation primarily occurred on the lee side of individual corals, especially along the canopy centreline (Fig. 3a). Negative streamwise velocities are recorded for the sparse canopy at $x = 0.79$ m (Fig. 5a) in the downstream wake for a coral, supporting the retention of microplastics in the middle of the canopy and behind the corals (Fig. 3c). This is explained by the development of a horseshoe vortex around the base of corals preventing the movement further downstream (Link et al., 2012). This conjecture is supported by supplementary video 1 and the visual circulation of microplastics in this regions, and is summarised in Fig. 6c,e. The permanent trapping of microplastics in the coral wakes indicates hydrodynamic processes control trapping. This is supported by microplastic retention throughout the sparse canopy in wake zones, despite the high accumulation region migrating further downstream in the sparse canopy (Fig. 4b).

While the bi-directional effects of wave driven flows were not tested here, they can enhance near bed flow relative to unidirectional flows (Lowe et al., 2005) and enhance mass transport deeper within the canopy (Reidenbach et al., 2007). Waves can prevent sedimentation and increase resuspension, theoretically resulting increased trapping in a coral structure following resuspension from the seabed, or a reduction of microplastic capture if particles are transported out of the canopy. There is a need to conduct comparable experiments under wave-driven flows, along evaluation of complex canopy heterogeneity and temporal changes in hydrodynamic forcing. However, in wave-driven environments, the generation of strong mean currents over canopies has been reported (Abdolahpour et al., 2017), providing comparability to the conditions presented here.

4.4. Ecological risk

Our experiments demonstrate how coral reefs can passively retain a considerable amount of microplastics due to their structural complexity,

especially at slower flow velocities and high canopy density. Exposure of reefs to microplastics can occur in several ways, especially at low tide, and is of increasing concern (Fisher et al., 2015). The full ecological implications of this must be considered.

Microplastics were observed on the branches and within coral structures, especially for the dense canopy at lower incoming bulk velocities (Fig. 3 a, b), highlighting how microplastics in the water column can come into contact with corals. Observations of microplastics in the water of reefs throughout the tropics including the Great Barrier Reef and the Maldives, suggest microplastics will be interacting with coral organisms (Hall et al., 2015; Saliu et al., 2018), especially as corals are unselective suspension feeders which tend to ingest particles in the range of 0.2–1000 μm (Anthony, 1999; Hall et al., 2015). With this evidence and the results from our study, it is highly likely that accidental ingestion is occurring *in situ*. Indeed, corals have been identified to ingest microplastic beads up to 2.8 mm in size (Hankins et al., 2018, 2021). Furthermore, there is growing evidence from laboratory studies that corals ingest microplastics which can result in several damaging impacts including reduced photosynthetic ability, feeding, growth, and survival (Allen et al., 2017; Chapron et al., 2018; Hall et al., 2015; Mendrik et al., 2021; Reichert et al., 2019, 2018). In addition, ingested microplastics can get stuck within gastrovascular cavities, or adhere to coral skeletons, resulting in permanent accumulation (Hierl et al., 2021; Krishnakumar et al., 2021; Reichert et al., 2018; Rotjan et al., 2019). As such, there is a high indication from the results presented that coral reefs will be exposed to, and may accumulate, microplastics, and therefore associated uptake and impacts could occur which could have considerable ecological implications. While the model corals simplify nature, the passive trapping mechanisms are expected to remain applicable. However, it is acknowledged that live corals will include additional variability in structural properties (coral shape, size, and species heterogeneity), in addition to polyps that are filter feeding and producing mucus, both of which are known to trap microplastic particles (Hall et al., 2015; Martin et al., 2019a,b).This highlights how live coral reefs may be trapping additional microplastics through active removal and therefore the combination of active and passive trapping should be considered in future studies.

The results presented here demonstrate that denser reefs are more likely to trap microplastics and retain a larger quantity (Figs. 2 and 3, d). Denser reefs with more structural complexity have been associated with higher abundance and diversity of fauna, through providing refuge spaces and nursery grounds, especially for reef fish (Baalkhuyur et al., 2018; Graham and Nash, 2013). As we concluded that denser reefs are more likely to trap and retain microplastics, it can be expected that a potentially higher number of reef species will be exposed to microplastic pollution compared to sparse reefs. Known environmental consequences include accidental ingestion by reef organisms and the spread of coral disease, especially if waves promote resuspension (de los Santos et al., 2021; Lamb et al., 2018). Microplastics have been observed in several reef fish which may have occurred through grazing on the epilithic algal matrix covering corals that had captured particles (Baalkhuyur et al., 2018; Wilson et al., 2021). However, we acknowledge the complexity of coral systems and associated organisms, with wider repercussions to various types of reefs needing further evaluation.

Moreover, a considerable amount of microplastics were found on the bed of the canopies (Fig. 3 a, b). It has been argued through field sampling that more microplastics are found within reef sediments than in the water column, supporting our results that corals increase particle settling (Jeyasanta et al., 2020). Although this may reduce exposure to certain reef species, benthic fauna such as deposit and detritus-feeding organisms may be more exposed to microplastics (Sayogo et al., 2020; Sweet et al., 2019; Tahir et al., 2020; Wright et al., 2013). This highlights how due to the high trapping efficiency of coral reefs, a complete environmental assessment of the impacts of microplastics on these ecosystems is needed.

5. Conclusions

This study examined the microplastic trapping efficiency of coral reef canopies in relation to coral density, hydrodynamics, and potential ecological risk. The microplastic retention by the coral canopies was considerable relative to the absence of corals, thus shallow coral reefs may form a sink for microplastic pollution, demonstrating the role of corals in the "missing" plastic problem. Three key trapping mechanisms by coral canopies were identified: a) interception of particles with the coral acting as a barrier; b) settling of microplastics on the branches and within the coral, and c) accumulation in downstream regions. Trapping efficiency and spatial deposition was driven by the flow dissipative effects and subsequent turbulence generation by the complex coral structures. Microplastic retention is promoted by reductions of in-canopy time-averaged streamwise velocity, while isolated deposits occur in the wake recirculation downstream of individual corals. The downstream distance of deposits is linked to the flow development length. Given that denser reefs with more structural complexity are often associated with higher biodiversity and microplastic trapping efficiency, the broader reef and ecosystem implications must be assessed in future research; recommendations include testing various types of canopy properties (arrangement, heterogeneity, and species), flow conditions (wave driven flows) and microplastics (polymer type, material density, and shapes).

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CRediT authorship contribution statement

Freija Mendrik: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualization, Writing - original draft, Writing - review & editing. **Robert C. Houseago:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing - original draft, Writing - review & editing. **Christopher R. Hackney:** Conceptualization, Methodology, Supervision, Visualization, Writing - review & editing, Funding acquisition. **Daniel R. Parsons:** Conceptualization, Funding acquisition, Methodology, Resources, Supervision, Visualization, Writing - review & editing.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2023.123094.

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