Marine Pollution Bulletin 189 (2023) 114763

Contents lists available at ScienceDirect

Marine Pollution Bulletin

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

Impact of the Covid-19 pandemic on microplastic abundance along the River Thames

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ARTICLE INFO

Keywords:
River Thames
Covid-19
Microplastics

ABSTRACT

In April 2020, the Covid-19 pandemic changed human behaviour worldwide, creating an increased demand for plastic, especially single-use plastic in the form of personal protective equipment. The pandemic also provided a unique situation for plastic pollution studies, especially microplastic studies. This study looks at the impact of the Covid-19 pandemic and three national lockdowns on microplastic abundance at five sites along the river Thames, UK, compared to pre-Covid-19 levels. This study took place from May 2019–May 2021, with 3-L water samples collected monthly from each site starting at Teddington and ending at Southend-on-Sea. A total of 4480 pieces, the majority of fibres (82.1 %), were counted using light microscopy. Lockdown 2 (November 2020) had the highest average microplastic total (27.1 L^{-1}). A total of 691 pieces were identified via Fourier Transform Infrared Spectroscopy (FTIR). Polyvinyl chloride (36.19 %) made up the most microplastics identified. This study documents changes in microplastic abundance before, during and after the Covid-19 pandemic, an unprecedented event, as well as documenting microplastic abundance along the river Thames from 2019 to 2021.

1. Introduction

In December 2019, Covid-19 was detected in China; the World Health Organisation (WHO) declared it a worldwide pandemic in the following months after almost every country reported cases (Elflein, 2023). The health crisis caused social, economic as well as environmental threats. To curb infection rates and flatten the infection curve, governments worldwide implemented preventive measures, including social distancing, lockdown and personal protective equipment (PPE) such as gloves, masks and hand sanitisers. The increase in plastic use driven by the rise in PPE, coupled with inefficient waste management practices and infrastructure worldwide, increased plastic pollution, particularly from facemasks and gloves (Zambrano-Monserrate et al., 2020). This increase in plastic pollution will eventually degrade and become microplastic (<5 mm), increasing concentration levels, an emerging contaminant already found in terrestrial and aquatic environments worldwide (Lambert and Wagner, 2018; Martín et al., 2022).

At first glance, the pandemic seemed to be advantageous for the environment, with a decrease in greenhouse gas emissions, air pollution, and noise pollution (Dutheil et al., 2020; Muhammad et al., 2020; Tobías et al., 2020). However, increased medical waste and PPE usage combined with waste management practices worldwide, such as the reduction in recycling and growth in incineration and landfilling, led to a rise in plastic waste potentially entering the environment (Abu Qdais et al., 2020; Zambrano-Monserrate et al., 2020). Environmental threats have seemingly been pushed aside during the pandemic to focus on public health. Whilst the positive indirect ecological impacts of Covid-19 may be short-term, the adverse effects may have long-term consequences. The increased use of plastic is concerning due to the implications on the environment and public health in the long run (Patrício Silva et al. (2020a, b)).

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https://doi.org/10.1016/j.marpolbul.2023.114763
Received 29 December 2022; Received in revised form 16 February 2023; Accepted 18 February 2023

The increase in plastic pollution due to the improper disposal of face masks alone by 2022 is estimated to be 0.15–0.39 million tons worldwide (Chowdhury et al., 2021). Peng et al. (2021a) estimated plastic waste associated with the pandemic to be 8.4 ± 1.4 million tons globally in 2021, with 12,000 tons being microplastics. Personal protective equipment has been documented in the natural environment worldwide, including Peru (De-la-Torre et al., 2021), Kenya (Okuku et al., 2021), Canada (Ammendolia et al., 2021; Prata et al., 2020). This increase in plastic pollution resulting from Covid-19 is coupled with the microplastics that enter the aquatic environment through other means, such as wastewater treatment plants and littering that enter oceans via rivers. Lebreton and Andrady (2019) reported an annual input of 5.1 million tons of plastic from land into oceans, with the main pathway being rivers.

This study investigates the impact of the Covid-19 pandemic and the mismanaged plastic waste that entered the environment, specifically microplastics (<5 mm) within the river Thames. The hypothesis is that there would be no impact on microplastic abundances during lockdowns

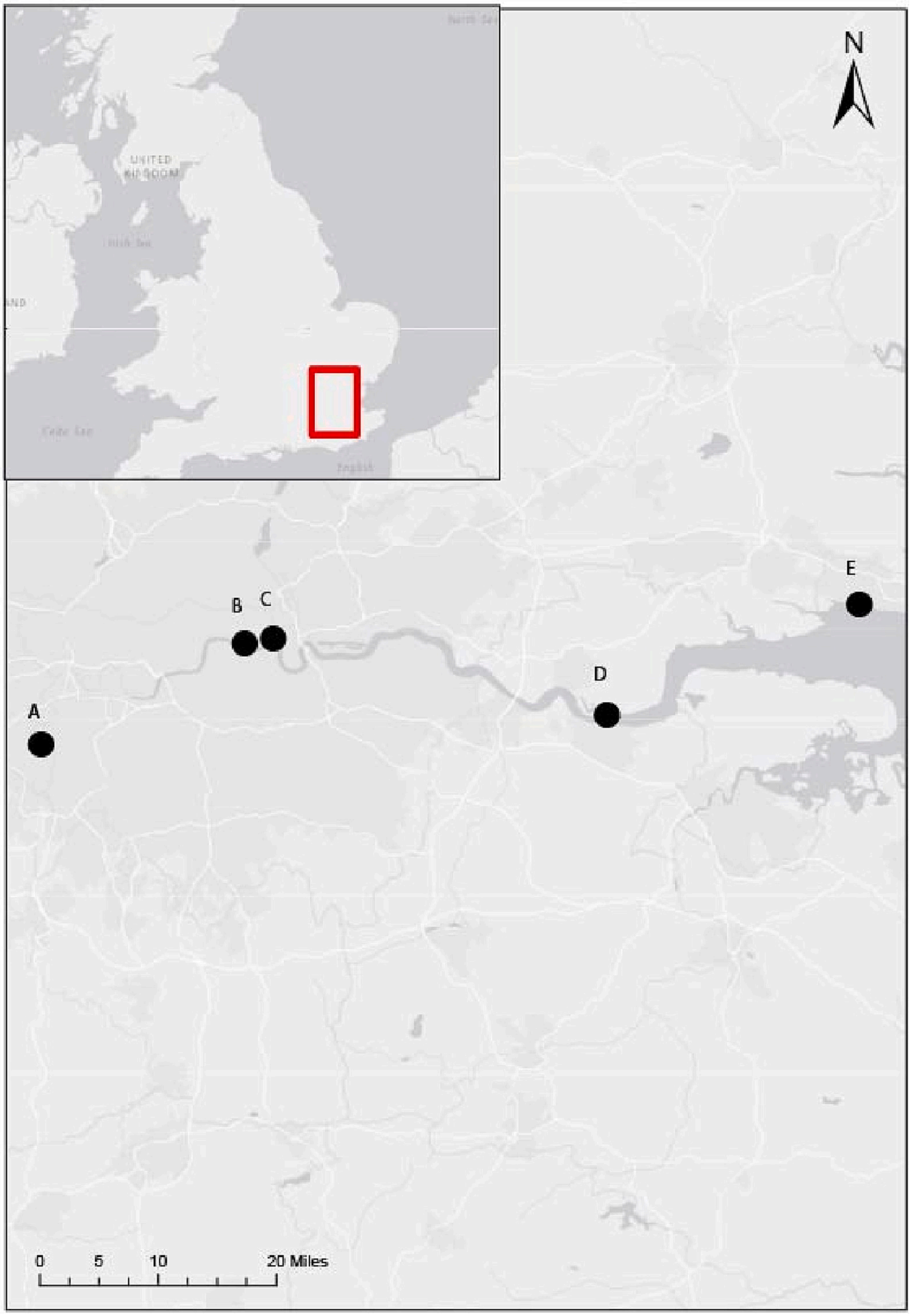

Fig. 1. Water sampling sites along the River Thames May 2019–May 2021; A) Teddington, B) St Katherines – Tower Bridge, C) Limehouse, D) Tilbury and E) Southend-on-Sea.

compared to before Covid-19. This is due to most, if not all, plastic entering the environment being macroplastics, i.e., masks and gloves, and as a result, not being counted or investigated during this study. This study aimed to; 1) investigate differences in MP abundances along the river Thames comparing pre-pandemic to during and post-pandemic, 2) investigate if lockdowns had an impact on microplastic abundances and morphology, and 3) investigate if changes in microplastic abundances and morphology could be due to another factor such as rainfall. The results provide a baseline for microplastic pollution in the River Thames and fill the knowledge gap of microplastic pollution in surface waters along a major river before, during, and after the Covid-19 pandemic. This can then be used to monitor for potential microplastic spikes originating from the degradation and breakdown of macroplastic from PPE used during the Covid-19 pandemic.

2. Material and methods

2.1. Study site and sampling

Five sites (Teddington Lock, St Katherines – Tower Bridge, Limehouse, Tilbury and Southend-on-Sea) along the tidal section of the river Thames were sampled pre-pandemic (May 2019–February 2020) during the Covid-19 pandemic 2020 (March 2020) and the month after the last Lockdown (May 2021) (Fig. 1, Table 1). The sites were chosen to obtain data from a range of areas along the river from Teddington Lock, which is the start of the tidal Thames, to Southend-on-Sea, where the river Thames enters the North Sea. Whilst the utmost care was taken to sample each month continuously. Southend-on-Sea and Tilbury were an exception in April 2020 due to self-isolating and the Teddington location changing from the island in the middle of the river to the side near a slipway. However, sampling was resumed in May 2020 at all sites. The change of site at Teddington was due to screening and barriers to prevent access to the usual sampling location on the island by the council and metropolitan police to prevent the public from getting access to the river from the "beaches" on the island as members of the public were using these to gain access to the river and were swimming near the lock (Richmond NUB News, 2022).

2.2. Sample collection

Water samples were collected monthly around the 15th of each month starting from May 2019 to June 2021 at high tide from land-based infrastructure at the site. Three 1 L surface water samples were collected from each site following protocols established by Devereux et al. (2022). High-density Polyethylene (HDPE) double-lidded bottles were used to store collected water and transport it from the site to the University of East London laboratory. Samples were filtered within a week of the collection; however, due to the pandemic and subsequent lockdowns, there were times (March 2020–June 2020; November 2020–December 2020; January 2021–February 2021) when this was not possible due to the University facilities being inaccessible. As a result, samples taken during these months were taken as soon as possible once the lockdown was lifted. However, it meant that some samples, such as March 2020, were not filtered for up to 4 months after collection. During these periods, samples were kept in a cool, dark cupboard to prevent degradation of MP, and samples were not placed in a freezer due to insufficient space.

Table 1
Water sampling site locations along the Thames Estuary.

Collection site	Address	Location coordinates	Width (km)	Depth (ft.)
Teddington Lock	Teddington Lock Footbridge, London Borough of Richmond upon the Thames, England, United Kingdom	N 51° 25′ 47.856″ W 0° 19′ 20.24″	0.06	7.5
St Katherine	River Thames, Shad Thames, London SE1 2NJ, United Kingdom	N 51° 30′ 22.504″ W 0° 4′ 24.324″	0.27	6.65–16.40
Limehouse	Ratcliff Cross Stairs, Jardine Road, London E1W 3WB, United Kingdom (Thames footpath)	N 51° 30′ 34.589″ W 0° 2′ 17.732″	0.23	6.6–16.4
Tilbury Fort	The World's End, Fort Road, Tilbury RM18 7NR, United Kingdom	N 51° 27′ 6.276″ E 0° 22′ 13.364″	0.79	32.81–49.21
Southend-on-Sea Pier	Lifeboat Station, Southend Pier, Southend-on-Sea SS1 2EL, United Kingdom	N 51° 30′ 54.705″ E 0° 43′ 18.069″	6.83	32.81–49.21

Upon the reopening of the laboratory, samples were filtered as soon as possible using a porcelain Buchner funnel and Whatman 1001–125 qualitative filter paper circles (11 μm, 10.5 s/100 mL flow rate, grade 1, 125 mm diameter).

After filtering the sample water, the high-density polyethylene (HDPE) double-lidded bottles used to store the collected sample water were rinsed with distilled water and filtered to ensure all MPs were collected from the bottles.

2.3. Microplastic characterisation

After filtration, the filter papers were initially examined using light microscopy and suspected MPs were visually identified, counted and then sorted into categories based on morphology or shape (fibre, fragment, particle, pellet and other) and colour (blue, black, red, white, yellow, orange, purple, green) (Fig. 2). 'The Guide for Microplastic Identification' (Marine and Environmental Research Institute, 2020), as well as a range of studies (Devereux et al., 2021; Devereux et al., 2022), was consulted to determine the microplastic observed.

After identifying and categorising the suspected MPs, the filters were placed under a Keyence digital microscope at ×50 magnification to measure the size range of the suspected plastic to ensure they fell within the size range of MP (>5 μm). Due to the Covid pandemic and lockdowns, a limited timeframe was left for laboratory work; only ten suspected MPs per filter were randomly selected to be measured.

In total, 691 pieces of suspected MPs were identified by Fourier-transform infrared spectroscopy (FTIR) (manufacturer Bruker model Alpha fitted with a platinum ATR Model with Opus 8.2 software), which was used to determine the composition of the materials appearing to be MPs to confirm they were plastics. OpenSpecy (Cowger et al., 2023) is an open-access database that identifies spectra matches from FTIR analysis (Supplementary Fig. 1).

Due to the size of MPs, it is impossible to be completely confident that cross-contamination did not occur during this study. However, extensive precautions were followed to reduce the likelihood of this occurring in the field and the laboratory.

Due to health, safety, and practicality, HDPE bottles (transparent with a red or blue lid) were used during sample collection. The sampling equipment was also plastic (orange and yellow). These samples were taken and identified by FTIR (bucket — polyethylene (PE), rope — polypropylene (PP)). Personal protective equipment in the laboratory included an orange cotton lab coat, latex gloves and, during Covid, a blue cotton face mask. Protocols to reduce atmospheric contamination of samples within the laboratory included covering filters when not in use. Equipment and surfaces were cleaned before and after use, including those used during filtering and FTIR.

Quality control tests were carried out to investigate the potential for plastic contamination, which included: 1) dampened filter paper placed on laboratory surfaces to monitor atmospheric contamination whilst filters were exposed and analysed daily (Supplementary Table 1); 2)

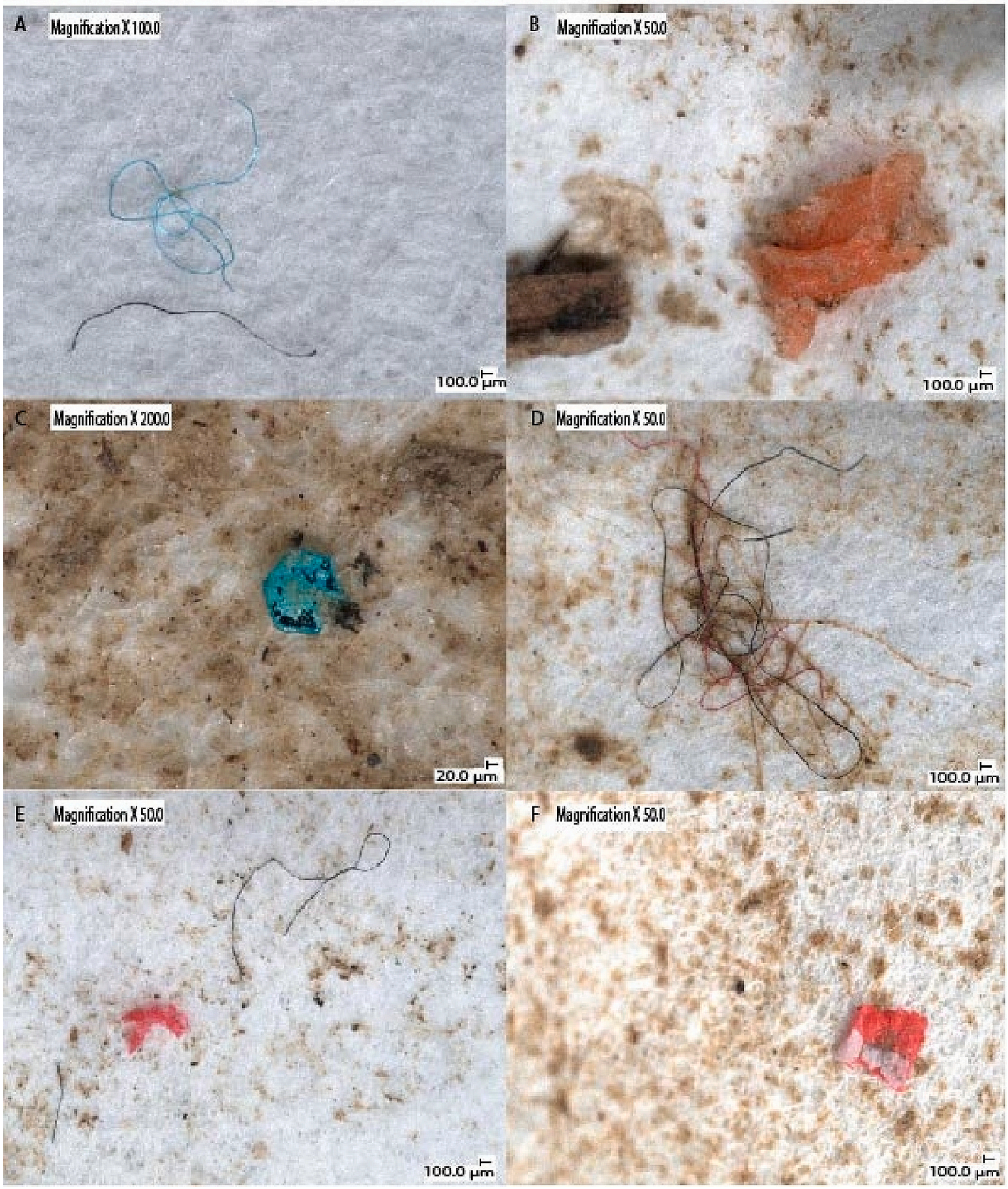

Fig. 2. Examples of microplastics observed during water samples taken from the River Thames 2019–2021. A) Blue and black fibres found at Teddington Lock June 2019, B) Red fragment found at Southend-on-Sea March 2021, C) Blue fragment found at Tilbury Fort February 2021, D) Fibres found at Tower Bridge January 2021, E) Red fragment and black fibres found at Limehouse November 2020, F) Red fragment found at Southend-on-Sea January 2020. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

three high-density polyethylene (HDPE) bottles rinsed with distilled water and filtered; 3) filtering blanks created using 3 × 3 L of distilled water passed through the filtration setup; and 4) testing the sampling equipment used for water collection (Supplementary Table 2).

To ensure microplastic abundances were accounted for, the visual counts of plastic identified by contamination controls were corrected by subtracting the corresponding procedural blanks, mainly from the filter papers used to test for atmospheric exposure. Orange or yellow microplastics that matched the polymer identified by FTIR for the sampling method were excluded and removed from the sample counts.

2.4. Statistical analysis

The following dates were used to classify samples; pre-Covid-19 (before March 2020), Lockdown 1 (April–June 2020), Lockdown 2 (5th November–2nd December 2020), Lockdown 3 (5th January–April 2021) and post-Covid-19 (May 2021). If a lockdown occurred after a sample had been taken, the corresponding month was not included in that lockdown. For example, the first national lockdown started on the 23rd of March 2020 and ended on the 24th of June 2020. As a result, March samples were taken before the 23rd, so they are included in the pre-Covid-19 data. The June 2020 samples were taken during the first lockdown (before the 24th of June, when the lockdown was lifted), so they are included in the Lockdown 1 data and statistics. Any sample taken after June 2020 but not included in the lockdowns was classified as during Covid-19 but not included in specific lockdown data.

ANOVA was used to test for significance between Covid-19 statuses and Covid-19 status vs site, then Covid-19 status vs site vs rainfall. Post hoc Tukey tests were used.

3. Results

A total of 4480 microplastics (MPs) were recorded across all five sites during all lockdown statuses. The highest MP abundance was recorded at Tilbury (1121 pieces) (Table. 2). The majority of MPs were recorded as fibres (3679 pieces, 82.1 %) and black (3003 pieces, 67.03 %) (Fig. 3).

Lockdown 2 (November 2020) had a higher average pieces L^{-1} across all sites except at Teddington (5.5 pieces L^{-1}) than at any other point (Fig. 3). The average microplastic total (MPT) abundance of L^{-1} along the river Thames during Lockdown 2 (27.1 pieces L^{-1}) was higher than at any other point; pre-Covid-19 (15.34 pieces L^{-1}), Lockdown 1 (10.19 pieces L^{-1}), Lockdown 3 (5.87 pieces L^{-1}), Covid-19 but no lockdown (8.12 pieces L^{-1}) and post-Covid-19 (5.27 pieces L^{-1}) (Fig. 3).

Microplastic abundance was significantly different between Covid-19 status (ANOVA, $F_{1,5} = 6.41$, $P > 0.001$). A post hoc test indicated the following were significantly different; pre-Covid-19 and Lockdown 3, Pre Covid-19 and Covid-19 no lockdown and Lockdown 2 compared to every other Covid-19 status except pre-Covid-19. There was no significance between site x Covid-19 status and MPT abundance (2-way ANOVA, $F_{1,20} = 1.87$, $P = 0.122$).

3.1.1. *Teddington*

Teddington's average MPT abundance was 10.01 pieces L^{-1} from 2019 to 2021. Pre-Covid-19 MPT average was 12.5 pieces L^{-1} during the 1st national lockdown; this decreased by 44 % to 5.5 pieces L^{-1} (Fig. 4). The average MPT abundance between Lockdown 1, 2 and 3 (5.08 pieces L^{-1}) was almost half that of pre-Covid-19, Covid-19 with no lockdown and post-Covid-19 abundance (10.72 pieces L^{-1}). The highest MPT was observed pre-Covid-19 in May 2019 (54.67 pieces L^{-1}), whereas the lowest MPT abundance was observed in October 2020 (1.67 pieces L^{-1}) during Covid-19 (Fig. 4). However, the UK was not in a national lockdown at the time. Microplastic abundance, however, did not significantly differ between the UK Covid-19 statuses (ANOVA, $F_{5,19} = 0.331$, $P = 0.88$). Even with the removal of May 2019 data which appears to be an anomaly with a microplastic abundance of 54.67 pieces L^{-1}, there is still no significant difference between microplastic abundance and Covid-19 status in Teddington. (ANOVA, $F_{5,18} = 0.482$, $P = 0.785$).

In total, 724 pieces of MP were identified and sorted from water samples collected at this site. All morphologies (fibre, fragment, bead, foam, pellet and others) of plastics were observed at this site. Fibres (84.49 %) were the most observed morphology, followed by fragments (8.66 %) (Fig. 4). Fibres ranged from 10.19 pieces L^{-1} (pre-Covid-19) to 3.67 pieces L^{-1} (Lockdown 2). However, there was no significant difference between fibres (ANOVA, $F_{5,19} = 0.253$, $p = 0.943$) or fragments (ANOVA, $F_{5,19} = 0.234$, $P = 0.943$) and Covid-19 status.

The colour black was the most predominant (62.12 %), followed by blue (17.44 %) and red (7.99 %). The colour black, on average, was higher during Covid-19 but not in a lockdown (7.4 pieces L^{-1}); however, there was no significant difference (ANOVA, $F_{1,19} = 0.208$, $P = 0.955$). Blue had the highest abundance pre-Covid-19 (2.64 pieces L^{-1}) and was observed during every Covid-19 status except lockdown 2 (Fig. 5).

3.1.2. *St Katherines – Tower Bridge*

St Katherines had an average MPT abundance of 13.17 pieces L^{-1} (2019–2021). The highest MPT abundance on average was observed in Lockdown 2 (November 2020) water sample (27 pieces L^{-1}), whilst the lowest on average was observed post-Covid-19 (6 pieces L^{-1}) (Fig. 4). There was an increase in MPT abundance between samples not in lockdown (10.39 L^{-1}) compared to those taken in Lockdown (14.39 pieces L^{-1}. However, there was no significant difference between all Covid-19 statuses and MP abundance (ANOVA, $F_{5,19} = 1.83$, $P = 0.15$).

In total, 987 pieces of MP were collected with fragments, fibres, foam, pellets, and other morphologies (Fig. 4). No beads were found at this site. Fibres (87.35 %) were the most identified, followed by fragments (6.89 %). There was a drop in fibre average between pre-Covid-19 (14.25 pieces L^{-1}) to lockdown 1 (4.17 pieces L^{-1}). However, there was no significant difference between fibres (ANOVA, $F_{5,19} = 2.12$, $P = 0.118$) or fragments (ANOVA, $F_{5,19} = 1.016$, $P = 0.42$ between the different Covid-19 statuses.

The majority of MP was classified as the colour black (69.2 %), followed by blue (11.15 %) and transparent (7.19 %) (Fig. 5). Although there was a drop in black MP from Pre-Covid-19 (11.44 L^{-1}) to lockdown 1 (2.17 L^{-1}), there was no significance between Covid-19 statuses (ANOVA, $F_{5,19} = 2.34$, $P = 0.09$). There was also no significance in blue MP abundances (ANOVA, $F_{5,9} = 0.56$, $P = 0.7$).

3.1.3. *Limehouse*

Limehouse had an average MPT abundance of 10.15 pieces L^{-1}. The highest average MPT abundance was observed during Lockdown 2 (61.3 pieces L^{-1}) with only one sample (November 2020) (Fig. 4). The lowest MPT abundance was observed post-Lockdown (2.67 pieces L^{-1}). There was a significant difference between MPT abundance during the different Covid-19 statuses (ANOVA, $F_{5,9} = 20.33$, $P > 0.001$.

In total, 889 pieces of MP were collected, of which the majority were fibres (86.39 %), followed by fragments (10.91 %), foam, pellets and others (Fig. 4). No beads were found during water samples. There was a significant difference between fibre abundance during the Covid-19 status (ANOVA, $F_{5,19} = 21.66$, $P > 0.001$), with the highest abundance being found during Lockdown. There was no significant difference between fragment abundance and Covid-19 status (ANOVA, $F_{5,19} = 1.7$, $P = 0.18$).

A total of 11 colours were observed, with black (637 pieces, 71.65 %) being the most predominant, followed by red (79 pieces, 8.89 %) and blue (60 pieces, 6.75 %). Most black MP was found during lockdown 2 (58.3 pieces L^{-1}) (Fig. 5). As a result, there was a significant difference

Table 2

Total microplastic abundance (MPT) and average MPT L^{-1} during the different stage of the Covid-19 pandemic across five sites (Teddington, Tower Bridge, Limehouse, Tilbury and Southend-on-Sea-on-Sea) located within the tidal river Thames. The different stages of the Covid-19 pandemic are defined as pre-Covid-19 (Before March 23rd, 2020), Lockdown 1 (April–June 2020), Lockdown 2 (5th November–2nd December 2020), Lockdown 3 (5th January–April 2021), post-Covid-19 (May 2021). Months where samples were taken from April 2020 to April 2021 but where a national UK lockdown was not in place are classified as during Covid-19 no lockdown (July–September 2020, October–November 2020).

Site	Total microplastic abundance	Average MPT L^{-1} pre-Covid-19 (±stderr/SE)	Average MPT L^{-1} Lockdown 1 (±stderr/SE)	Average MPT L^{-1} Lockdown 2 (±stderr/SE)	Average MPT L^{-1} Lockdown 3 (±stderr/SE)	Average MPT L^{-1} during Covid-19-no lockdown (±stderr/SE)	Average MPT L^{-1} post Covid-19 (±stderr/SE)
Teddington	751	12.5 (14.52)	5.5 (4.48)	4 (0)	5.75 (3.78)	10.68 (7.54)	9 (0)
St Katherine	987	17 (10.3)	7 (2.17)	27 (0)	9 (4.43)	8 (3.49)	6 (0)
Limehouse	889	12.11 (5.18)	15.3 (7.3)	61.3 (0)	4.5 (1.5)	7.67 (4.39)	2.67 (0)
Tilbury	1121	21.17 (16.49)	15.83 (5.42)	29.3 (0)	4.83 (2.08)	7.4 (1.38)	2.33 (0)
Southend-on-Sea	732	13.94 (10.61)	7.33 (1.41)	14.3 (0)	5.25 (1.52)	6.87 (3.64)	6.33 (0)

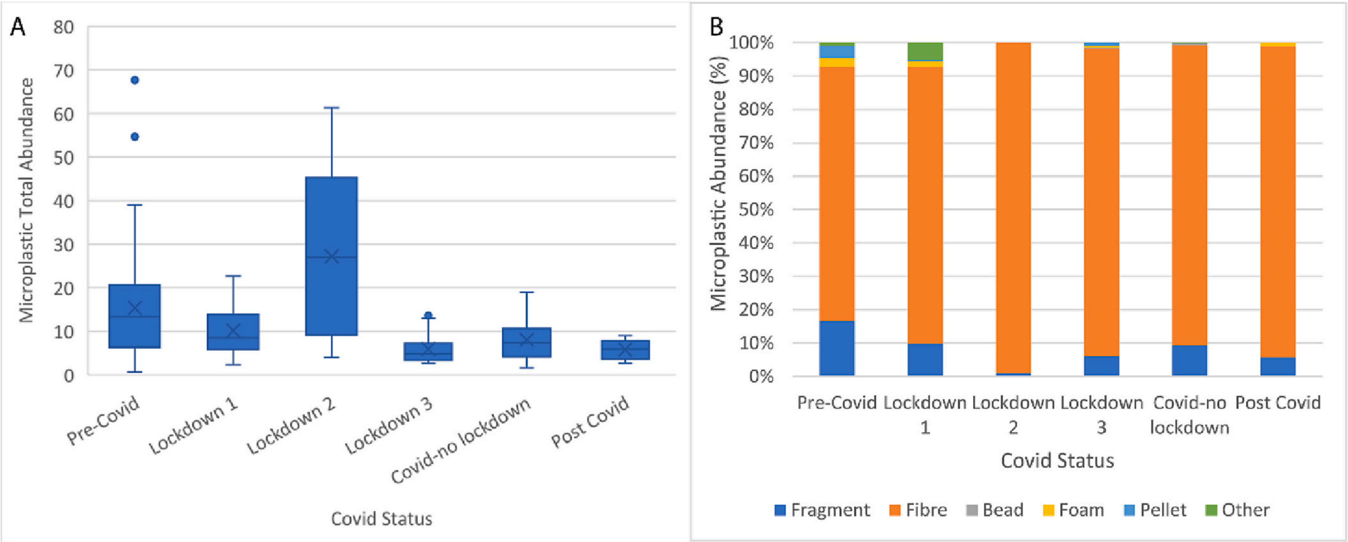

Fig. 3. Microplastic A) Abundance L^{-1} and B) Type found in water samples along the river Thames during the different stages of the Covid-19 pandemic.

between black and Covid-19 status (ANOVA, $F_{5,19} = 27.66$, $P > 0.001$).

3.1.4. *Tilbury*

The average MPT abundance for Tilbury was 10.01 pieces L^{-1} between 2019 and 202. The highest MPT was found during Lockdown 2 (29.3 pieces L^{-1}), and the lowest was found post-Covid-19 (2.3 pieces L^{-1}) (Fig. 4). There was an increase in MPT abundance during lockdowns (16.67 pieces L^{-1}) compared to samples taken when not in a national lockdown (10.3 pieces L^{-1}). However, there was no significant difference between MP abundance and Covid-19 status (ANOVA, $F_{5,19} = 1.87$, $P = 0.148$).

In total, 1121 pieces of MP were counted and classified as fragments, fibres, beads, pellets, foam or other. Most MP was identified as fibres (89.66 %) and fragments (7.85 %) (Fig. 4). On average, samples collected during lockdowns (16.31 pieces L^{-1}) contained more fibres than samples taken at any other time except pre-Covid-19 (18.31 pieces L^{-1}), but this was not significant (ANOVA, $F_{5,19} = 2.395$, $P = 0.076$).

Black (74.49 %), blue (8.47 %) and red (6.6 %) were the most commonly identified colours (Fig. 5). Whilst the average of black MP was higher during lockdowns (36.83 pieces L^{-1}) compared to when not in lockdowns (22.49 pieces L^{-1}), there was no significance (ANOVA, $F_{5,19} = 2.055$, $P = 0.116$).

3.1.5. *Southend-on-Sea*

The average MPT abundance for Southend-on-Sea 2019–2021 was 10.01 pieces L^{-1}. The highest average MPT abundance was observed in June 2019 (35.67 pieces L^{-1}), pre-Covid-19 (Fig. 4). The lowest abundance was also pre-pandemic in February 2020 (0.67 pieces L^{-1}). Lockdown 2 had the highest average MPT (14.3 pieces L^{-1}), followed by pre-Covid-19 (13.94 pieces L^{-1}). There was no significant difference between no lockdown (9.05 pieces L^{-1}) compared to lockdown (8.96 pieces L^{-1}) samples (ANOVA, $F_{5,18} = 1.079$, $P = 0.405$).

A total of 732 pieces of MP were counted from Southend-on-Sea water samples, including fragments, fibres, foam, pellets and others. Fibres (54.92 %) and fragments (34.56 %) were the most common (Fig. 4). The abundance of microfibres during the three lockdowns (7.67 pieces L^{-1}) was higher than samples not taken during a lockdown (5.34 pieces L^{-1}), but there was no significant difference between Covid-19 statuses and fibres (ANOVA, $F_{5,18} = 0.67$, $P = 0.651$) or fragments (ANOVA, $F_{5,18} = 1.079$, $P = 0.405$).

Black (53.14 %) was the most commonly identified colour, followed by white (11.48 %) and transparent (7.92 %) (Fig. 5). Although blue microplastic was not one of the most frequently identified MP colours, it was significantly different (ANOVA, $F_{5,18} = 12.573$, $P > 0.001$) between Covid-19 statuses. Lockdown 2 had the highest blue MPT average (15 pieces L^{-1}). The second highest blue MP average was found during the COVID-19 but not lockdown samples (2.2 pieces L^{-1}).

3.2. *Polymer type*

In total, 691 pieces (15.42 %) of plastic were identified across all sites. Whilst there was variation between the sites, some polymers were more prevalent throughout the river. A total of 42 different polymers were identified during this study. The most abundant polymers found across the river Thames were PVC (181 pieces, 36.19 %), PS (70 pieces, 10.13 %) and PCP (52 pieces, 7.53 %) (Fig. 6, Fig. 7). As well as polymers, there were 122 ‘no hits’ (17.66 %) as well as anthropogenic microfibres/particles identified, such as cotton, wool, silk, nylon, and silicon (17 pieces, 2.46 %).

When comparing polymer abundances across all sites, PVC was the most identified polymer during the various Covid-19 statuses, except during Lockdown 2, where rubber (average two pieces) polymers were the most abundant (Fig. 6). Polyvinyl chloride saw a 50.94 % drop from pre-Covid-19 samples (average 1.963 pieces) to Lockdown 1 (average one piece), after which it gradually increased throughout the lockdowns and was more abundant on average post-Covid-19 (average three pieces), with the most pieces being found at Tilbury (33.33 %) during this time. Polymers identified via FTIR varied between sites and throughout the Covid-19 pandemic (Fig. 7).

3.2.1. *Teddington*

Teddington's (28 polymers identified) most abundant polymer was PVC (32 pieces, 28.32 %), with Lockdown 3 having only a total of 10 pieces compared to the lowest abundance found during Covid-19 with no lockdown (4 pieces) (Fig. 7). However, when this data was averaged out, Lockdown 3 (average 3 pieces) had the highest abundance of PVC compared to any other Covid-19 status, including pre-Covid (1.083 pieces). Acrylonitrile butadiene styrene (ABS) was only observed post-Covid-19 with a total of 2 pieces observed, whilst polyethylene chlorinated (PEC), polyethylene terephthalate (PETE), polycarbonate (PC), polyphenylene sulphide (PES) and polyester were only observed pre-Covid-19. Polystyrene, PCP, PP and polysulfone increased in abundance post-Covid-19 from pre-Covid-19 abundances.

3.2.2. *St Katherines – Tower Bridge*

St Katherines had 32 different polymers identified. The most

Fig. 4. Microplastic abundances across water sample sites along the river Thames during the different stages of the Covid-19 Pandemic; A) Teddington, B) St Katherines – Tower Bridge, C) Limehouse, D) Tilbury and E) Southend-on-Sea.

Fig. 5. Colours of microplastics found within water samples at sites along the river Thames during the different stages of the Covid-19 Pandemic; A) Teddington, B) St Katherines – Tower Bridge, C) Limehouse, D) Tilbury and E) Southend-on-Sea.

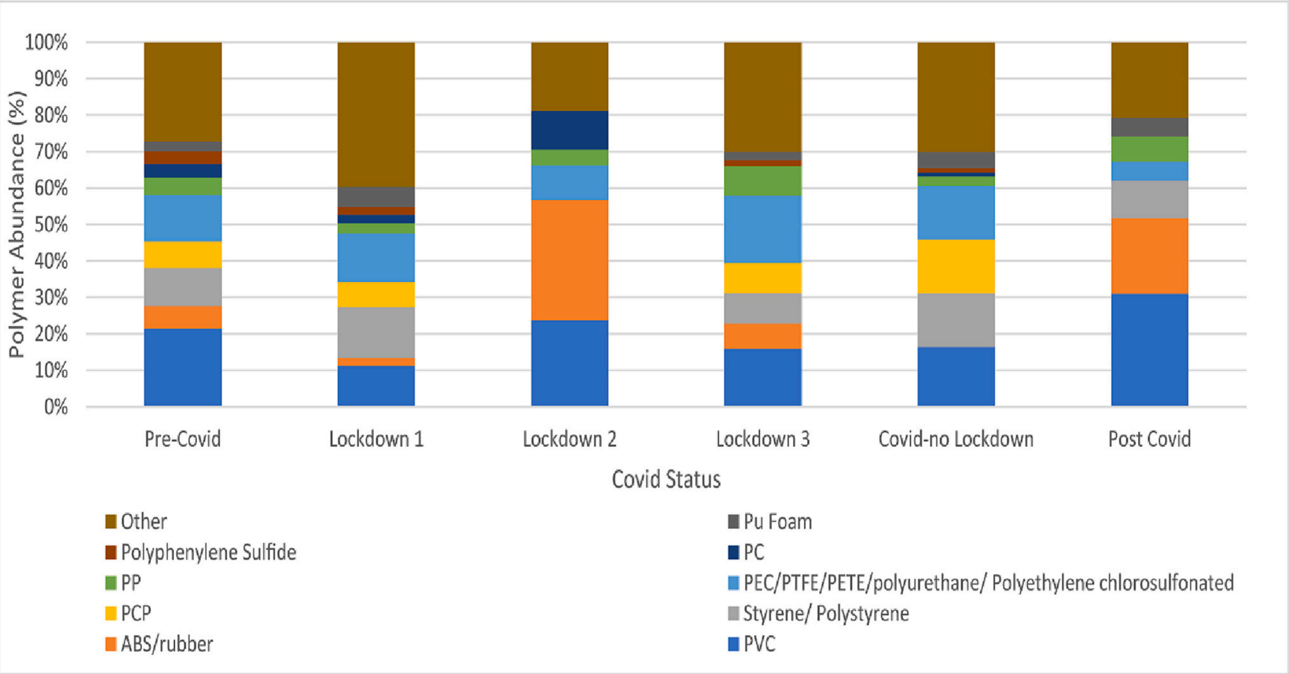

Fig. 6. Overall polymer abundances (%) of microplastics found in water samples along the River Thames May 2019–May 2021 during different stages of the Covid-19 pandemic.

abundant were PVC (28 pieces, 24.78 %) and Polystyrene (PS) (16 pieces, 14.16 %) (Fig. 7). However, unlike Teddington, St Katherine had fewer polymers in post-Covid-19 water samples, with only PVC (7 pieces) and PP (3 pieces) identified at both sites. Polyvinyl chloride decreased from pre-Covid levels (Average 1.25 pieces) during Lockdown 1 (average 0.5 pieces) and low during the Covid pandemic, only increasing in abundance in post-Covid-19 water samples (average 7 pieces). Polystyrene increased from pre-Covid-19 abundances (average 0.75 pieces) and increased during lockdown 1 (average 1 piece) and spiked during lockdown 2 (average 2 pieces), and continued to decline by post-Covid samples, which did not contain PS. Higher levels of PP were observed post-covid-19 (average 3 pieces) compared to pre-Covid-19 (average 0.33 pieces).

3.2.3. *Limehouse*

Limehouse had 26 polymers identified throughout this study. The most abundant polymers identified were the same as St Katherines PVC (39 pieces, 34.2 %), followed by PS (13 pieces, 11.4 %) (Fig. 7). PVC also rose at Limehouse from pre-Covid-19 (average 2.6 pieces) abundances to post-Covid-19 (average 3 pieces), which was similar to St Katherines although there was a decrease during Lockdown 1 (average 1 piece). Limehouse had fewer polymers identified in post-Covid water samples, with only PVC (3 pieces, 2.65 %) and PP (1 piece, 0.89 %) identified.

3.2.4. *Tilbury*

Samples from Tilbury had 18 different polymers, with 17 polymers identified Pre-Covid-19. The only polymer not found in Pre-Covid-19 samples was polyamide, which was found in water samples taken during Covid with no Lockdown. The most abundant polymers identified were PVC (39 pieces) and PP (21 pieces) (Fig. 7). PVC was found in samples taken during all Covid-19 pandemic statuses except for Lockdown 2, after which PVC abundance increased, and Post-Covid-19 (5 pieces) was found in a higher average abundance than Pre-Covid (2.4 pieces). Unlike the other Covid statuses where multiple polymers were identified, ABS was the only polymer identified in Lockdown 2, and PVC was the only polymer identified post-Covid-19.

3.2.5. *Southend*

Southend-on-Sea had 27 polymers identified throughout this study, the highest variation at any other site (Fig. 7). The most abundant polymer was PVC (42 pieces) and observed in every Covid status except Lockdown 2. This was followed by PCP (13 pieces), which was not observed in Lockdown 1 and 2. Pre-Covid-19 had the most different polymers identified with 17 types, which decreased to 7 polymers during Lockdown 1. Post-Covid-19 had the lowest abundance of polymer types, with only three polymers identified (PVC, PS and PCP). PVC decreased throughout the Covid pandemic from pre-Covid-19 abundances (average 28 pieces) with a massive decrease during Lockdown 1 samples (average 2 pieces). PVC remained below pre-Covid-19 abundances, only slightly increasing from Lockdown 1 abundances in Lockdown 3 (average 3 pieces) and Covid-no lockdown (average 7 pieces). Polystyrene and PCP also decreased from pre-Covid-19 levels during the pandemic from an average of 6 pieces and 7 pieces, respectively, to an average of 1 piece during Post-Covid samples.

3.3. *Rainfall*

Rainfall at this time ranged from 8.9 mm (Teddington, May 2020)–162.2 mm (Tilbury Fort, January 2021). Whilst there was a variation in rainfall from May 2019 to May 2021, there was no significance between rainfall and MPT during this study (ANOVA $F_{1,39} = 0.418$, $P = 0.996$) or MPT × rainfall × Covid-19 status (ANOVA, $F_{1,95} = 3.148$, $P = 0.087$). Post hoc tests could not be carried out for rainfall because some groups had less than two factors.

4. Discussion

The increase in plastic production, usage of PPE and change in public behaviour during the Covid-19 pandemic will eventually lead to an increase in MPs resulting from the inadequate disposal of facemasks and other PPE worldwide. This research specifically looked at the short-term impact of the Covid-19 pandemic on MP abundance within the river Thames, and every water sample contained microplastics. A difference was not expected immediately in MP abundance within the river Thames

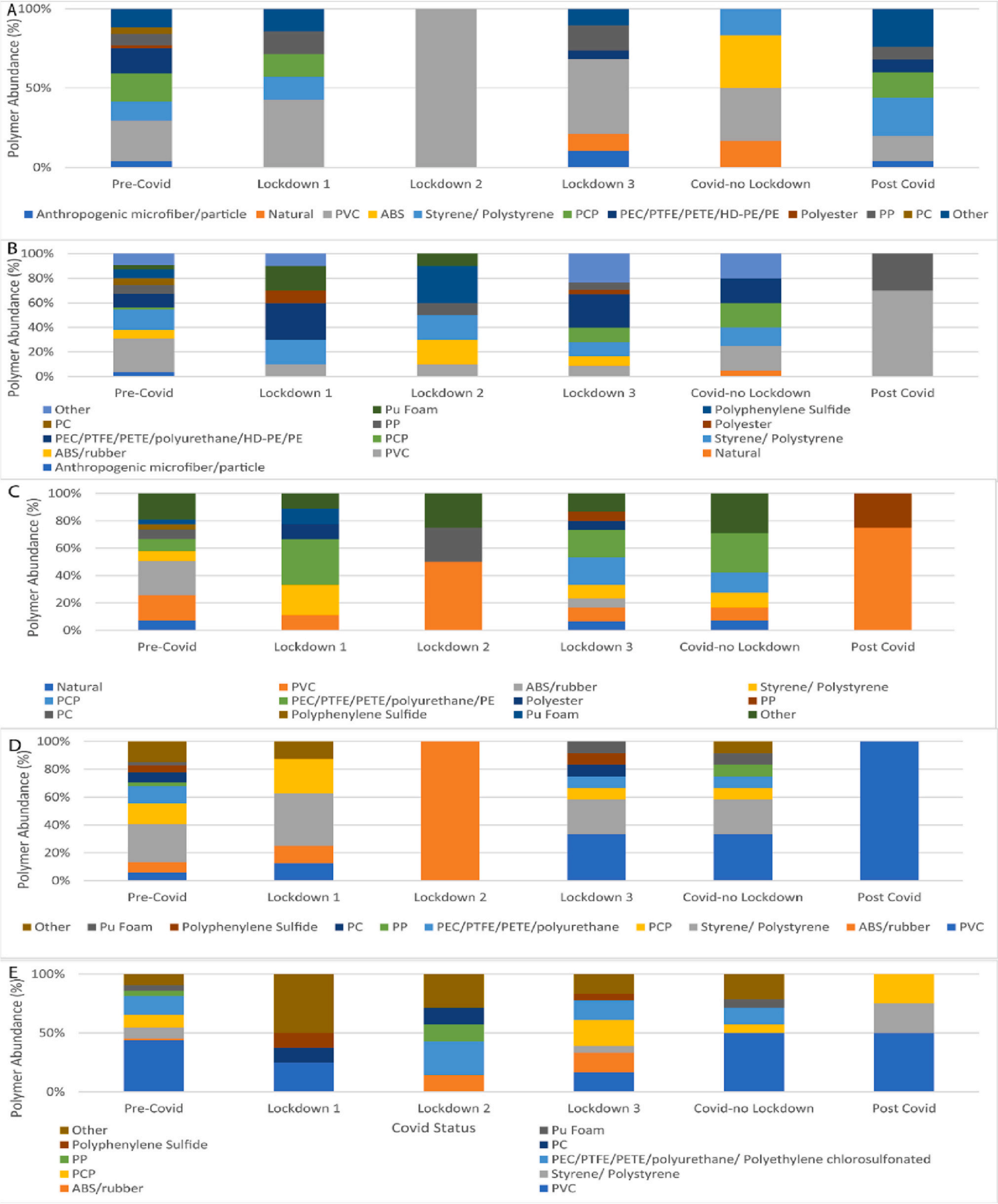

Fig. 7. Polymers identified via FTIR at water sample sites along the river Thames; A) Teddington (other – polysulfone, polyacetal, polyurethane, polyphenylene sulfide, alkyd varnish, resin – dispersion, Pu foam, polyvinyl butyral, polyhydroxyl butrylic acid and polyisoprene chlorinated), B) St Katherine (other – alkyd varnish, resin – dispersion, vinylidene chloride, polyamide, polyvinyl alcohol, polylactic acid, polyvinyl fluoride and polybutadiene), C) Limehouse (other – alkyd varnish, resin – dispersion, vinylidene chloride, polyamide, polyvinyl alcohol, polylactic acid, polyvinyl fluoride, polybutadiene and zein purified), D) Tilbury (other – alkyd varnish, vinylidene chloride, polyamide, polylactic acid, polyvinyl fluoride and polyoxymethylene) and E) Southend-on-Sea (other – edterepolymer, polyacetal, alginic acid, alkyd varnish, resin – dispersion, polyvinyl butyral, polyisoprene chlorinated, vinylidene chlorinated, polyamide, polyvinyl fluoride, poly (2,4,6-tribromostyrene), poly acrylic acid).

upon the announcement and implementation of Lockdown 1 due to plastics taking many years to degrade (Aragaw, 2020; Fadare and Okoffo, 2020; Saliu et al., 2021). Saliu (et al., 2021) suggested that face masks could degrade into MPs within two years. However, the abundance of MP fibres released from disposable face masks varies among studies. One mask has been reported as releasing 24,300 fibres per wash, whilst using one mask daily for a year will produce 66,000 tons of plastic waste (Shen et al., 2021; Shetty et al., 2020). Whereas Idowu et al. (2023) suggested that a single face mask can release 3686.24 MPs and degrade within 60 weeks, dependent on environmental factors such as temperature, ultraviolet light and natural weathering.

The data showed a slight decrease in MP abundances from pre-Covid-19 samples to Lockdown 1 samples; however, significant differences were not seen until Lockdown 2, roughly seven months after the start of the first lockdown. Except for Lockdown 2, MP abundances never reached pre-Covid-19 levels (15.34 pieces L^{-1}) or even post-Covid-19 (5.26 pieces L^{-1}). Whilst the river Thames average MP never reached pre-Covid-19 numbers. There were some site exceptions. Limehouse in Lockdown 1 had a higher MP abundance than pre-Covid-19 possibly because the area surrounding this site was the most residential (population 7817 in 0.409 km^2) (City population, 2022) as well as being within proximity of Limehouse harbour and marina, which has 75 permanent residential moorings and 56 leisure moorings (Aquavista, 2022). Teddington also had a higher MP during Covid-19, with no lockdown compared to pre-Covid-19. This is possible because members of the public were using the river recreationally when the country was not in lockdown, which led to the island and beach being barricaded by the council and police. The decrease at Tilbury could be explained by the lack of cruises leaving the area, as the sampling area is close to Tilbury port. During the Covid-19 pandemic, cruises to or from this port were suspended (Richards and Ilozue, 2020). As a result, there would have been less grey water from cruises, which was high in MPs (Peng et al. (2021b)).

The low MP abundance in the post-Covid-19 (May 2021) sampling may be due to only having one sample from each site or the fact that the UK had been in lockdown for four months before the samples were collected. However, MP was lower across the river Thames than at any other time, including Lockdown 3 (January–April 2021).

Studies focusing on macroplastics found an increase in PPE waste over time within riverine environments. For example, the presence of gloves and masks within river outlets increased at the start of the Covid-19 pandemic in Hong Kong (Fadare and Okoffo, 2020), Indonesia (Cordova et al., 2021), and Italy (Wang et al., 2021) to name a few. Studies investigating microplastics also found similar results to this study. Lin et al. (2023) attributed a decrease in MPs abundance from 2019 to 2021 within Xiamen Bay (14.0 to 1.03 items m^{-3}) and Jiulong River estuary (11.1 to 1.30 items m^{-3}) to the pandemic.

During the Covid-19 pandemic, single-use plastics (SUPs) increased due to concerns about catching Covid from reusable containers and bags, as well as some countries postponing plastic return schemes, i.e., Scotland (Silva et al., 2020); this was in addition to the increase in PPE use. Eventually, there will be an influx of plastic pollution resulting in an increase in microplastics entering the environment. Regional and national actions and policies should be developed that focus on decreasing sources of plastic pollution and changing public behaviour, as well as prioritising clean-ups to limit the long-term impacts of plastic use during the Covid-19 and similar future pandemics.

4.1. Microplastic characteristics at sample sites

Generally, all types of plastic are lower in abundance from pre-Covid-19 samples to post-Covid-19, excluding Lockdown 2. Although there was no significance between the type of MP or Covid-19 status, there was a decline from pre-Covid-19 samples to Lockdown 1 samples in fragments, fibres, beads, foam, pellets and others. Fragments, beads, foam, pellets and others may be lower because only “essential work” could be carried out. It may also be because members of the public were told to stay at home, so there was possibly less litter on the street in the usual forms (plastic bottles or wrappers). This was especially the case during Lockdown 1. It is possible that there was no significance between Covid-19 status and MP abundance because PPE, such as masks and gloves, take a long time to break down.

The most common colours observed were black, blue, red and transparent. These colours have previously been noted as the most abundant in the digestive tracts of European flounder and European smelt (McGoran et al., 2017). Coloured microplastics are common in other studies, possibly because they originate from commonly used items that have fragmented, and much of the plastic used is coloured (Zhang et al., 2015).

4.2. FTIR

The majority of plastic polymers identified within the river Thames were PVC, PS, and PCP. The high presence of PVC, PS, and PCP among samples is not surprising as they are among the most commonly produced and used plastic polymers worldwide (Chia et al., 2020), whilst also being previously found within the River Thames water samples (Devereux et al., 2022; Horton et al., 2017; McGoran et al., 2017). Polypropylene increased from pre-Covid-19 abundances during post-Covid-19 and Lockdown 3 samples, and Lockdown 3 had the highest abundance of PP found. This is possibly due to the use of PPE, especially masks. Masks are composed of various polymers such as PP, PS, PE, and Polyester (Aragaw, 2020). Polypropylene was higher post-Covid-19 and during Lockdown 3 than pre-Covid-19. Although it was lower post-Covid-19 with no MP identified, polystyrene was higher during Covid-19, with no lockdown, than pre-Covid-19. The increase in polypropylene over time is similar to Cordova et al. (2021), who monitored the Jakarta area, Indonesia, as well as reported by Ramesh and Nagalakshmi (2022) in water samples of the Adyar and Cooum Estuary, India.

A higher variation of polymers was seen across all sites in pre-Covid samples, especially when compared to post-Covid samples. However, this may be due to only one sample being taken post-Covid compared to the 12 samples taken pre-Covid. A similar result was seen during Lockdown 2 across all sites, which may also be due to only one sample being taken at each site. As a result, it is more likely to assume that the amount of sampling taken during the different Covid-19 statuses caused a decrease in the types of polymers observed rather than less variety of polymers being observed in the river due to Covid-19.

ABS is regularly referred to as tire wear particles. ABS decreased from pre-Covid-19 abundances during Lockdown 1 at every site it was found. This is possibly due to only essential workers being allowed out during the Lockdown, with the majority of people staying at home. As a result, fewer cars were on the roads, especially within the London area, with car traffic down to 23 % of its usual baseline (Zhang and Cheng, 2022). This decrease in ABS was not consistent throughout all the Lockdowns, with ABS abundance increasing to pre-Covid levels or above, eventually resulting in ABS being more abundant post-Covid-19 than pre-Covid-19. It is possible that the increase was due to everyone returning to pre-Covid-19 routines. For example, by June 2019 (after Lockdown 1), heavy goods traffic was back to normal, and car usage was back to 80 % of pre-Covid-19 levels (Vickerman, 2021). The increase during further lockdowns may have been due to more people using individual cars rather than relying on public transport due to fears of catching Covid-19. In London, underground usage decreased to 5 % of its average passenger figures and rose to 40 % between Lockdown 1 and 2; however, at the start of Lockdown 2, this fell to below 25 % (Vickerman, 2021).

Similarly, buses in London had just 14 % of average passenger figures during Lockdown 1, rising to 60 % between Lockdowns 1 and 2 and decreasing to 40 % in Lockdown 2 (Vickerman, 2021). When asked 65 % of public transport users in the UK in June 2020, lockdowns and unlock phases, respectively (Vega et al., 2021). However, the increase in ABS, especially in Lockdown 3, may also be because sampling coincided with stage 3 in the UK lockdown (17th May 2021), which involved opening pubs, restaurants, and hotels and allowing people to meet in groups of 30. It is possible that rivers, especially within heavily commuted areas, will show similar results with an initial decrease of ABS during the first initial lockdown. However, to this author's knowledge, no study has reported ABS abundance in rivers pre- and post-pandemic yet.

4.3. Impact of rainfall on microplastic abundances

Whilst rainfall in this study did not impact MP abundance, other studies have found that rain has a significant impact (Hitchcock, 2020; Veerasingam et al., 2016). This is due to rainfall putting pressure on sewage and stormwater systems and increasing MP abundance within these systems, especially tire wear particles (TWPs) and degraded litter (Müller et al., 2020; Vogelsang et al., 2019). This increased pressure can cause combined sewage outflows to open, resulting in the direct input of untreated wastewater into rivers (Fendall and Sewell, 2009). Whilst three named storms (Alex, Barbara and Aiden) occurred in October 2020, the last Storm Aiden (Met Office, 2020a, b, c), occurred two weeks roughly before sampling took place for the Lockdown 2 samples. It is possible that whilst rainfall in the 24 h pre-sample did not impact MP abundance, it is possible that the storms the previous month did put pressure on sewers around the river Thames and caused the release of sewage water from CSOs. The average rainfall across the London area in October 2020 was 174.3 mm (double the moderate rain) (Met Office, 2020b); because samples were taken in the middle of the month, the impact of monthly rainfall was not considered during this study. Whilst it was also not possible to find data on specific CSO releases to see if there was a correlation, there were six sewage alerts for the river Thames between October 21st and November 15th from Mogden (4 alerts) and Hammersmith (2 alerts) (River Thames CSO, 2022). This could have increased the MP abundance seen during Lockdown 2.

However, for this study, rainfall appeared not to impact Lockdown 2 or any other Covid-19 Status. As a result, a conclusion may be drawn that the increase in MP abundance may be down to multiple factors, including the three storms the month before and the lifting of lockdown for the four months between June and November.

5. Conclusions

This study aimed to investigate the impact of the Covid-19 pandemic on microplastic abundance at sites along the river Thames. Whilst previous studies have documented microplastic abundances within the river Thames, continuous monitoring at multiple sites along the river for multiple years is lacking. The Covid-19 pandemic provided a unique opportunity to study the effects of a pandemic and subsequent lockdowns on microplastic abundance within a major river. Microplastics were present in every sample conducted throughout this study. This study showed that MP abundance was linked to Covid-19 status, especially regarding pre-Covid-19 samples and Covid-19 samples taken not in a lockdown, especially in Lockdown 2. The increase in PP throughout this study could be attributed to the use, inefficient disposal and breakdown of face masks used throughout the pandemic. Rainfall was investigated as a potential explanation for the high MP abundances seen in Lockdown 2. However, the previous 24-h rainfall did not affect the abundances; however, whilst this study was not investigated, the three major storms in October 2020 may have affected Lockdown 2 samples. Whilst the Covid 19 pandemic did affect some samples along the river Thames, the true impact of the Covid-19 pandemic on plastic pollution worldwide may not be seen for some years as the plastic items that had increased production, such as masks and gloves, degrade and caused an increase in MP release into the environment. The results show a decrease in microplastic abundance as a whole during the Covid-19 pandemic and an increase in PP used in PPE throughout the lockdowns. This data could be used to influence policies on waste management as well as influencing public behaviour on plastic waste. This data could be used to influence policies on waste management as well as influencing public behaviour on plastic waste.

CRediT authorship contribution statement

Ria Devereux: Conceptualisation, Methodology, Investigation, Writing – original draft preparation.

Elizabeth Kebede Westhead: Supervision, Writing- reviewing and editing.

Ravindra Jayaratne: Supervision, Writing- reviewing and editing.

Bamdad Ayati: Supervision, Writing- reviewing and editing.

Darryl Newport: Methodology, Supervision, Writing- reviewing and 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

No data was used for the research described in the article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2023.114763.

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