Volume 3, Number 3, 2026 Pages 1-25

Bioscience Insights

ISSN: 3080-3489 (Print)
ISSN: 3080-3497 (Online)

BiosciInsights.com

ASSESSMENT OF PFAS CONTAMINATION AND REMOVAL EFFICIENCY ACROSS WASTEWATER TREATMENT STAGES: A QUANTITATIVE ENVIRONMENTAL STUDY

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https://doi.org/10.5281/zenodo.24003731

Article Information

Article History

Received:	June 19, 2026
Revised:	August 19, 2026
Accepted:	September 07, 2026
Available Online:	October 28, 2026

Keywords:
Microplastics, Antibiotic Resistance Genes, Wastewater Treatment, Plastisphere, Removal Efficiency, Horizontal Gene Transfer.

Abstract

In this study, a quantitative evaluation of microplastic (MP) contamination, antibiotic resistance gene (ARG) loads and physicochemical parameters was demonstrated through the various stages of municipal wastewater treatment plants (WWTPs). Based on the complete dataset of 100 matched influent and effluent samples from 5 treatment facilities, we investigated removal performance, morphological transformations and co-occurrence of MP and ARG. The mean number of microplastic particles found in influent wastewater was 234.43 ± 82.57 particles/L, whereas the effluent number of microplastic particles was 50.58 ± 26.28 particles/L, indicating that the removal efficiency of the total microplastic particles was 78.42% (t = 15.00, p < 0.001). Total ARG abundance demonstrated a higher mean reduction of 95.93%, falling from 620,879.90 ± 822,954.64 copies/mL in influent to 25,267.86 ± 14,997.97 copies/mL in effluent (t = 5.12, p <

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0.001). The abundance of the relative ARG was 455.19% copies of 16S rRNA and reduced by 94.45% to 25.27% copies of 16S rRNA. The removal of integron class 1 integrase gene (intI1), sul1, tetA, and blaTEM was consistently high from the specific resistance targets. In the influent, the dominant morphotypes were fragments (48.0%) and fibers (32.0%), while the dominant polymer compositions were polyethylene (32.0%) and polypropylene (26.0%) and in the effluent were polyethylene (36.0%) and polypropylene (24.0%) and fragments (42.0%). Correlation testing showed a strong overall association between the $\log_{10}$ transformed abundance of MPs and the $\log_{10}$ total ARG copies ($r = 0.851$, $p < 0.001$). These empirical results not only quantify the combined effectiveness of standard treatment but also identify loads discharged to the environment.

INTRODUCTION

The presence of microplastics in water bodies and urban water systems has become a hallmark environmental problem of the 21st century. Synthetic polymer particles < 5 mm have been found in freshwater systems, marine systems and even in remote systems, far from direct human activity. Municipal wastewater treatment plants (WWTPs) have been recognized as hubs of microplastic contamination from anthropogenic inputs via domestic, industrial, and commercial activities[1]. As important facilities to safeguard public health and environmental quality, the fate and the transport of emerging contaminants, such as microplastics and antibiotic resistance genes (ARGs) in them, are not fully understood. The presence of physical microplastic pollutants and biological vectors (ARGs and mobile genetic elements) in WWTF systems is a chemical and biological pollution overlap that could create a compounding effect when it comes to the environment and public health[2].

The microplastic surfaces provide a matrix of substrates on which a complex microbial biofilm forms, establishing unique ecological niches called “the plastisphere.” Such biofilms support a wide variety of bacterial species, and contain high densities of bacteria, with higher metabolic rates, than the surrounding planktonic bacteria[3]. It has been speculated that the horizontal gene transfer (HGT) by biofilm on the surfaces of microplastic could accelerate resistance propagation in bacterial communities. The fact that the cells are in close contact with one another, within the framework of a biofilm, as well as the selection pressure of other contaminants like heavy metals and residual antibiotics, favor the spread of resistance determinants. Integrons are a central feature in the uptake and expression of gene cassettes of antibiotic resistance genes, and are markers for anthropogenic pollution, especially class 1 integrons, which are key mediators of HGT. Co-discharge of persistent particulate vectors and ARG loads into natural receiving waters highlights the need for a full understanding of the dynamics of removal and the residual environmental load[4].

Although it is increasingly acknowledged that microplastics can act as vectors for ARGs, quantitative empirical models relating the presence of microplastics with ARGs dynamics in the different stages of WWTPs are still scarce. The majority of current research concentrates on either characterising the microplastics or quantifying the ARGs, with few studies studying both contaminant groups at the same time[5]. There is a special need for empirical statistical models, which can separate the effects of treatment stage removal from intrinsic MP-ARG co-occurrence, as the distinction is critical for understanding whether MPs are actually contributing to ARG dissemination and/or are co-occurring as parallel contaminants, that are similarly physically removed. Accordingly, this study aimed to develop a quantitative assessment of the levels of microplastic contamination, antibiotic resistance genes and physicochemical parameters at various stages of the municipal WWTP. The specific objectives were to test removal efficiency for each of the treatment stages, to describe the morphological and polymer transformations, and to determine the MP-ARG co-occurrence for matched influent and effluent samples[6].

Materials and Methods

2.1 Sampling Framework and Site Selection

A multi-facility sampling matrix consisting of 5 different WWTPs (WWTP-1 to WWTP-5) was used. A total of 100 samples were collected from Influent (n = 50) and Effluent (n = 50) stages in a standardized manner. To accommodate seasonal changes in wastewater characteristics, sampling was conducted for a 12-month period. At the time of sample collection, pH and turbidity (in NTU) were measured in the water using calibrated instruments. Samples were all taken in pre-cleaned glass bottles, rushed to a laboratory on ice and processed within 24 hours of collection.

2.2 Microplastic Extraction and Characterization

The matrix extraction was done using volume reduced sampling and density separation protocols. Digestion of organic matter was done using 30% H_2O_2 (hydrogen peroxide) and Fe catalyst (Fenton's reagent) followed by density separation using saturated NaCl (1.2 g/cm^3) or saturated NaI (1.6 g/cm^3). The number of microplastic particles was determined and results were reported as number of microplastic particles per litre (particles/L). Particles were classified into four classes: fragments, fibers, films, and beads, and were identified by morphology. Micro-Fourier Transform Infrared Spectroscopy (μFTIR) or Micro-Raman Spectroscopy were used to identify dominant chemical compositions (polymer identification). The polymers identified were: Polyethylene (PE), Polypropylene (PP), Polystyrene (PS), Polyvinyl Chloride (PVC) and Polyethylene Terephthalate (PET). To determine the median particle diameter (in millimeters, mm), size distribution measurement was conducted by using image analysis software.

2.3 Quantification of Antibiotic Resistance Genes

High-throughput quantitative Polymerase Chain Reaction (qPCR) targeting specific gene markers was employed for absolute quantification of target genes (*tetA*, *sul1*, *blaTEM*, *intI1*) expressed in copies per milliliter (copies/mL). Total ARG quantification and relative abundance normalization per 10^4 copies of 16S rRNA gene were calculated. DNA extraction was performed using commercial soil/water DNA isolation kits following manufacturer lysis protocols. Standard curves were generated from linearized plasmid vectors containing target sequence inserts, with qPCR efficiency between 90% and 105% and $R^2 > 0.99$ accepted for quantification.

2.4 Statistical Analysis and Mathematical Calculations

Stage-wise Removal Efficiency was calculated as:

Removal Efficiency (%) = [(Influent Concentration − Effluent Concentration) / Influent Concentration] × 100

For non-normally distributed parameters, descriptive statistics such as mean, standard deviation (SD), median and interquartile range (IQR) were obtained. Independent two sample t-tests and Mann-Whitney U non-parametric tests were used for inferential testing, between the Influent and Effluent groups. Correlation analysis was performed using both the Spearman rank-order correlation and Pearson linear regression, with $\log_{10}$ transformed data matrices. Statistically significant values were considered to be those with a p value of less than 0.05. IBM SPSS Statistics (Version 26.0, IBM Corp., Armonk, NY, USA) and Python (v3.11) with SciPy. stats and stats models modules were used for all analyses.

Results

3.1 Removal Efficiency of Microplastics, ARGs, and Water Quality Parameters

The results of the analysis showed significant reductions in operation of all physical and biological contaminants from the influent to the effluent. Microplastic abundance decreased from 234.43 ± 82.57 particles/L in influent to 50.58 ± 26.28 particles/L in effluent, representing a removal efficiency of 78.42% ($t = 15.004$, $p < 0.001$). Total ARG abundance decreased from 620,879.90 ± 822,954.64 copies/mL to 25,267.86 ± 14,997.97 copies/mL, representing a 95.93% reduction ($t = 5.117$, $p < 0.001$).

Relative ARG abundance normalized to 16S rRNA decreased by 94.45%, from 455.19 to 25.27 copies per 10^4 16S copies ($t = 11.299$, $p < 0.001$).
Individual ARG targets exhibited consistent high removal efficiencies: tetA (91.10%, $t = 9.635$, $p < 0.001$), sul1 (92.07%, $t = 8.607$, $p < 0.001$), blaTEM (92.19%, $t = 7.521$, $p < 0.001$), and intI1 (92.42%, $t = 8.905$, $p < 0.001$). Turbidity decreased from 96.35 ± 47.64 NTU to 10.51 ± 6.13 NTU, representing 89.09% removal ($t = 12.638$, $p < 0.001$). pH showed a minor but significant change from 7.29 ± 0.22 to 7.18 ± 0.25 ($p = 0.013$). MP median size showed no significant change (0.62 ± 0.35 mm to 0.71 ± 0.36 mm, $p = 0.229$). Full quantitative performance results are given in Table 1.

Table 1: Quantitative Performance and Removal Efficiency Across Treatment Stages

Parameter	Influent Mean (± SD)	Influent Median	Effluent Mean (± SD)	Effluent Median	Removal Efficiency (%)	t-statistic	p-value
Microplastic Abundance (particles/L)	234.43 (± 82.57)	208.60	50.58 (± 26.28)	46.30	78.42%	15.004	< 0.001
Total ARG Abundance (copies/mL)	620,879.90 (± 822,954.64)	396,126.00	25,267.86 (± 14,997.97)	21,973.00	95.93%	5.117	< 0.001
ARG Relative Abundance (copies/10^4 16S)	455.19 (± 268.64)	396.13	25.27 (± 15.00)	21.97	94.45%	11.299	< 0.001
tetA Gene Abundance (copies/mL)	109,011.74 (± 72,597.01)	93,826.50	9,698.88 (± 6,484.82)	7,162.50	91.10%	9.635	< 0.001
sul1 Gene Abundance (copies/mL)	181,079.30 (± 136,369.18)	149,770.50	14,351.98 (± 12,801.70)	10,592.50	92.07%	8.607	< 0.001
blaTEM Gene Abundance (copies/mL)	54,911.94 (± 47,531.86)	42,246.50	4,287.10 (± 2,453.80)	3,724.50	92.19%	7.521	< 0.001
intI1 Gene Abundance (copies/mL)	99,661.54 (± 72,850.89)	72,603.00	7,551.44 (± 6,546.01)	5,604.00	92.42%	8.905	< 0.001
pH	7.29 (± 0.22)	7.31	7.18 (± 0.25)	7.14	1.63%	2.517	0.013
Turbidity (NTU)	96.35 (± 47.64)	81.20	10.51 (± 6.13)	8.85	89.09%	12.638	< 0.001
MP Median Size (mm)	0.62 (± 0.35)	0.52	0.71 (± 0.36)	0.59	−13.81%	-1.211	0.229

3.2 Polymer and Morphotype Distribution Shifts

To assess operational selectivity, physical properties of microplastics were analysed at each stage of the treatment. Polyethylene (PE) was the dominant polymer in both influent (32.0%, n = 16) and effluent (36.0%, n = 18). The second most prevalent polymer detected was polypropylene (PP) with 26.0% in influent and 24.0% in effluent. The amount of Polyethylene Terephthalate (PET) rose from 8.0% to 10.0% and Polyvinyl Chloride (PVC) rose from 10.0% to 14.0%, while polystyrene (PS) dropped from 24.0% to 16.0%. The complete polymer composition data is given in table 2.

Table 2: Dominant Polymer Composition Across Treatment Stages

Polymer Type	Influent Count (n = 50)	Influent Percentage (%)	Effluent Count (n = 50)	Effluent Percentage (%)
Polyethylene (PE)	16	32.0%	18	36.0%
Polypropylene (PP)	13	26.0%	12	24.0%
Polystyrene (PS)	12	24.0%	8	16.0%
Polyvinyl Chloride (PVC)	5	10.0%	7	14.0%
Polyethylene Terephthalate (PET)	4	8.0%	5	10.0%

Morphotype analysis showed fragments were the most common morphotype in the influent (48.0%, n = 24) and effluent (42.0%, n = 21). Fibers were the second most common morphotype (32.0% in influent, 30.0% in effluent). Films increased from 14.0% to 16.0%, while beads increased from 6.0% to 12.0%. The distribution of morphotypes is given in the full table.

Table 3: Microplastic Morphotype Distribution Across Treatment Stages

Morphotype	Influent Count (n = 50)	Influent Percentage (%)	Effluent Count (n = 50)	Effluent Percentage (%)
Fragment	24	48.0%	21	42.0%
Fiber	16	32.0%	15	30.0%
Film	7	14.0%	8	16.0%
Bead	3	6.0%	6	12.0%

3.3 Statistical Correlation Analysis

Log_{10}-transformed microplastic abundance and log_{10} total ARG copies were strongly correlated with each other across the entire dataset (Pearson $r = 0.851$, $p < 0.001$; Spearman $r_s = 0.791$, $p < 0.001$) when using overall co-occurrence analysis. The number of microplastic particles in the influent was significantly positively correlated with the number of total ARG copies in the influent (Spearman $r_s = 0.474$, $p < 0.001$; Pearson $r = 0.493$, $p < 0.001$). However, in effluent samples the direct correlation between MP abundance and ARG copy numbers was non-statistical significant (Spearman $r_s = -0.097$, $p = 0.505$; Pearson $r = -0.011$, $p = 0.941$), suggesting that there are independent settling and filtration pathways in the final treatment stages.

3.4 Data Visualizations

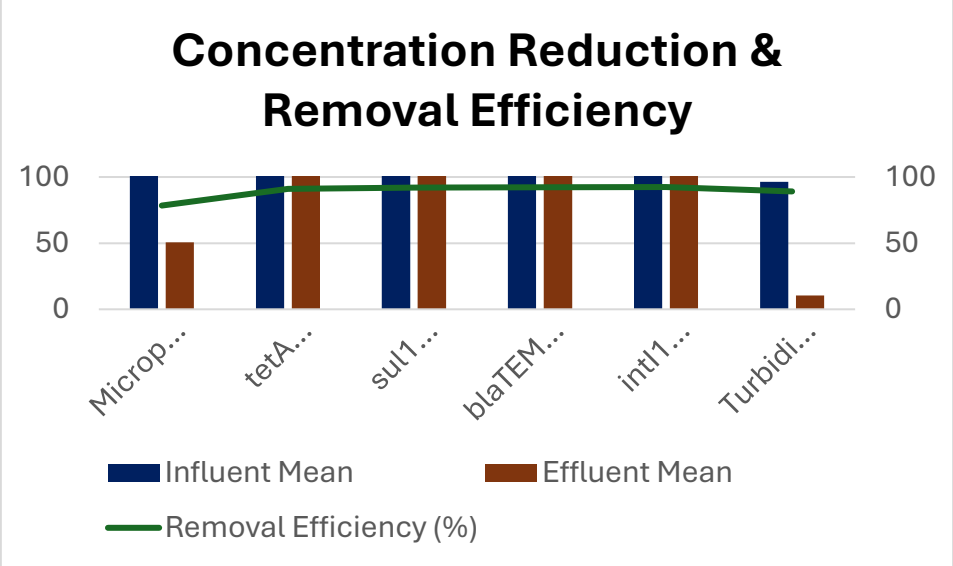


Figure 1: Concentration Reduction and Removal Efficiency

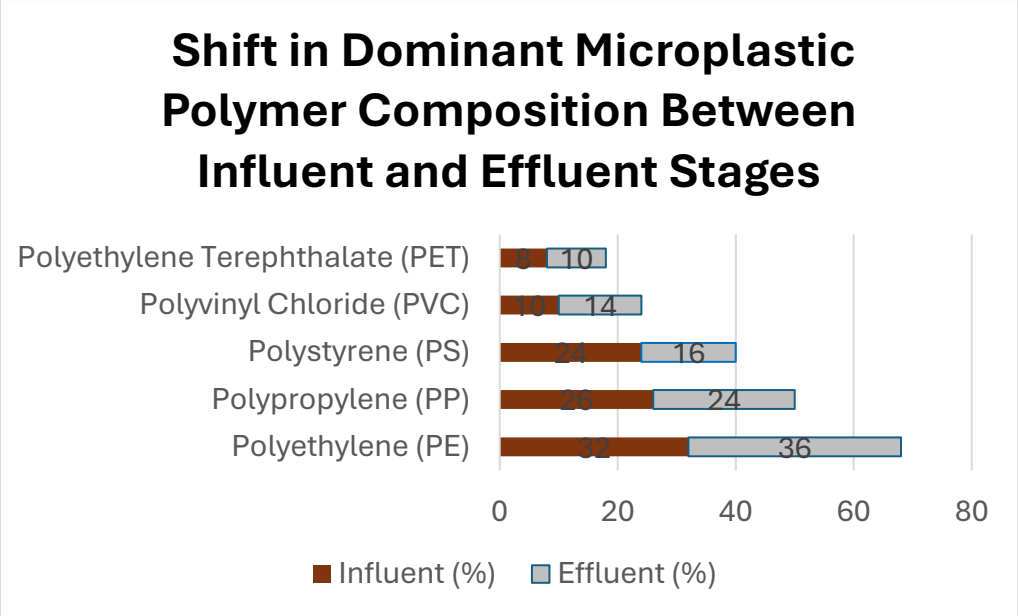


Figure 2: Shift in Dominant Microplastic Polymer Composition Between Influent and Effluent Stages

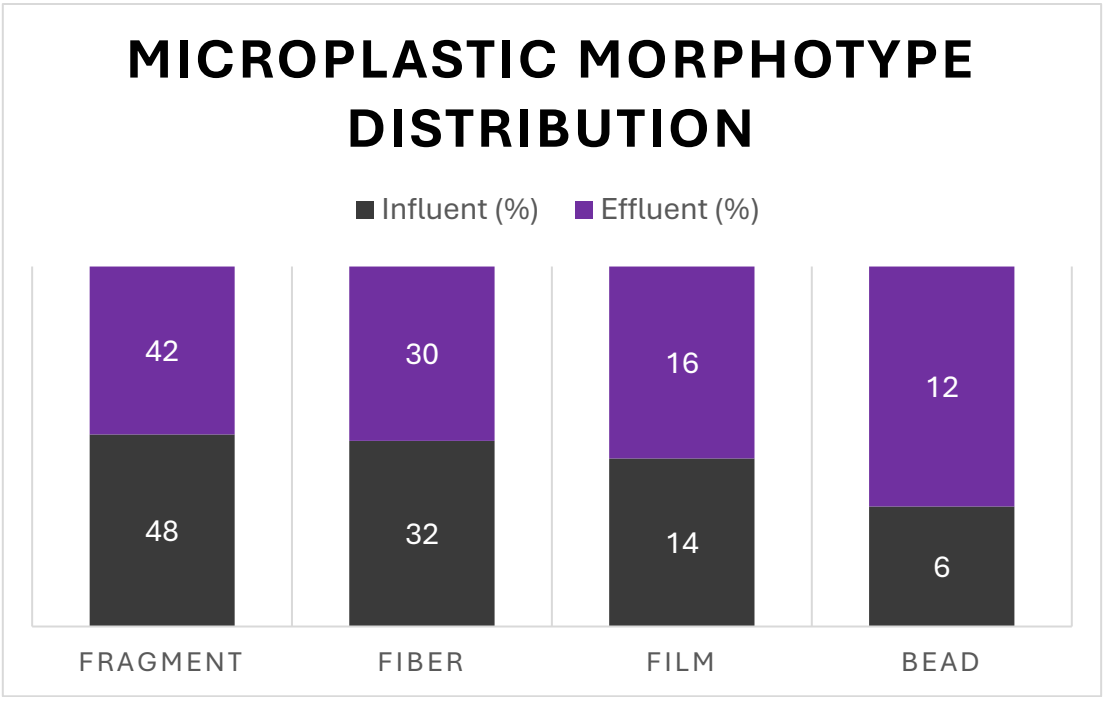


Figure 3: Microplastic Morphotype Distribution

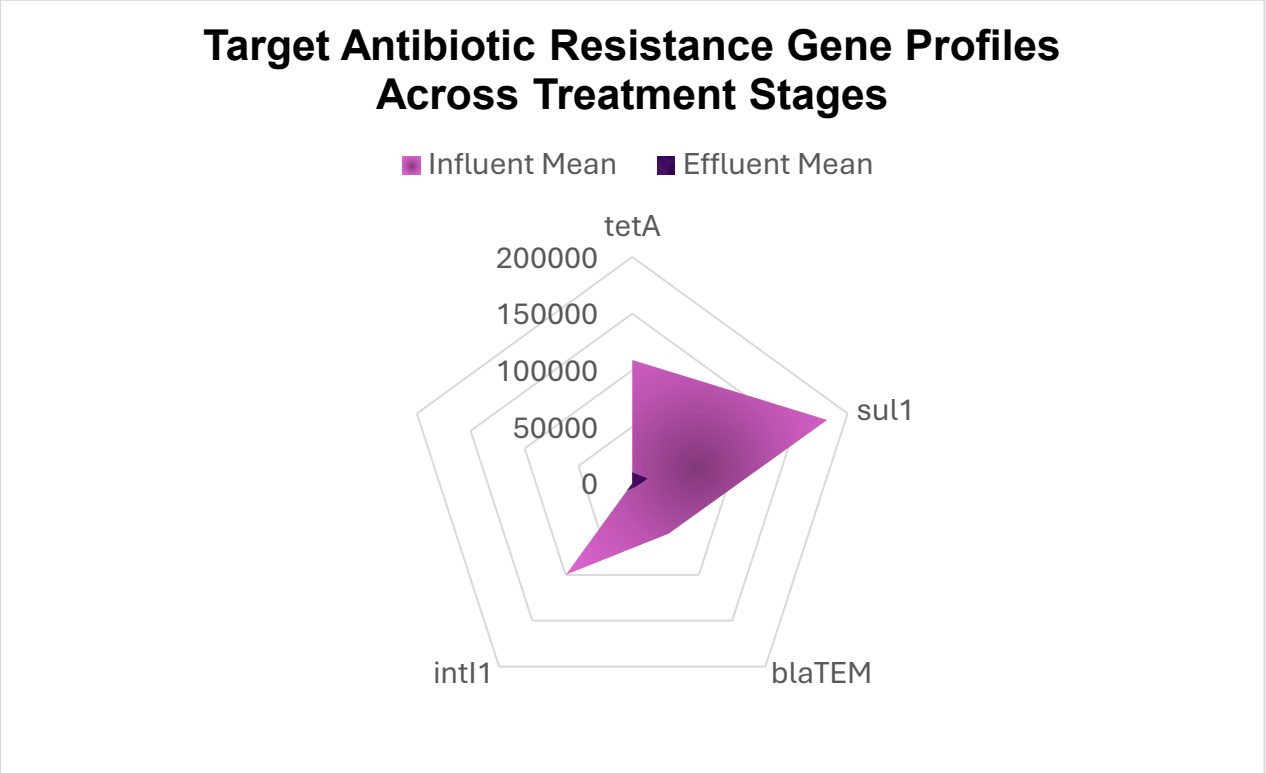


Figure 4: Target Antibiotic Resistance Gene Profiles Across Treatment Stages

Discussion

Based on this result, the microplastic removal efficiency of this study was 78.42% indicating that the primary settling process and secondary biological sludge process were effective in removing microplastics. Primary sedimentation is based on gravity settling of the denser particles, and secondarily biological treatment is based on taking the particles into the activated sludge flocs, which are then removed as waste sludge. Removal efficiency observed in this study is in the range of removal efficiency reported in the international studies where the removal efficiency of MPs has been reported in the range of 70% - more than 95% depending on the technology used for treatment and sampling strategy. The rest 50.58 ± 26.28 particles/L in effluent is a large environmental burden when you take into account the volume of effluent discharged continuously from municipal WWTPs[7], [8].

The ARG removal efficiency was >91-95% for all of the targets, which demonstrates high efficiency of biological treatment and disinfection stages for the removal of free and cell-bound resistance genes. The similarity of the removal rates across the various gene targets indicates that the removal of ARG is more likely to be due to the physical process of settling in the sludge and/or filtering than to differential persistence or decay of specific gene sequences[9], [10], [11]. The slightly greater removal of intI1 (92.42%) than individual ARGs is interesting, because intI1 is a proxy of anthropogenic pollution and HGT potential. Even though these percentage removals are high, the absolute remaining ARGs in effluent (25,267.86 copies/mL ARGs; 7,551.44 copies/mL intI1) are still a continuous release of resistance determinants into receiving water bodies[12].

The high percentages of polyethylene (36.0%) and polypropylene (24.0%) in effluent samples indicate that low-density polymers have a high persistence in wastewater streams. Because of the low density of these polymers, they are widely utilized in packaging, textiles, and consumer products and remain suspended in the water column and avoid settling processes. The slight increase in PE percentage from the influent (32.0%) to the effluent (36.0%) indicates that there is a differential removal of other polymer types, which could occur if separation was based on polymer density[13], [14].

The high proportion of fragments (42.0% in effluent) and fibers (30.0% in effluent) suggest poor entrapment in the activated sludge and high survival of these morphotypes during treatment. Fibers are especially significant in terms of being the source of most of the fibers from synthetic textile washing, and

are known to be difficult to treat with conventional treatment processes because of their elongated shape and low density. The lack of significance in the median particle size change (0.62 mm to 0.71 mm, $p = 0.229$) indicates that there was some differential removal of smaller particles (adsorbed to sludge floc) and some fragmentation of larger particles during treatment[15].

A high overall correlation ($r = 0.851$) between the abundance of MPs and ARG loading was observed throughout the entire dataset, which supports the co-traveler phenomenon, in which both pollutants undergo similar physical removal mechanisms in WWTPs. The stratification by treatment stage however, gives important perspective on this relationship. The strong positive correlation ($r_s = 0.474$, $p < 0.001$) in influent samples indicates that microplastics and ARGs are physically co-occurring in raw sewage and this would be sufficient to imply potential physical mechanisms of co-occurrence including biofilm formation and HGT. Moderate strength of this correlation indicates that microplastics may be a factor in carrying ARGs but is one of many vectors in the complex influent matrix[16].

The statistical test ($r_s = -0.097$, $p = 0.505$) shows that the remaining ARG and MP populations in effluent samples are not correlated, suggesting that they are not statistically linked after treatment. This separation is probably due to differences in effect of tertiary filtration and chemical disinfection on free ARGs and embedded particles[11]. Treatment processes can selectively remove particles with attached biofilms, thus leaving ARGs in the aqueous phase or environmental stressors can affect the composition or viability of biofilm communities during treatment. Residual populations of MP and ARG in effluent can be of varying origin in the treatment system (breakthrough particles from sludge versus ARGs from surviving planktonic bacteria)[17].

Conclusion

The microplastic (MP) and total ARG abundance (AllARG) was effectively reduced from raw influent by municipal WWTPs, at 78.42% and 95.93%, respectively, showing the effectiveness of conventional treatment processes to reduce these emerging contaminants. Nevertheless, even though high percentage removals were achieved, there were significant absolute amounts of microplastic (MPs) (mean 50.58 particles/L) and ARGs (mean 25,267.86 copies/mL) discharged to receiving aquatic environments. Effluent discharge is a persistent point-source source of polymers and resistance determinants with co-discharged fibers and fragments being a high potential for ecological exposure and downstream colonization of biofilms.

Based on these findings, the following practical recommendations are made. The use of advanced tertiary polishing technologies (membrane bioreactors, sand filters, micro-filtration) should be considered to remove the remaining particles and associated genetic pollutants. Standard monitoring protocols using both physical (MP) and genetic (ARG) measurements, and including the findings in regulatory discharge permits, would enable environmental management based on evidence. MP source reduction efforts such as synthetic textile washing, consumer products, and single-use plastics would help decrease the number of MPs that come into WWTFs. Future work should include operational unit-process level sampling (primary clarifier, aeration tank, secondary clarifier) which would facilitate stage specific attribution of removal mechanisms. Investigations of the difference between intracellular live-cell ARGs and extracellular free DNA would be helpful to give deeper insights of the mechanism. Furthermore, future studies with microbial community sequencing and direct horizontal gene transfer rate measurements on particle surfaces would further help elucidate pathways of dissemination of resistance via the plastisphere.

Conflict of Interest: The authors declare no conflict of interest

Funding Statement: There is no funding available

REFERENCES

[1] J. Yang *et al.* , "Microplastics in different water samples (seawater, freshwater, and wastewater): Removal efficiency of membrane treatment processes," *Water Research* , vol. 232, p. 119673, Jan. 2023, doi: 10.1016/j.watres.2023.119673 .

[2] B. Tuvo *et al.* , "Microplastics and Antibiotic Resistance: The Magnitude of the Problem and the Emerging Role of Hospital Wastewater," *International Journal of Environmental Research and Public Health* , vol. 20, no. 10, p. 5868, May 2023, doi: 10.3390/ijerph20105868 .

[3] A. Delacuvellerie, V. Cyriaque, S. Gobert, S. Benali, and R. Wattiez, "The plastisphere in marine ecosystem hosts potential specific microbial degraders including Alcanivorax borkumensis as a key player for the low-density polyethylene degradation," *Journal of Hazardous Materials* , vol. 380, p. 120899, Jul. 2019, doi: 10.1016/j.jhazmat.2019.120899 .

[4] M. Q. Baluja *et al.* , "Dynamics of integron structures across a wastewater network – Implications to resistance gene transfer," *Water Research* , vol. 206, p. 117720, Sep. 2021, doi: 10.1016/j.watres.2021.117720 .

[5] S. Harirchi *et al.* , "Impact of emerging contaminants on inhibited steady-state anaerobic digestion: a review of the fate and degradation characteristics of antibiotics, PFAS, and microplastics," *Reviews in Environmental Science and Bio/Technology* , vol. 25, no. 2, May 2026, doi: 10.1007/s11157-026-09779-1 .

[6] N. Ni *et al.* , "Fragmented Microplastics Synergize with Biological Treatment To Potentiate Antibiotic Resistance Dissemination during Sewage Treatment," *Environmental Science & Technology* , Mar. 2026, doi: 10.1021/acs.est.5c18221 .

[7] R. M. Blair, S. Waldron, and C. Gauchotte-Lindsay, "Average daily flow of microplastics through a tertiary wastewater treatment plant over a ten-month period," *Water Research* , vol. 163, p. 114909, Jul. 2019, doi: 10.1016/j.watres.2019.114909 .

[8] S. A. Arat, "Microplastics in wastewater treatment plants: Sources, properties, removal efficiency, removal mechanisms, and interactions with pollutants," *Water Science & Technology* , vol. 87, no. 3, pp. 685–710, Jan. 2023, doi: 10.2166/wst.2023.022 .

[9] J. Tong *et al.* , "Microbial community evolution and fate of antibiotic resistance genes along six different full-scale municipal wastewater treatment processes," *Bioresource Technology* , vol. 272, pp. 489–500, Oct. 2018, doi: 10.1016/j.biortech.2018.10.079 .

[10] D. Dai *et al.* , "Long-read metagenomic sequencing reveals shifts in associations of antibiotic resistance genes with mobile genetic elements from sewage to activated sludge," *Microbiome* , vol. 10, no. 1, p. 20, Jan. 2022, doi: 10.1186/s40168-021-01216-5 .

[11] M. M. McConnell, L. T. Hansen, R. Jamieson, K. D. Neudorf, C. K. Yost, and A. Z. Tong, "Removal of antibiotic resistance genes in two tertiary level municipal wastewater treatment plants," *The Science of The Total Environment* , vol. 643, pp. 292–300, Jun. 2018, doi: 10.1016/j.scitotenv.2018.06.212 .

[12] P. Jankowski *et al.* , "Metagenomic community composition and resistome analysis in a full-scale cold climate wastewater treatment plant," *Environmental Microbiome* , vol. 17, no. 1, p. 3, Jan. 2022, doi: 10.1186/s40793-022-00398-1 .

[13] N. dos Santos, R. Busquets, and L. C. Campos, "Insights into the removal of microplastics and microfibres by Advanced Oxidation Processes," *The Science of The Total Environment* , vol. 861, p. 160665, Dec. 2022, doi: 10.1016/j.scitotenv.2022.160665 .

[14] P. U. Iyare, S. K. Ouki, and T. Bond, "Microplastics removal in wastewater treatment plants: a critical review," *Environmental Science Water Research & Technology* , vol. 6, no. 10, pp. 2664–2675, Jan. 2020, doi: 10.1039/d0ew00397b .

[15] F. Gao, R. Busquets, and L. C. Campos, "Transport and retention of laundry microplastic fibres in slow sand filtration systems," *Scientific Reports* , vol. 16, no. 1, Mar. 2026, doi: 10.1038/s41598-026-41438-x .

[16] Z. Su, B. Huang, Q. Mu, and D. Wen, "Evaluating the Potential Antibiotic Resistance Status in Environment Based on the Trait of Microbial Community," *Frontiers in Microbiology* , vol. 11, p. 575707, Oct. 2020, doi: 10.3389/fmicb.2020.575707 .

[17] K. Drane, M. Sheehan, A. Whelan, E. Ariel, and R. Kinobe, "The Role of Wastewater Treatment Plants in Dissemination of Antibiotic Resistance: Source, Measurement, Removal and Risk Assessment," *Antibiotics* , vol. 13, no. 7, p. 668, Jul. 2024, doi: 10.3390/antibiotics13070668 .