AUTHOR & SCHOOL

Impact of our shorelines on the fragmentation of microplastics

ACKNOWLEDGMENTS

This investigation quantifies the influence of shoreline movement on the fragmentation of macroplastic debris into microplastics (<5 mm) within marine environments. A model was developed to evaluate the contribution of surf-zone turbulence, and suspended particulates (e.g., sand) to the fragmentation ofmicroplastics. Experimental trials utilizing the tumbler method with suspended sand demonstrated a statistically significant increase in fragmentation rates compared to control conditions (t-test, p < 0.05). These findings enhance our understanding of the role of shoreline processes as primary drivers of microplastic generation and provide insight into the potential effectiveness of localized mitigation and cleanup strategies.

0.1 Literature Review

The industrial revolution of the 18th century led to plastic such as polystyrene being used as opposed to animals materials (Science Museum, 2019), with the growth in production now resulting in nearly 459.1 million metric tons were produced in 2019, a 2.3 x 104 % increase from 1950 (Our world in data, 2019). Unfortunately, only 9% of plastic materials are ever recycled, with most plastic products being single use (MIT technology review, 2023). Plastic materials such as Polystyrene and Polyethylene have started to impact biodiversity and health of marine ecosystems and have become a pressing concern, mainly due to their fragmentation into microplastics. The breakdown of these plastics has the potential to cause mass physical and toxicological threats to all surrounding organisms (Ziani, 2023).

Microplastics, plastic particles < 5mm in diameter are typically considered to be harmful and harder to retrieve out of the ocean than larger plastic debris due to their small particle size. MPs, due to the high surface area to volume ratio, have the capacity to absorb harmful chemicals and pollutants from its surroundings such as persistent organic pollutants, heavy metals, and antibiotics (Rafa et. al, 2023). This property allows pollutants to spread through wide regions of marine ecosystems and make removal of these harmful compounds nearly impossible. They are incredibly persistent as a vector leading to bioaccumulation of plastic and pollutants within food webs. It is due to this longevity that they are slowly entering the diet of many marine organisms that are then consumed by humans, such as shrimp as shown by the research of Mohan and Raja (2024), which found that all parts of shrimp contain MPs and changes to shrimp morphology and physiology were observed some in the samples studied, showing the impact of plastic on the chemical structure of shrimp. While these changes were not observed in all shrimp samples, it demonstrates the detrimental effects of MPs are affecting human food sources. The ocean is currently the largest reservoir of plastic, with over eight million tons of plastic deposited since 2010 (National Geographic, 2015). Plastic materials have been found in highest concentrations in remote areas and main ocean gyres, with the North Pacific Subtropical Gyre and the South Pacific Gyre accumulating enough plastic partciles to cover 334,271 km² and 26,898 km² respectively (e.g. Eriksen et al. 2013; Moore et al. 2001). Outside of major gyres, MPs have been found in high quantities on coastal ecosystems and remote areas of the ocean, posing major issues for removal efforts due to the difficulty to reach these areas and the ocean movement through waves creating an unstill environment. It remains an open question, where the fragmentation of larger plastic debris entering the ocean to MPs is occurring. This is what the research aims to investigate

An investigation conducted by Allen *et. al.* (2020) found MP within marine ecosystems may be returning to beaches or entering the atmosphere via strong winds and sea turbulence through the processes of bubble burst ejection and wave action mechanisms. Trials from different bodies of water, and at different wind levels, found that air-water droplets showed higher MP concentration during high humidity conditions. As the ocean and shorelines have a humidity level that averages 80% (Callum J. Shakespeare, Michael L. Roderick), the study showed a clear correlation between the higher humidity of shorelines to the percentage of MPs found within the local atmosphere. The turbulent surf zone along sandy shorelines would be a likely candidate for where this type of transport into the atmosphere is readily occuring. Larger light microplastics have been shown to reach land within uniform beach zones due to their observed buoyancy (Soyoung Kim, Dae-hong Kim, 2024). Thus, clarification of how plastic debris is fragmenting into MPs in the surf zone, the focus of this study, is a gap within the literature where further research is likely to add to our understanding of this phenomenon. Research conducted by Sipe et. al. (2022) to quantify how plastic products are breaking down has shown that a polymer's mechanical properties cannot clearly predict how consumer-based plastic products break down into MPs during mechanical abrasion during the use-phase or in the environment. Highlighting the gap in our understanding of the mechanism by which plastic debris fragments into MPs in real environments.

02. Research Question

Research Question: To what extent does suspended sand impact the breakdown of plastic debris to microplastics in the surf zone of coastlines?

Hypothesis

H0: If there is no association between plastic debris fragmentation and shoreline ecosystems, then suspended sand and waves in the surf zone will not increase the fragmentation of plastic debris into microplastics

HA: If there is an association between shoreline ecosystems and microplastic degradation, then suspended sand and waves in the surf zone will increase the fragmentation of plastic debris to microplastics

03. Methodology

The particular materials proposed to complete this experiment

- Spinning barrel based on rock tumbler design
  - Wooden frame (Bunnings)
  - 2 x 16mm external diameter plastic hollow rods cut from polycarbonate burettes (MTA))
  - Ozito 18V rechargeable power drill (Bunnings)
  - Retort stand clamp
  - 4 x Bearings (Bunnings)
  - 4 x Rubber wears salvaged from Roller Blades
  - Large circular glass kitchen storage mason jar with watertight seal (Ikea, 30.5 x 11cm)
  - 4 x Quick release box clamps (Bunnings)
  - 1 x Quick release band clamp (Bunnings)
  - Ozito 18V rechargeable power drill (Bunnings)
  - 11 mm diameter masonry drill bit (Bunnings)
  - 2-part epoxy Gorilla Grip glue (Bunnings)
  - Electrical tape (bunnings)
- Strainer (10mm x 10mm holes)
- Plastic sieves (5 mm mesh) & Large chunks of Polystyrene (approximately 25cm^2)
- Glass dish, Graduated measuring cylinder & Misc. lab glassware
- Saxa Rock Salt (Coles)
- Mobile phone

04. Experimental Design

The physical mechanism that the experiment will be run with is made up of a wooden box frame with the dimensions of 351mm per each of the four wooden planks (Figure 1). Two plastic rods were run through the bearings that sit in two sides of the frame, parallel to each other, to allow the rods to spin smoothly for the simulation. On the rods, four rubber wheels were placed parallel to each other along the two rods to allow for the large glass kitchen mason jar to be rotated with the rods. An 11 mm diameter masonry bit was then fixed with 2-part epoxy glue in the one end of one of the tubes external to the box frame and attached to a 18V drill which can be used to rotate the large glass kitchen mason jar by spinning one of plastic rods. The drill speed, and hence the rotation of the glass mason jar, was controlled by engaging the trigger of the drill with a retort stand clamp. The entire wooden frame of the apparatus and the 18V drill was fixed to the lab bench using quick release clamps, and a band clamp was secured around both the frame and glass mason jar to prevent slipping out of the frame while spinning. By controlling the distance the trigger of the 18V drill was engaged, the speed of the drill was able to be consistently varied to control the speed of the spinning mason jar. By setting up a tripod and placing a dot on the spinning glass mason jar, a video recording was used to measure the revolutions per minute (RPM) of the glass mason jar.

The reynold number (*Re*) at 200C, which reflects the turbulence of the water , was calculated using these RPM measurements via:

Re = wd^2/v where

w = Angular velocity of the rotating cylinder, which is calculated by multiplying the rotational speed in RPM (N) by 2π/60

d = hydraulic diameter of the cylinder = 0.11 m

v= Kinematic viscosity of the fluid = 1.00 x 10-6 m2s-1 for water at 200C (Ksb, kinematic viscosity. n.d.)

Reynold's number values > 103 are indicative of turbulent flow, with the full range of RPM investigated (Table 1).

Speed 3 was selected for use in experiments to ensure that both the control and experimental conditions experienced similar high levels of turbulent

Speed setting	RPM	*Re*
Control - Barrel with 1.0 L water		
1	60	9.8×10^4
2	120	$2.0 \times \times 10^5$
3	180	2.9×10^5
Experimental - Barrel with 0.7 L water and 300 cm³ suspended sand (total volume water + sand = 1.0 L)		
1	66	1.1×10^5
2	120	2.0×10^5
3	180	2.9×10^5

Figure 1. Spinning barrel apparatus based on rock tumbler design used to simulate the surf zone along a sandy beach coastline and open ocean in this investigation.

Table 1. Rotational Reynolds numbers calculated for the experimental and control condition in the tumbler showing that the water within the barrel is undergoing turbulent flow in both configurations (*Re* > 103).

Collection of data

The rock tumbler barrel was prepared with 1.0 L of a salt solution of 35 ppt (equivalent to seawater) for the control condition, with 0.3 L then being filled with beach sand instead of the salt solution for the experimental condition. A known mass of 4-6 cm3 expanded polystyrene chunks, referred to as macro plastics, was placed inside of the tumbler. The macro plastics will then be agitated by the spinning barrel for 30 minutes to simulate the action of waves in open water and within the surf zone on the macro plastics. After the sample has been spun for 30 minutes, the remaining large macroplastics will be sieved out of the water, washed and weighed out as a wet mass before being dried and weighed again for the dry mass. Any mass difference observed was attributed to the fragmentation of macro plastics into MPs within the cycle of the rock tumbler. Ten trials of each experimental condition were repeated to give a reliable measure of the mass of MPs fragmented from the macro plastics chunks for each condition.

Data analysis: To analyse the data, descriptive statistics such as mean and standard deviation werecalculated, as the data is primary and quantitative, and these measurements were represented graphically to illustrate any patterns and trends present. The mean mass of MPs fragmented from the macro plastic chunks under the experimental condition (suspended sand) and compared against the control condition (no sand) via a two sample *t*-test to determine whether the observed differences were statistically significant.

05. Results/Findings

Table 2 - Mass of microplastic particles formed after 30 minutes in the simulated Control condition (open ocean) and Test condition (surf zone).

Trials	Control Condition (Open Ocean)	Experimental Condition (Surf Zone)
1	0.04	0.08
2	0.19	0.29
3	0.09	0.09
4	0.11	0.07
5	0.06	0.15
6	0.02	0.08
7	0.02	0.07
8	0.03	0.05
9	0.01	0.18
10	0.02	0.11
M	0.06	0.12
SD	0.06	0.07

Figure 1 - Box and whisker point showing the mass of microplastic particles formed after 30 minutes in the simulated Control condition (open ocean) and Test condition (surf zone).

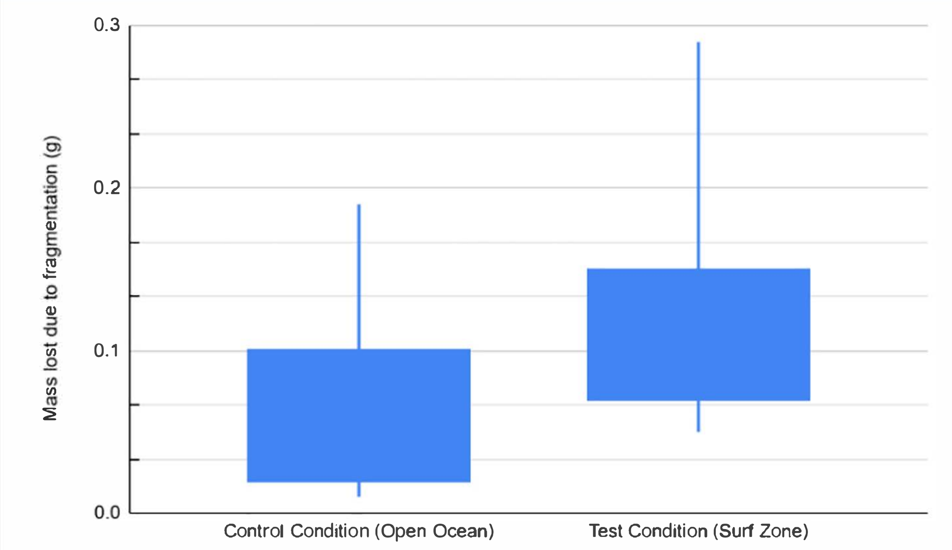

Table 3 - Summary statistics based mass of microplastic particles formed after 30 minutes in the simulated Control condition (open ocean) and Test condition (surf zone).

Statistic	Experimental condition (surf zone)	Control condition (open ocean)
Mean	0.117	0.059
Variance	0.005	0.003
Observations	10	10
DF	17	
t_{Stat}	1.99	
t_{Crit}	1.74	
P-Value	0.03	

The observed loss of mass due to MP fragmentation is shown in Table 2 and Figure 1. The formation of MP fragments observed within the spinning barrel simulation of turbulent water in the open ocean and surf zone, were observed to occur over narrow ranges for both the control condition (M = 0.06g, SD = ± 0.06g) and the experimental condition (M = 0.12g, SD = ± 0.07g) respectively. Notably, a greater number of MP fragments were observed for the majority of the experimental condition trials. This is indicative that the suspended sediment (sand) within the experimental condition increased the abrasive wear on the macro plastic chunks, resulting in greater formation of MPs. Comparing the mean average mass of fragmented microplastic particles of both Control condition (open ocean) and Test condition (surf zone) with a right-tailed t-test, $t(17) = 1.99$, $p=0.03$, confirmed that the observed higher mass of microplastic particles in the Experiment condition (surf zone) was a statistically significant difference in microplastic formation. This means the observed difference in mass is unlikely to be due to random chance, and the suspended sediment present in the surf zone likely plays a significant role in the creation or accumulation of these particles.

06. Analysis

Due to the rise in plastic demand and usage, microplastic breakdown is currently placing a huge toll on biodiversity, as the persistent nature of the particles allow for them to permeate throughout all layers of ecosystems (Allen et. al.). Oceanic MP particles have been linked to creation of atmospheric microplastics and adverse health impacts (Amelia et al, 2021).Thus, these risks and impacts are the driving force for this research, as building a greater understanding of MP fragmentation and the locale where it is happening highlight both practical and regulatory measures that can be put in place to address this growing problem. The results of this investigation strongly indicate that the presence of suspended sediment within the turbulent water of the surf zone contributes significantly to the creation or accumulation of MPs from macroplastics, with the mean mass of MPs formed in the experimental condition being shown to be statistically significantly higher than that of the control condition. The findings collected from isolating the factor of sediment abrasion as a driver for microplastic fragmentation provide clear evidence that the mechanical forces associated with sediment contact represent a key mechanism in the creation of shoreline microplastics. This suggests that sediment dynamics in high-energy coastal environments may play a critical role in accelerating microplastic fragmentation or facilitating their aggregation.

These findings suggest that suspended sediment sand, particularly sand particles within surf zones, facilitate higher rates of mechanical breakdown of larger plastic debris into smaller particles. The abrasive interaction between sediment and plastic along with the increased plastic-on-plastic contact due to more agitation, intensified by turbulent wave action, likely accelerates fragmentation. In contrast, open-ocean environments, which lack significant sediment presence, will depend more on slower degradation mechanisms such as photodegradation and small wave-induced mechanical stress (Andrady, 2022). This contrast underscores the role of coastal zones as hotspots for microplastic generation, with the findings of this investigation not only providing a foundation for further research into MP fragmentation along shorelines, but also have potential implications for mitigation and sustainability strategies. Specifically, they highlight the importance of implementing technological interventions and barriers to prevent macro plastics from entering surf zones. Coastal regions are hotspots for plastic-build up and disposal, leading to accumulation of plastic within surf zones which then accelerate the process of MP fragmentation. By enhancing our understanding of the processes driving microplastic formation within the environment, this study contributes to the development of more effective measures aimed at reducing both the influx and generation of microplastics within marine ecosystems. Such measures may include the design and implementation of sediment filtration barriers at river mouths and coastal inlets, the deployment of floating containment booms to intercept macroplastic debris before it reaches surf zones, and the optimization of waste management practices to limit plastic pollution at the source. Additionally, these insights could inform policy frameworks targeting plastic interception before surf zone entry through the reduction of plastic use and encourage the development of biodegradable materials to minimise long-term environmental impact.

The dataset, however, does have limitations and potential improvements that can be made in future to improve the reliability of the data set. Despite extensive washing measures, the weights measured for the experimental trial had the potential to be impacted by sand that had become embedded within the macro plastic chunks, resulting in an underestimation of the mass lost. A second limitation of this investigation scope was the need to examine wave action at only a single rotational speed of the tumbler's spinning barrel; however, marine environments, particularly along coastlines, experience a wide range of hydrodynamic conditions and wave intensities. This variability could significantly influence the fragmentation and accumulation processes of microplastics, and future studies should aim to incorporate multiple wave speeds and turbulence levels to better replicate natural conditions. Further optimisation and variety of the experimental conditions sediment loading within the tumbler's barrel and use of baffles lining the inside of the barrel to improve the intermixing of the suspended sediment with macro plastic chunks are also likely to yield additional insights into the fragmentation mechanism of plastic debris entering the surf zone.

07. Conclusion

This investigation found that suspended sand within the surf zones along shorelines enhances the fragmentation of larger plastic debris into MPs. Experimental trials completed with suspended sand to simulate surf zones using the tumbler method produced the highest mass loss, whilst trials completed with no additional aggravation to simulate open ocean produced lower mass loss due to MP fragmentation, leading to the rejection of the null hypothesis. Using this research, we can see how focusing efforts on cleaning shorelines not only reduces the amount of plastic dispersed into the marine environment, but also would have the secondary benefit of removing a route by which larger plastic debris contributes to the formation of microplastics present in the ocean.

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