Science of the Total Environment 902 (2023) 166090

Contents lists available at ScienceDirect

Science of the Total Environment

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

Evaluating the generation of microplastics from an unlikely source: The unintentional consequence of the current plastic recycling process

Michael J. Stapleton [a], Ashley J. Ansari [a], Aziz Ahmed [b], Faisal I. Hai [a,*]

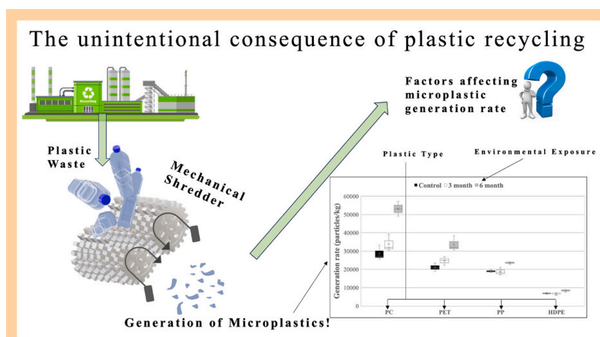
[a] Strategic Water Infrastructure Laboratory, School of Civil, Mining, Environmental and Architectural Engineering, University of Wollongong, Wollongong, NSW 2522, Australia

[b] School of Civil, Mining, Environmental and Architectural Engineering, University of Wollongong, Wollongong, NSW 2522, Australia

HIGHLIGHTS

- Large amounts of microplastics are generated during the plastic recycling process.
- Polymer type and environmental exposure affect microplastic generation rates.
- PC generated 3.3 times more microplastics (size: 0.212–0.5 mm) than HDPE
- Environmental exposure increased PC microplastic generation rates by 185 %.
- Material hardness is correlated to microplastic generation rates.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Paromita Chakraborty

Keywords:
Plastic waste
Microplastic pollution
Recycling
Mechanical shredding
Contamination

ABSTRACT

This study casts light on the potential of microplastic generation during plastic recycling – an unintended consequence of the process. To date, microplastics have been detected in the wastewater and sludge from plastic recycling facilities; however, generation pathways, factors and minimisation strategies are understudied. The purpose of this study is to identify the factors affecting microplastic generation, namely, plastic type and weathering conditions. The size reduction phase, which involved the mechanical shredding of the plastic waste material, was identified to be the predominate source of microplastic generation. Material type was found to significantly affect microplastic generation rates. Focussing on the microplastic particles in the size range of 0.212–1.18 mm, polycarbonate (PC), polyethylene terephthalate (PET), polypropylene (PP), and high-density polyethylene (HDPE) generated 28,600 ± 3961, 21,093 ± 2211, 18,987 ± 752 and 6807 ± 393 particles/kg of plastic material shredded, respectively. The significant variations between different plastic types were correlated ($R^2 = 0.88$) to the hardness of the plastic. Environmental weathering was observed to significantly affect microplastic generation rates. Generation rates increased for PC, PET, PP, and HDPE by 185.05 %, 159.80 %, 123.70 % and 121.74 %, respectively, over a six-month environmental exposure period. The results in this study confirm production of large amounts of microplastics from the plastic recycling industry through its operational processes, which may be a significant source for microplastic pollution if measures to reduce their production and removal from wastewater and sludge are not considered.

* Corresponding author.
E-mail address: faisal@uow.edu.au (F.I. Hai).

https://doi.org/10.1016/j.scitotenv.2023.166090
Received 6 July 2023; Received in revised form 3 August 2023; Accepted 4 August 2023
Available online 6 August 2023

1. Introduction

Public concern over the environmental impacts of microplastic pollution has continued to increase over the years. This has led to research into the different sources of microplastic pollution, the wide distribution of microplastics in virtually all environments and the potential hazards that microplastics play on the health of fauna and flora (Deng et al., 2020). Microplastics are classed as plastic particles <5 mm, which can then also be sub-categorised into large microplastics (1–5 mm) and small microplastics (< 1 mm) (Yuan et al., 2022). Small microplastics have become the focus of the current research as they pose the most potential risk to the environment as they can be absorbed by organs and cells (Lusher et al., 2017; Novotna et al., 2019; Yuan et al., 2022). Researchers have endeavoured to estimate the amount of microplastic pollution that is in the environment, however, the numbers are likely to be underestimated due to the significant number of unknown variables (Lindeque et al., 2020). Slowing the amount of microplastics entering the environment by identifying key sources and implementing preventative measures has become one of the main focuses in the current literature.

Through emerging research, an unlikely source of microplastic pollution has been discovered in an industry built on reducing the impacts of our overconsumption of plastics. A few recent studies have revealed that the plastic recycling industry may be a significant source of microplastic pollution into our environment (Brown et al., 2023; Guo et al., 2022; Suzuki et al., 2022). Investigations on plastic recycling facilities has shown that annual microplastic emissions into the environment can range from 14 to 5800 kg/year (Suzuki et al., 2022). Although the plastic recycling industry has been highlighted in these preliminary studies as a potential source for microplastic pollution, significant gaps still remain in the literature. Current data for microplastic emission rates are only based on the analysis of samples gathered from wastewater sludge or downstream waterbodies. This methodology is useful in source detection but can only provide an estimation in regard to the severity of the issue. A methodology into accurately estimating microplastic generation rates and factors that can influence microplastic generation during the plastic recycling process are still required to gain a greater understanding of this issue.

According to the latest approximation of global plastic production and recycling rates done in 2015, of the 6300 million metric tonnes of plastic waste ever generated, only 9 % has been recycled (Geyer et al., 2017). Although recycling rates are low, 9 % of all plastic waste generated still equates to approximately 567 million metric tonnes. While there are many different types of commercially available plastics, polyethylene terephthalate (PET), high-density polyethylene (HDPE), low-density polyethylene (LDPE), and polypropylene (PP) make up 85 % of the current plastic recycling market (Eskandarsefat et al., 2022). When comparing the total amount of plastics that have ever been recycled to the results found by Guo et al. (2022) an Suzuki et al. (2022), a significant amount of microplastics may have been emitted from plastic recycling facilities over the last 40 years.

By investigating the individual processes associated within plastic recycling, a greater understanding of how it may potentially be a significant source of microplastic pollution can be gained. Fig. 1 illustrates the steps used by the industry when a plastic is mechanically recycled, which, due to its simplicity is currently the most popular method for plastic recycling (Maris et al., 2018). As seen in Fig. 1, once the plastic waste enters the recycling facility it is sorted, reduced in size, and then washed. Mechanical rotating blades are used to reduce the plastic waste into a transportable and manageable size. It is recommended that plastic flakes should be of 10–20 mm in size and <10 mm to facilitate proper recycling (Maisel et al., 2020). To improve the quality of the final product, shredded plastics are washed to remove any impurities and contaminants (Sebastian and Paul, 2021). It is predicted that due to the mechanical nature of the process, microplastics are being generated during the size reduction stage, which, then has the ability to be discharged into the environment through the wastewater produced from the washing process (Brown et al., 2023; Guo et al., 2022; Suzuki et al., 2022).

The potential issues that microplastics pose on fauna, flora and human health are the drivers for current research into the discovery of new sources of microplastic pollution. New sources not only have to be

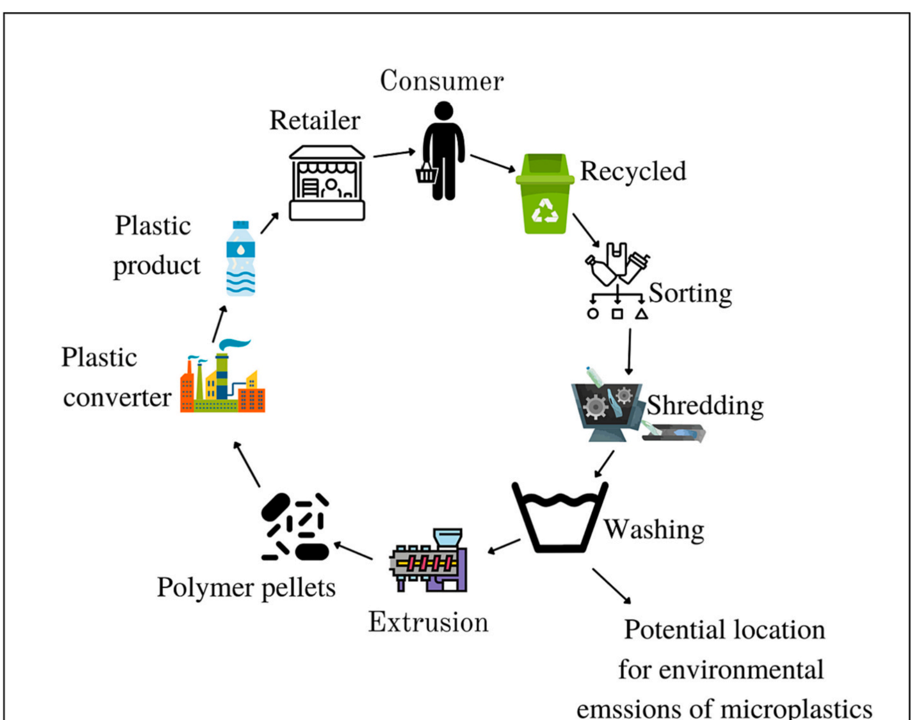


Fig. 1. The cycle of mechanical recycling of plastics and the site of potential emission of microplastics.

identified but studied in detail to understand the scale of microplastics being generated by each source. To date research has only focussed on identifying microplastics in the wastewater at plastic recycling facilities. Further analysis, such as the contributing factors that influence the generation rates of microplastics remains to be elucidated. In this context, this study aims to identify the key factors influencing microplastics generation rate during the size reduction stage at a mechanical recycling facility. The critical factors examined include the type of the plastic and plastic degradation due to environmental exposure during storage prior to processing. Through this investigation, a greater understanding of the plastic recycling industry being an unintentional source of microplastic pollution is gained.

2. Materials and methods

2.1. Sample preparation

Virgin 250 ml polyethylene terephthalate (PET) bottles, 250 ml high-density polyethylene (HDPE) bottles, 500 ml polypropylene (PP) containers and polycarbonate (PC) sheets (300 mm × 625 mm × 1 mm) were commercially purchased from online suppliers. These plastic types were chosen based on their importance in the current plastic recycling market. Plastic samples were placed in an outside environment at the main campus of University of Wollongong, New South Wales, Australia (34.4053° S, 150.8778° E) for three- and six-month periods to determine if degradation affects the generation rate of microplastics during the shredding process. Supplementary Fig. S1 shows the location of the plastics during the three- and six- month periods.

2.2. Lab-scale simulation of the plastic recycling shredding process

Simulation of the shredding process found at a plastic recycling facility was done using a GP20 hybrid plastic shredder (3devo, The Netherlands). The GP20 is a double shaft, lab scale plastic shredder equipped with 14 shredding blades, which can operate at a maximum speed of 14 RPM. A schematic of the shredder can be found in Fig. 2. The GP20 hybrid plastic shredder produces similar end products as the plastic recycling industry through the use of the same double shaft shredding mechanisms (Wong et al., 2022).

200 g of each plastic type was shredded for further analysis. It was found that a single pass through the shredder did not reduce the plastic into the recommended workable flake size of 10–20 mm (Maisel et al., 2020), so a second pass through the shredder was required for all types of plastics. The rotational speed of the shredder was set to 14 RPM for all experiments.

2.3. Analytical analysis

2.3.1. Quantification of the weight of microplastics generated

To quantify the weight of microplastics generated, a sieve analysis on the shredded plastic material was done following the ASTM D1921–01 (ASTM, 2017) standard. As the aim of this study was to investigate microplastics generated from the shredding processes, the following sieve sizes were chosen for the analysis: 6.7 mm, 4.75 mm, 2 mm, 1.18 mm, 0.85 mm, 0.5 mm, 0.212 mm, and 0.106 mm. 200 g of shredded plastics was mixed thoroughly, and a 50 g sub-sample was collected. The sub-sample was mechanically shaken for 10 min in accordance with the standard. Once completed, the plastics that were retained on each sieve were carefully removed and accurately weighed using precision scales with a minimum range of 1.0×10^{-4} g. Three sub-samples were analysed for each plastic and the average was established. A percent retained figure was produced as the result. Microplastic loading rates were reported in terms of weight of microplastics generated (g)/weight of plastics shredded (kg).

2.3.2. Quantification of the number of microplastics generated

A plastic particle count was performed on each 50 g sub-sample that had been previously sieved to determine the number of microplastics generated during the shredding process. The plastic count focused on the following plastic particle size ranges: 0.212–0.500 mm, 0.500–0.085 mm, and 0.850–1.180 mm. A count was performed on the sieved material using a smartphone camera equipped with a 12 MP camera system with digital zoom up to 15× and the software, CountThis (AIBY Inc., USA). The complete method of how the software was used for the counting of microplastic particles can be found in Supplementary Figs. S2 – S3. The average count was obtained from the three 50 g sub-

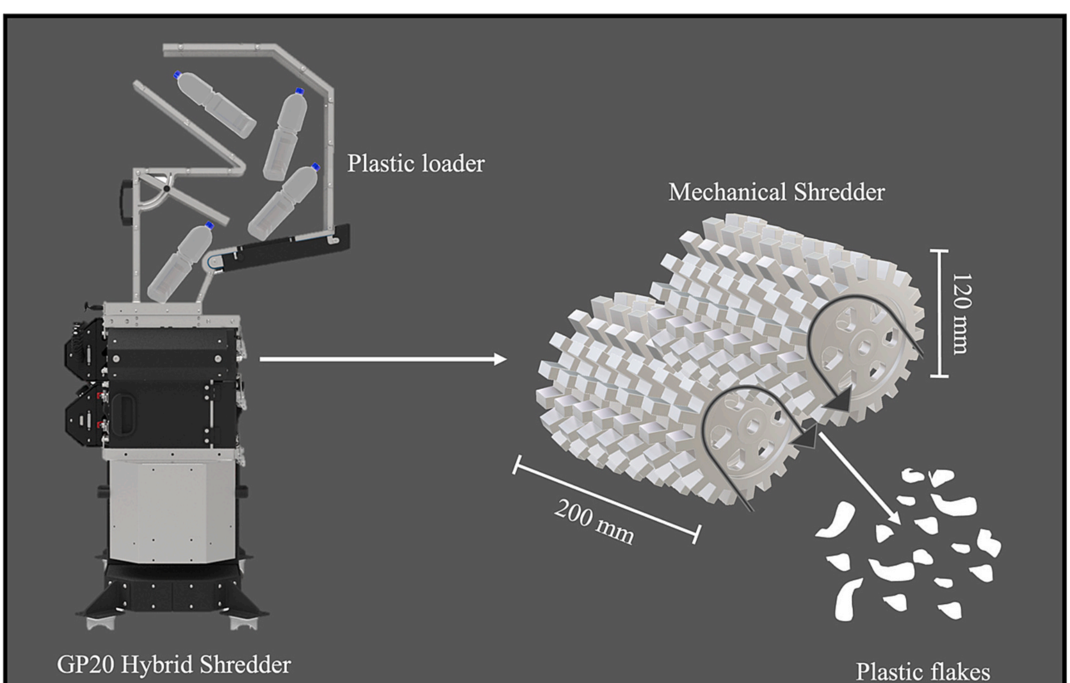


Fig. 2. Experimental set-up for imitating the shredding process at a plastic recycling facility.

samples and the final figure was expressed as ‘number of particles counted per kilogram of material shredded’. Microplastic loading rates were reported in terms of number of microplastics generated/weight of plastics shredded (kg).

2.3.3. Nanoindentation testing

The mean hardness of each plastic was determined through nanoindentation testing. Each plastic type was tested prior to the shredding processes. Nanoindentation tests were performed by a Hysitron TriboIndenter TI 950 (Bruker, USA), equipped with a Berkovich tip having an apex radius of 150 nm. The maximum load was set at 1 mN and the loading program consisted of five seconds of loading, two seconds of holding followed by five seconds of unloading. Nine separate measurements were taken on each sample to ensure repeatability.

2.3.4. Stereo microscopic images

Microscopic imagery of plastic samples before and after the shredding process was performed to further understand surface degradation that occurs due to the shredding process. A Leica EZ4W stereo microscope (Wetzlar, Germany) was used in conjunction with the Leica Application Suite v4.12 to digitalise and investigate the plastic samples.

2.3.5. Fourier transform infrared (FTIR) spectroscopy

FTIR spectroscopy was used to investigate degradation by analysing whether changes to the chemical structure of the plastic samples occurred over the three- and six-month periods (Stapleton et al., 2023). FTIR analysis was performed using a Shimadzu IRAffinty-1S fitted with a MIRacle-10 ATR. Transmittance was measured in the infrared spectrum range of 4000–600 cm^{-1}. LabSolutions IR software was used to analyse the results and develop FTIR plots. Samples were measured in triplicates to assess and check the reproducibility of the results.

2.4. Statistical analysis

Using Microsoft Excel, an ANOVA single factor analysis was performed on the microplastic particle count data in excel to determine the

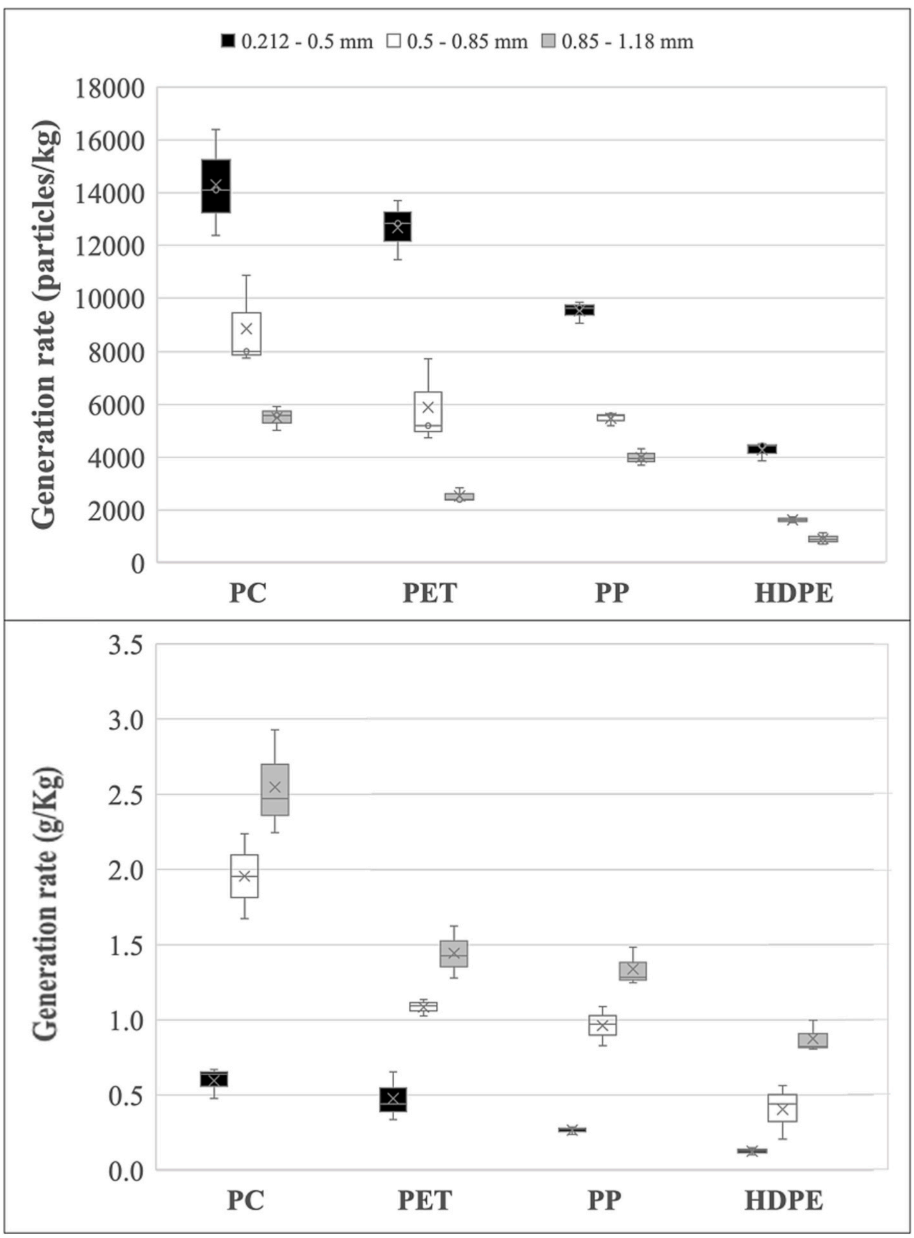


Fig. 3. Comparison between the number (top) and weight (bottom) of microplastics being generated by different types of plastics during the shredding process. Error bars are showing mean, median and standard deviation of three samples. Samples were standardised by displaying results in terms of 1 kg of material shredded.

significance of the results (Nagy et al., 2023). A result of $p < 0.05$ was concluded as a rejection of the null hypothesis that the two populations had the similar means.

3. Results and discussion

3.1. Factors affecting microplastic generation rates during the shredding process

3.1.1. Influence of plastic type

As there is no accepted standard for reporting microplastic loading rates, the literature is divided into either displaying the loadings rates by weight (Conkle et al., 2018; Dong et al., 2021; Suzuki et al., 2022) or by particle count (Goehler et al., 2022; Schmidt et al., 2020; Werner et al., 2016). To understand and provide comparable data for future analysis, a weight analysis and a particle count were both conducted on the microplastics generated through the shredding process (Fig. 3). Investigating the microplastics generated in the size range of 0.212–1.18 mm, it was discovered that the generation rate for both the particle count and the weight produced increased in the following order HDPE < PP < PET < PC. It is clear from Fig. 3 that PC generated considerably more microplastics than the three other types of plastics. The notable variations between plastic types can be highlighted when examining the particle size range of 0.212–0.5 mm. In this size range, PC generated 12,380–16,400 particles/kg of material shredded, whereas HDPE only generated 3860–4520 particles/kg of shredded material. When compared to HDPE, on average, PC generated 3.3 times more microplastics in the 0.212–0.5 mm range. Surface hardness varied between the four plastic types and is a plausible reasoning for the differences in the microplastic generation rates. This correlation is explained in more detail in Section 3.1.3.

Previous literature had identified plastic recycling facilities as being a potential source of microplastic pollution (Guo et al., 2022; Suzuki et al., 2022), however up until now, it was not known that the plastic type significantly influenced the amount of microplastics being generated. This discovery may provide insights to the plastic recycling industry into how they will need to develop microplastic mitigation plans depending upon the material they process.

3.1.2. Influence of environmental degradation

Although complete degradation of plastics can take as long as thousand years in standard environmental conditions (Ali et al., 2022), measurable degradation can be see within the first 12 months of environmental exposure (Pathak and Navneet, 2017). Environmental degradation of plastics can be caused by UV exposure, changes in temperatures, or through exposure to biological matter (Zhang et al., 2021). The level of degradation of the plastic materials that are processed by recycling facilities can vary significantly. In many cases, plastic recycling facility may also increase plastic degradation by storing their waste plastic in external compounds prior to reprocessing. This study aimed to determine whether environmental degradation (Section 2.1) affected the microplastic generation rates during the shredding process.

An FTIR analysis was performed to determine if environmental degradation had occurred on the plastic material that was collected from the outside storage location after the three- and six-month periods (Fig. S4). A change in absorbance levels between the zero-, three- and six-month was observed when investigating the carbonyl stretching region (1750 cm^{-1} to 1650 cm^{-1}) in PET, the C—H bending region (1450 cm^{-1} to 1550 cm^{-1}) in PC, and the C—H stretching region (1750 cm^{-1} to 1650 cm^{-}1) in HPDE and PP. The change in absorbance levels indicated chemical structure changes had occurred to the plastics as a consequence of the environmental exposure (Celina et al., 1997; Rajandas et al., 2012; Xu et al., 2018), and confirmed that environmental degradation had occurred.

Fig. 4 shows the number of microplastics generated in the 0.212–1.18 mm size range from the plastic material that had been exposed to environmental conditions for zero-, three- and six-month periods. Using an ANOVA single factor analysis on the data seen in Fig. 4, an evaluation on whether plastic degradation affected the microplastic generation rate was determined. For the three-month samples, the ANOVA analysis resulted in all four plastics having a $p > 0.05$, indicating that a significant change between the control and three-month samples had not occurred. It can also be seen in Fig. 4, the particle counts from the control sample and the three-month sample overlap, further validating the conclusion of the ANOVA test. An investigation between the control and six-month sample illustrates a different result. First by looking at the percent changes between the average counts, PC, PET, PP and HDPE changed by 185.05 %, 159.80 %, 123.70 %, and 121.74 %, respectively. Already, a definitive change in the microplastic generation rates can be seen and is reinforced by the ANOVA analysis showing all plastic types resulting in a $P < 0.05$ value.

The methodology for environmental exposure used within this study was to simulate how waste plastics are stored when exterior storage compounds are used by recycling facility (Ranjan and Goel, 2021). Fig. 5 illustrates the mean temperatures and solar exposures for each month that the plastics were placed in the outside location. High temperatures and UV exposure are found to be key influencing factors for degradation of plastic materials (Ammala et al., 2011; Zhao et al., 2007; Zhu et al., 2020). It was discovered that after the three-month period of environmental exposure, no significant change in microplastic plastic generation had occurred (Fig. 4). This correlated to the data in Fig. 5, which showed no noticeable change in the temperatures recorded or the solar exposure levels. However, in the second three-month period, the temperature and solar exposure levels began to rise. The mean solar exposure in November 2022, was double that of what was recorded for June, July or August. The increase in temperature and solar exposure, increased the rate of degradation of the plastics, which ultimately saw an increase of microplastics being formed during the shredding process (Fig. 4).

The significant increase in microplastic generations between the control and six-month samples is likely due to the environmental exposure changing the mechanical, chemical, and physical properties of plastics (Brebu, 2020). In particular, previous literature has noted that environmental degradation can increase the number of flakes, cracks and holes on the surface of different plastics (Iñiguez et al., 2018; Lin et al., 2022; Ranjan and Goel, 2021). The deterioration of the plastic surface may act as a weak location during the shredding process and be an underlying property that increases microplastic generation rates.

This study is the first to link environmentally degraded plastics to an increase in microplastics generated during the shredding process at a plastic recycling facility. The importance of these findings is to highlight to the plastic recycling industry that the method for storing pre-processed plastic waste (e.g., outside compounds) can ultimately affect the amount of microplastic that are generated.

3.1.3. Influence of plastic hardness

Our data clearly shows that microplastic generation rates vary significantly depending upon the material type and degradation levels (Figs. 3 & 4). Further analysis via nanoindentation testing provided insight into the underlying plastic properties affecting microplastic generation rates. Fig. 6 compared the results from the nanoindentation testing (hardness) to the microplastic generation rate from the shredding process. A significant correlation ($R^2 = 0.88$) is seen between the two parameters, demonstrating the impact that hardness of a material has on the generation of microplastics. Indentation hardness has been found to be proportional to Young's modulus (Sun et al., 2018), which is the parameter associated to a materials stiffness. A material with a high Young's modulus is classified as brittle and a low Young's modulus is classified as ductile (Ma et al., 2016). It can be concluded using the data shown in Fig. 6, and the knowledge that Young's modulus is proportional to hardness, that brittle materials will generate more microplastics during the shredding process compared to ductile materials.

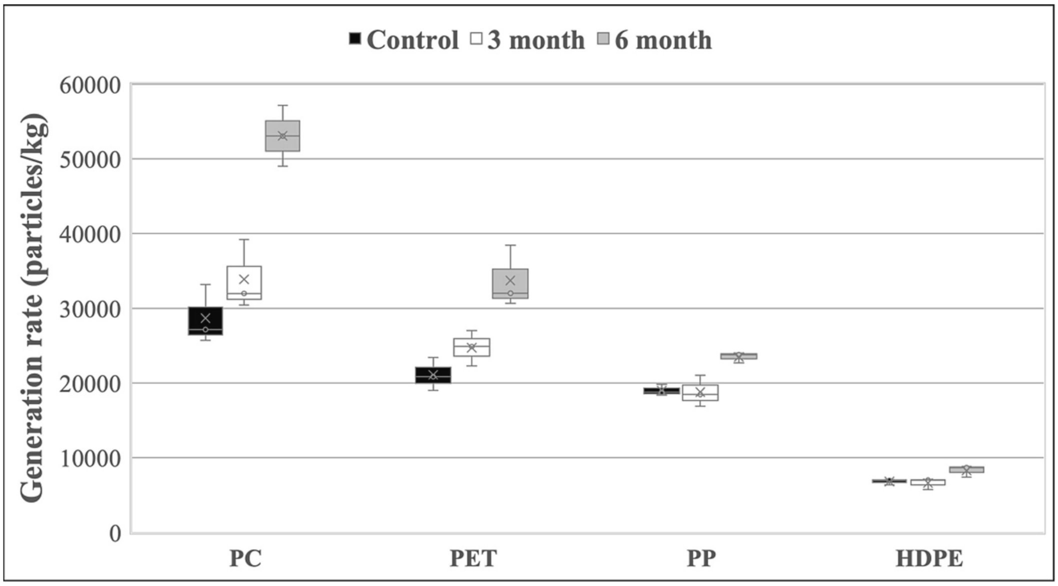


Fig. 4. Microplastics generated during the shredding process from plastics exposed to environmental conditions for zero-, three- and six-month periods. Error bars are showing mean, median and standard deviation of three samples. Only microplastics in the 0.212–1.18 mm size range where counted. Samples were standardised by displaying results in terms of 1 kg of material shredded.

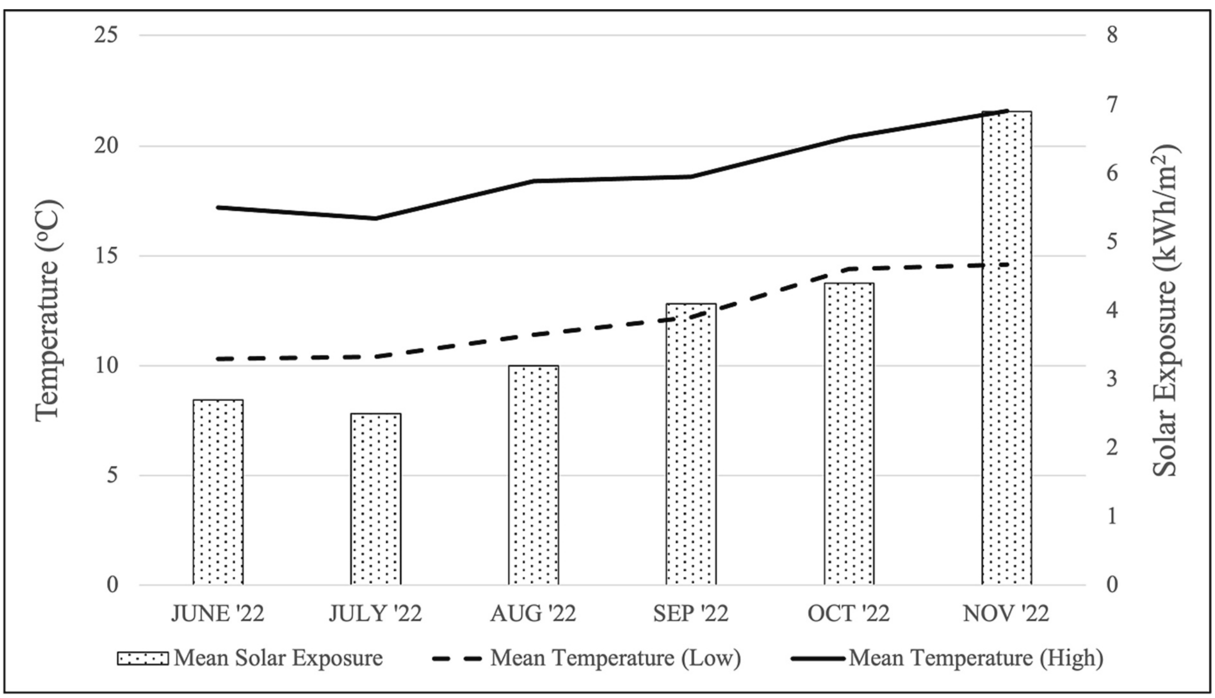


Fig. 5. Weather data for the study location (34.4053° S, 150.8778° E) over the three- and six-month period in which the plastics were located (Australian Government - Bureau of Meteorology 2023).

Microscopic analysis of the shredded material can further support this conclusion. Fig. 7 illustrates the physical surface changes that occurred to the plastic material after being shredded. Through nano-indentation testing, PC and PET were found to have the highest hardness levels and therefore are more brittle than PP and HDPE. The microscopic inspection of the PC and PET particles after shredding showed notable surface damage, with indication that the material potentially shattered due to the force generated from the rotating blades. The shattering of the PC and PET material can explain the higher amounts of smaller microplastics (0.212–0.5 mm) produced compared to PP and HDPE.

Until now, there was a significant gap in the knowledge about the factors that increase microplastic generation rates during the shredding process during plastic recycling. Not only has this study shown the variations in microplastic generation rates between plastic types and variations in degradation levels (Figs. 3 & 4), but it has also correlated the findings to the polymers property of hardness (Fig. 5). Young's modulus is seen to reduce with an increase in temperature (Moll and LeFevre, 1948), and is proportional to hardness (Sun et al., 2018). Therefore, an increase in temperature would also decrease the plastic hardness levels. This information can be used by the plastic recycling

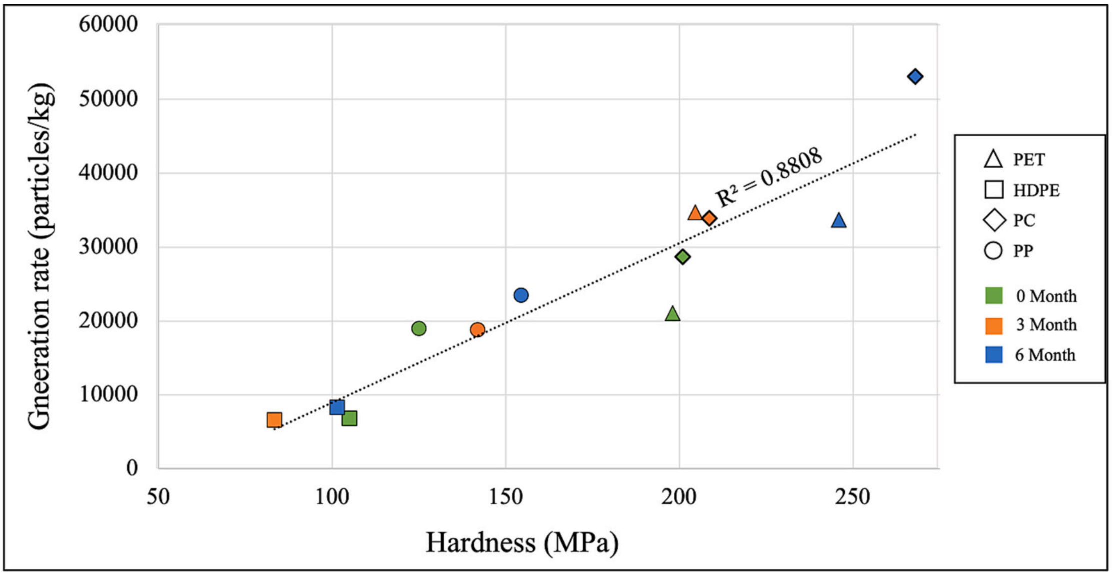


Fig. 6. Relationship between the hardness of a plastic and the generation rate of microplastics. Microplastic generation rates are the average count of three samples in the size range of 0.212–1.18 mm. Mean hardness is the average of 9 nanoindentation tests.

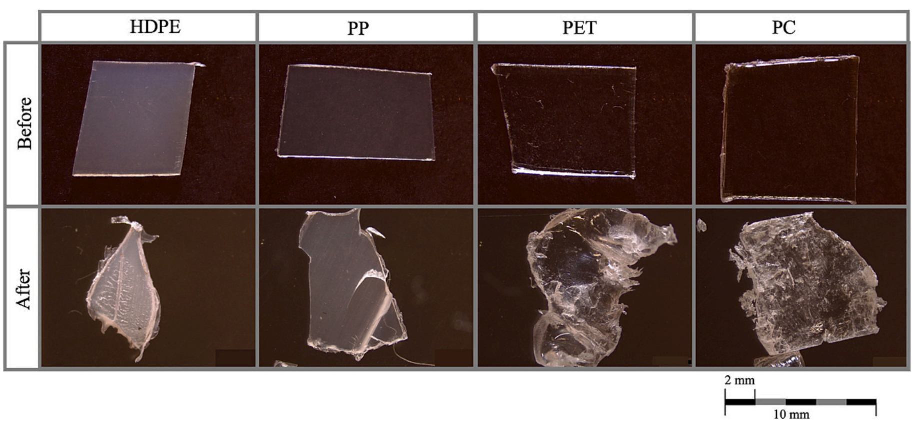


Fig. 7. Microscopic inspection of the surfaces of plastics before and after being mechanically shredded. PC and PET surface shows signs of significant fractures illustrating a brittle material. The surface of PP and HDPE remained relatively unchanged after the shredding process.

industry to investigate the recycling process and look for methods to manipulate the hardness of the plastic waste with the aim of reducing the amount of microplastics being generated.

3.2. Variations in the reporting of microplastic loading rates

Within the current literature, there is a variation in the way microplastics loading rates are reported, that is, either by weight or by count (Conkle et al., 2018; Dong et al., 2021; Goehler et al., 2022; Schmidt et al., 2020; Suzuki et al., 2022; Werner et al., 2016). Although determining the weight of the particles produced is a simpler method to indicate microplastics are being generated during the shredding process, it does not represent the entire picture. Fig. 3 compared the number of microplastics generated against the weight of microplastics generated. When the weight generation rate is the only data available, it would be concluded that microplastics in the 0.85–1.18 mm size range would be those of greatest concern due to having significantly higher values than those in the 0.212–0.5 mm size range. However, when the particle count data is available it depicts the microplastics in the smaller size range to have a higher abundance. Another factor that needs to be considered if weight is the only data available is the influence that density has on reported generation rates. The densities of the four plastics increase in the following order PP (0.9–0.92 g/cm^3) > HDPE (0.93–0.97 g/cm^3) > PC (1.2 g/cm^3) > PET (1.38 g/cm^3) (Margolis, 2006). Consequently, if the particle count was the same for all four plastic types, the weight analysis would illustrate variances in generation rates, which may generate misleading information. For the first time this study highlights how the weight and count analysis can produce significantly different results and illustrates that a standardised reporting method needs to be established within this field of work.

3.3. Extrapolation of the findings to an Australian and a global setting

The data discovered within this study can be used as a preliminary estimation tool for the amount of microplastics that are being generated through the mechanical recycling of plastics. Fig. 3 shows the generation rates of microplastics in the size rage of 0.212–1.18 mm to be between 1.1 and 5.8 g/kg of plastic material shredded. By applying the generation rates to the Australian National Waste Report 2022, an annual generation rate can be estimated. Within the financial year of 2020/21, there was 340,000 t of plastic waste recycled in Australia (Pickin et al., 2022), which equates to approximately 375–1972 t of microplastics (in the size range 0.212–1.18 mm) being generated. On a global scale, estimations of plastic waste generation and recycling rates have not been published or updated since 2017 (Geyer et al., 2017). However, by using the latest approximation of amount of plastic waste ever recycled (567,000,000 tones), an estimated 620,000–3,200,000 t of microplastics (0.212–1.18 mm) may have been unintentionally generated. These estimates are not intended to be taken as absolute numbers but as a demonstration of the scale of the potential problem.

3.4. Environmental implications

From the rough estimate presented in the previous section it is evident that the mechanical recycling of plastic may be a significant source of microplastic pollution. Understanding the fate of the microplastics that are generated and its environmental impact is essential to drive change in the operational processes within the recycling industry.

As previously mentioned, after the size reduction process, plastic waste is washed to remove any impurities (Sebastian and Paul, 2021). It is during this phase where the potential for environmental loading of microplastics can occur. Countries such as Australia have strict environmental laws and regulations regarding the disposal of industrial wastewater, which include the prohibition of discharging natural or synthetic resins and plastic materials (NSW Government, 2021). Although these laws are active, due to the difficulties in monitoring and removing microplastic contamination for wastewater, microplastic loading is still found to be a significant issue for Australian wastewater treatment plants (Okoffo et al., 2023; Yaseen et al., 2022; Ziajahromi et al., 2021). Through the use of tertiary technologies, up to 97 % of microplastics can be captured at a wastewater treatment plant (Long et al., 2019). Even if not directly discharged to natural waterbodies (oceans or rivers), they are still encompassed in the sludge, which needs to be further treated (Corradini et al., 2019). It is clear that unless microplastics are collected prior to entering the wash water at a plastic recycling facility there is a high probability of the material being emitted into the natural environment.

4. Recommendations

This study is the first to examine the generation rates of microplastics during the shredding process at a plastic recycling facility and the factors that affect the microplastic generation rates. Prior to this study, only the occurrence of microplastics in the wastewater and sludge at a recycling facility had been examined (Brown et al., 2023; Guo et al., 2022; Suzuki et al., 2022). The findings from this study not only confirms the issue that had been highlighted previously, but also provides insights into the factors that affect the generation of microplastics during the recycling process. From the knowledge gained from this study, the following recommendations are made:

1. Plastic degradation due to natural exposure during storage prior to processing significantly increased the microplastic generation rates during the shredding process. Plastic recycling facilities should aim to reduce unnecessary environmental degradation by storing material in an internal storage facility.
2. In this study the shredder had rotational speed of 14 RPM. Research into the influence that rotational speed has on microplastic generation rates is needed for further understanding of actual generation rates.
3. Previous research has linked plastic recycling plants to the environmental pollution of microplastics (Brown et al., 2023; Guo et al., 2022; Suzuki et al., 2022). Whitin this study, the microplastic generation rates during the shredding phase in the plastic recycling process was examined. An investigation is required to determine what proportion of the microplastics being generated are actually being released into the environment and how to minimise that.
4. This research has further confirmed that mechanical recycling of plastics generates significant levels of microplastics. Research into methods for capturing the microplastics within the recycling process are required.

The plastic recycling industry is essential for reducing our environmental impacts from plastic overconsumption. The purpose of this research is not to villainise the industry as a source of microplastic pollution but to provide insights about what factors increase microplastic generation during the shredding process. This will allow further research to grow and expand into finding solutions to the problem.

5. Conclusions

The results from this study fill important gaps in the emerging research into the plastic recycling industry as being a potentially significant source of microplastic pollution. We report that the size reduction phase can generate microplastics during the recycling process. The material type and the degradation levels of the material (during storage) have significant effect on microplastic generation rates. Material hardness is highly correlated to the amount of microplastics (size range of 0.212–1.18 mm) that are generated during the shredding process. The results discovered in this study are the first to highlight the factors that contribute to the plastic recycling industry unintentionally being a significant source for microplastic generation and emphasises the importance for further research into its mitigation.

CRediT authorship contribution statement

Michael J. Stapleton: Conceptualization, Methodology, Investigation, Writing – original draft. **Ashley J. Ansari:** Supervision, Writing – review & editing. **Aziz Ahmed:** Resources, Supervision. **Faisal I. Hai:** Conceptualization, Supervision, Project administration, 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.

Acknowledgments

This research has been carried out with the support of the Australian Government Research Training Program Scholarship to Michael Stapleton, through University of Wollongong (UOW). The authors acknowledge the use of facilities available within the School of Civil, Mining, Environmental and Architectural Engineering of UOW. We acknowledge the access to the Hysitron TriboIndenter TI 950 at the Engineering Materials Research Centre, and FTIR and Stereo Microscopes at the School of Chemistry and Molecular Bioscience of UOW, Australia.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.166090.

References

Ali, A., Bahadar, A., Khan, A., Sanaullah, K., 2022. 8 - Role of agricultural waste in recycled plastic biocomposites. In: Rahman, M.R., Bakri, M.K. Bin (Eds.), Recycled Plastic Biocomposites. Woodhead Publishing, pp. 165–194.

Ammala, A., Bateman, S., Dean, K., Petinakis, E., Sangwan, P., Wong, S., Yuan, Q., Yu, L., Patrick, C., Leong, K., 2011. An overview of degradable and biodegradable polyolefins. Prog. Polym. Sci. 36 (8), 1015–1049.

ASTM, 2017. Test Methods for Particle Size (Sieve Analysis) of Plastic Materials (ASTM D1921). Available online: https://www.astm.org/d1921-18.html. (Accessed 4 May 2023).

Brebu, M., 2020. Environmental degradation of plastic composites with natural fillers—a review. Polymers 12 (1), 166.

Brown, E., MacDonald, A., Allen, S., Allen, D., 2023. The potential for a plastic recycling facility to release microplastic pollution and possible filtration remediation effectiveness. J. Hazard. Mater. Adv. 10, 100309.

Celina, M., Ottesen, D.K., Gillen, K.T., Clough, R.L., 1997. FTIR emission spectroscopy applied to polymer degradation. Polym. Degrad. Stab. 58 (1), 15–31.

Conkle, J.L., Christian, D.B.D.V., Turner, J.W., 2018. Are we underestimating microplastic contamination in aquatic environments? Environ. Manag. 61 (1), 1–8.

Corradini, F., Meza, P., Eguiluz, R., Casado, F., Huerta-Lwanga, E., Geissen, V., 2019. Evidence of microplastic accumulation in agricultural soils from sewage sludge disposal. Sci. Total Environ. 671, 411–420.

Deng, L., Cai, L., Sun, F., Li, G., Che, Y., 2020. Public attitudes towards microplastics: perceptions, behaviors and policy implications. Resour. Conserv. Recycl. 163, 105096.

Dong, H., Wang, L., Wang, X., Xu, L., Chen, M., Gong, P., Wang, C., 2021. Microplastics in a remote lake basin of the Tibetan plateau: impacts of atmospheric transport and glacial melting. Environ. Sci. Technol. 55 (19), 12951–12960.

Eskandarsefat, S., Meroni, F., Sangiorgi, C., Tataranni, P., 2022. Chapter 8 - fatigue resistance of waste plastic-modified asphalt. In: Giustozzi, F., Nizamuddin, S. (Eds.), Plastic Waste for Sustainable Asphalt Roads. Woodhead Publishing, pp. 145–162.

Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made. Sci. Adv. 3 (7).

Goehler, L.O., Moruzzi, R.B., Tomazini da Conceição, F., Júnior, A.A.C., Speranza, L.G., Busquets, R., Campos, L.C., 2022. Relevance of tyre wear particles to the total content of microplastics transported by runoff in a high-imperviousness and intense vehicle traffic urban area. Environ. Pollut. 314, 120200.

Guo, Y., Xia, X., Ruan, J., Wang, Y., Zhang, J., LeBlanc, G.A., An, L., 2022. Ignored microplastic sources from plastic bottle recycling. Sci. Total Environ. 838, 156038.

Iñiguez, M.E., Conesa, J.A., Fullana, A., 2018. Recyclability of four types of plastics exposed to UV irradiation in a marine environment. Waste Manag. 79, 339–345.

Lin, Z., Jin, T., Zou, T., Xu, L., Xi, B., Xu, D., He, J., Xiong, L., Tang, C., Peng, J., Zhou, Y., Fei, J., 2022. Current progress on plastic/microplastic degradation: fact influences and mechanism. Environ. Pollut. 304, 119159.

Lindeque, P.K., Cole, M., Coppock, R.L., Lewis, C.N., Miller, R.Z., Watts, A.J.R., Wilson-McNeal, A., Wright, S.L., Galloway, T.S., 2020. Are we underestimating microplastic abundance in the marine environment? A comparison of microplastic capture with nets of different mesh-size. Environ. Pollut. 265, 114721.

Long, Z., Pan, Z., Wang, W., Ren, J., Yu, X., Lin, L., Lin, H., Chen, H., Jin, X., 2019. Microplastic abundance, characteristics, and removal in wastewater treatment plants in a coastal city of China. Water Res. 155, 255–265.

Lusher, A., Hollman, P., Mendoza-Hill, J., 2017. Microplastics in Fisheries and Aquaculture: Status of Knowledge on Their Occurrence and Implications for Aquatic Organisms and Food Safety. FAO.

Ma, Y.Z., Sobernheim, D., Garzon, J.R., 2016. Chapter 19 - glossary for unconventional oil and gas resource evaluation and development. In: Ma, Y.Z., Holditch, S.A. (Eds.), Unconventional Oil and Gas Resources Handbook. Gulf Professional Publishing, Boston, pp. 513–526.

Maisel, F., Chancerel, P., Dimitrova, G., Emmerich, J., Nissen, N.F., Schneider-Ramelow, M., 2020. Preparing WEEE plastics for recycling – how optimal particle sizes in pre-processing can improve the separation efficiency of high quality plastics. Resour. Conserv. Recycl. 154, 104619.

Margolis, J.M., 2006. Engineering Plastics Handbook. McGraw-Hill Education.

Maris, J., Bourdon, S., Brossard, J.-M., Cauret, L., Fontaine, L., Montembault, V., 2018. Mechanical recycling: compatibilization of mixed thermoplastic wastes. Polym. Degrad. Stab. 147, 245–266.

Moll, H., LeFevre, W., 1948. Some "temperature–Young's Modulus" relationships for plastics. Ind. Eng. Chem. 40 (11), 2172–2179.

Nagy, D., Trunic, N., Prémusz, V., Krutek, L., Lipcsik, Z., Ács, P., 2023. Comparison of metabolic characteristics of physically active individuals with different training habits during incremental treadmill test. Int. J. Environ. Res. Public Health 20 (1), 70.

Novotna, K., Cermakova, L., Pivokonska, L., Cajthaml, T., Pivokonsky, M., 2019. Microplastics in drinking water treatment – current knowledge and research needs. Sci. Total Environ. 667, 730–740.

NSW Government, 2021. Liquid Trade Waste Management Guidelines, viewed 22nd of February 2023. https://www.industry.nsw.gov.au/_data/assets/pdf_file/0010/147088/trade-waste-management-guidelines.pdf.

Okoffo, E.D., Rauert, C., Thomas, K.V., 2023. Mass quantification of microplastic at wastewater treatment plants by pyrolysis-gas chromatography–mass spectrometry. Sci. Total Environ. 856, 159251.

Pathak, V.M., Navneet, 2017. Review on the current status of polymer degradation: a microbial approach. Bioresour. Bioprocess. 4 (1), 15.

Pickin, J., Wardle, C., O'Farrell, K., Stovell, L., Nyunt, P., 2022. National Waste Report 2022. Blue Environment Pty Ltd., Melbourne, Australia.

Rajandas, H., Parimannan, S., Sathasivam, K., Ravichandran, M., Su Yin, L., 2012. A novel FTIR-ATR spectroscopy based technique for the estimation of low-density polyethylene biodegradation. Polym. Test. 31 (8), 1094–1099.

Ranjan, V.P., Goel, S., 2021. Recyclability of polypropylene after exposure to four different environmental conditions. Resour. Conserv. Recycl. 169.

Schmidt, C., Kumar, R., Yang, S., Büttner, O., 2020. Microplastic particle emission from wastewater treatment plant effluents into river networks in Germany: loads, spatial patterns of concentrations and potential toxicity. Sci. Total Environ. 737, 139544.

Sebastian, J., Paul, L., 2021. Chapter 13 - Plastic recycling and regeneration. In: Gupta, K., Salonitis, K. (Eds.), Sustainable Manufacturing. Elsevier, pp. 339–365.

Stapleton, M.J., Ansari, A.J., Ahmed, A., Hai, F.I., 2023. Change in the chemical, mechanical and physical properties of plastics due to UVA degradation in different water matrices: study on the recyclability of littered plastics. Environ. Pollut. 334, 122226.

Sun, W.-J., Kothari, S., Sun, C.C., 2018. The relationship among tensile strength, Young's modulus, and indentation hardness of pharmaceutical compacts. Powder Technol. 331, 1–6.

Suzuki, G., Uchida, N., Tuyen, L.H., Tanaka, K., Matsukami, H., Kunisue, T., Takahashi, S., Viet, P.H., Kuramochi, H., Osako, M., 2022. Mechanical recycling of plastic waste as a point source of microplastic pollution. Environ. Pollut. 303, 119114.

Werner, S., Budziak, A., Van Franeker, J., Galgani, F., Hanke, G., Maes, T., Matiddi, M., Nilsson, P., Oosterbaan, L., Priestland, E., 2016. Harm Caused by Marine Litter.

Wong, J., Gan, M., Chua, B., Gakim, M., Siambun, N., 2022. Shredder machine for plastic recycling: a review paper. In: IOP Conference Series: Materials Science and Engineering, 1217, p. 012007.

Xu, F., Wang, B., Yang, D., Hao, J., Qiao, Y., Tian, Y., 2018. Thermal degradation of typical plastics under high heating rate conditions by TG-FTIR: pyrolysis behaviors and kinetic analysis. Energy Convers. Manag. 171, 1106–1115.

Yaseen, A., Assad, I., Sofi, M.S., Hashmi, M.Z., Bhat, S.U., 2022. A global review of microplastics in wastewater treatment plants: understanding their occurrence, fate and impact. Environ. Res. 212, 113258.

Yuan, Z., Nag, R., Cummins, E., 2022. Human health concerns regarding microplastics in the aquatic environment - from marine to food systems. Sci. Total Environ. 823, 153730.

Zhang, K., Hamidian, A.H., Tubić, A., Zhang, Y., Fang, J.K.H., Wu, C., Lam, P.K.S., 2021. Understanding plastic degradation and microplastic formation in the environment: a review. Environ. Pollut. 274, 116554.

Zhao, X., Li, Z., Chen, Y., Shi, L., Zhu, Y., 2007. Solid-phase photocatalytic degradation of polyethylene plastic under UV and solar light irradiation. J. Mol. Catal. A Chem. 268 (1–2), 101–106.

Zhu, K., Jia, H., Sun, Y., Dai, Y., Zhang, C., Guo, X., Wang, T., Zhu, L., 2020. Long-term phototransformation of microplastics under simulated sunlight irradiation in aquatic environments: roles of reactive oxygen species. Water Res. 173, 115564.

Ziajahromi, S., Neale, P.A., Telles Silveira, I., Chua, A., Leusch, F.D.L., 2021. An audit of microplastic abundance throughout three Australian wastewater treatment plants. Chemosphere 263, 128294.