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Ultraviolet aging of polyethylene microbeads and cadmium (Cd^{2+}) uptake in water: Surface morphology, kinetics, and isotherm analysis

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ABSTRACT

Polyethylene (PE) microbeads were subjected to three months of ultraviolet (UV) aging and evaluated for surface transformation and cadmium (Cd^{2+}) uptake in aqueous solution. Scanning electron microscopy analysis showed that UV-aged microbeads developed pronounced surfaces, roughening with cracks and pit-like defects compared with virgin beads. This indicated an increased surface heterogeneity. Batch adsorption experiments (initial concentration, $C_0 = 0.2–1.0$ mg L^{-1}) exhibited rapid Cd^{2+} uptake during the first few hours, followed by a slower approach to equilibrium at approximately 24–32 hours. Kinetic modelling showed that the pseudo-second-order (PSO) model better described the time-dependent data than the pseudo-first-order (PFO) model (coefficient of determination, $R^2 \approx 0.94–0.98$ vs. 0.00–0.39), although model fits are treated as empirical descriptors rather than definitive evidence of a single adsorption mechanism. Equilibrium data were included using both Langmuir and Freundlich isotherms, which gave similarly good fits ($R^2 = 0.95$ and 0.96, respectively) within the tested concentration range; therefore, no conclusive preference for one isotherm was asserted. The Langmuir maximum adsorption capacity ($q_{max} = 0.0060$ mg g^{-1}) was extremely low, indicating that UV-aged PE microbeads are not suitable as engineered sorbents for water treatment. Instead, their environmental relevance is better interpreted as auxiliary sorbent phases and mobile vectors that may contribute to Cd^{2+} redistribution in aquatic systems. This study supports SDG 14 by demonstrating that UV-aged PE microbeads can adsorb and transport Cd^{2+}, underscoring their role in spreading pollutants and threatening aquatic ecosystem health.

1. INTRODUCTION

Microplastics are tiny plastic particles. Often measuring less than 5 mm, it was formed from the breakdown of larger plastics or from original sources like cosmetic microbeads, synthetic fibers, and industrial pellets[1,2]. They have been shown to be present in large numbers all over the world, for example, in surface waters, sediments, and living

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organisms[3,4]. In contrast, heavy metals, including cadmium, lead, copper, and zinc, enter water bodies through mining, industrial discharges, agriculture, and urban runoff, persist in the environment, accumulate in living organisms, and remain toxic at low doses[5,6]. In natural water bodies, dissolved metals are found not only as ions but also as components of natural suspended particles, such as clays, oxides, and organic matter, and they are also associated with anthropogenic particles, such as microplastics, which can serve as additional sorbents and carriers[4–6]. Studies have found that PE microbeads can capture divalent metals at levels comparable to those of some natural particulates, raising concerns about their role in the transport of metals through food webs and wastewater systems[4,7,8].

The fresh plastic releases are not only subject to environmental factors; other factors may also affect the polymer's physical structure and chemical properties. This will ultimately cause the polymer to disintegrate and change its surface[9–11]. The characterisation of plastic waste from landfills revealed indicative signs, increases in roughness and microcracking. Additionally, the formation of functional groups containing oxygen, such as carbonyl, carboxyl, and hydroxyl, is also evident[11–13]. These alterations result in microplastics changing their physical properties, including variations in density and surface charge, as well as becoming either more or less hydrophobic[11,13,14]. Consequently, the interaction of microplastics with existing contaminants, including heavy metals and organic pollutants, is altered[11,13,14]. More precisely, aging usually increases the number and strength of metal-binding sites, while for very hydrophobic organic pollutants, it can either increase or decrease sorption depending on which prevails, the introduction of polar groups or the loss of hydrophobic domains[9–11,13].

Microplastics' initial characteristics faded in light-exposed surface waters and on beaches worldwide, and solar radiation drove photooxidation via UV, the primary and most notable mechanism. Photo-oxidation by UV light is the main method throughout the process; consequently, UV lab techniques are often used to hasten and control the process during the analysis[1,11,15,16]. In particular, the issue with PE microplastics is that exposure to UV light, whether in air or water, causes the disintegration of long molecular chains and oxidation. As a result, new carbons and other oxygenated groups are formed, while a rougher, more uneven surface with a larger specific surface area is created[11,15,16]. Furthermore, the introduction of cationic species has been linked to the modifications induced by UV radiation: the adsorption of Cu^{2+} and Pb^{2+} on UV-aged PE and polypropylene microplastics is 1.3–1.6 times greater than that on the original particles, primarily due to electrostatic attraction and surface complexation at the oxidised sites[13,16,17]. It has been observed that the interplay of aging severity, particle size, and water chemistry (encompassing pH, salinity, coexisting ions, and natural organic matter) dictates the quantity and processes of metal absorption by aged microplastics [4,10,16].

Building on these advances, UV-aged PE microbeads are used in this study as a practical model system to examine how controlled photo-aging modifies microplastic surfaces and influences their interactions with dissolved Cd^{2+} in aqueous solution[17,18]. Specifically, this work aims to (i) characterise UV-aging induced alterations in the surface morphology of PE microbeads and (ii) evaluate how these changes affect Cd^{2+} absorption kinetics and equilibrium behaviour under batch conditions. In doing so, the study also clarifies the environmental relevance of UV-aged PE microbeads as potential pollutant carriers (vectors) and auxiliary sorbent phases, rather than high-capacity engineered adsorbents for intentional water treatment[4,13]

2. MATERIALS AND METHODS

Commercial PE microbeads were sourced from Avares (M) Sdn. Bhd. and used as the medium of an adsorbent material. The beads were spherical with a nominal diameter of about 300 µm. In this study, PE microbeads served as the solid adsorbent phase in a batch experiment to evaluate Cd^{2+} uptake following UV aging. The supplier did not specify the presence of manufacturing additives (e.g., stabilisers or antioxidants), and therefore, they cannot be excluded. Cadmium ($Cd(NO_3)_2$) solution of the selected heavy metal was obtained from VNK Scientific Instruments (M) Sdn. Bhd. Analytical-grade cadmium ($Cd(NO_3)_2$) salts were dissolved in deionized water to prepare stock solutions. Working solutions were freshly prepared by serial dilution on the day of use. All the experimental work involved deionized water, cleaning ethanol, and analytical instruments. Glassware and sampling vessels were acid-washed to minimise trace-metal contamination. The surface morphology was examined using a JEOL JSM-IT300LV variable-pressure scanning electron microscope (SEM) (JEOL Ltd., Japan). Cadmium concentrations were measured using a PerkinElmer PinAAcle 900 Series Atomic Absorption Spectrophotometer (AAS), USA[19].

2.1 Aging process of microplastics

The microplastics were put through a weathering process that imitated future environmental conditions, with the temperature, irradiance, and moisture being continuously monitored[20]. The virgin PE microbead sample was washed with deionized water, dried, and finally deposited in a thin layer in quartz dishes[21]. Afterwards, the sample was exposed to the sun for a total of three months. The collected sample was subsequently rinsed with ultrapure water, dried, and stored for future utilisation[21].

2.2 Characterisation of microplastic particles

The PE microbeads were examined in terms of surface morphology, texture, and edges, as well as chemical changes before and after aging, performing SEM, and their implications towards adsorption ability were also studied[20]. SEM was the primary apparatus for the investigation of the surface of the beads in terms of roughness, cracks, and composition of the elements[20]. FTIR analysis was not performed in this study; therefore, the discussion of surface chemistry changes is limited to SEM-based morphology and literature context.

2.3 Adsorption experiments

The process of batch adsorption tests was conducted wherein aged PE microbeads of different concentrations were mixed and added to one litre of deionised water to make solutions of 0.2, 0.4, 0.6, 0.8, and 1.0 mg L^{-1}. The concentrations were changed to analyse the effect of aging on the adsorption characteristics of aged PE microbeads[4]. The adsorption tests were done in a transparent beaker, consisting of 5 mg aged PE microbeads and five different metal ion concentrations[4]. Around 0.4 mg aged PE microbeads were taken out at the specified times (1, 2, 4, 8, 24, 32, 48, 72, 96 h)[18]. The samples of aged PE microbeads were all weighed at 0.3 mg and combined with 6 mL of 65% nitric acid. The samples were subsequently placed in an oven vessel, sealed, and heated in a digester at 110 °C for 4 minutes. The sample was subsequently cooled in ice-cold water for 15 minutes and then reheated to 200 °C. The resultant solution was diluted to 25 mL in a volumetric flask and subsequently filtered[22]. The solution sample was analysed using atomic absorption spectroscopy (AAS) [22].

2.4 Data analysis

Data analysis and model fitting were conducted using OriginPro 2025. The adsorption capacity at time t, (q_t, mg g^{-1}) and at equilibrium, (q_e, mg g^{-1}) were calculated from mass balance using $q_t = (C_0 - C_t)V/m$ and $q_e = (C_0 - C_e)V/m$, where C_0, C_t, and C_e (mg L^{-1}) are the initial, time-dependent, and equilibrium Cd^{2+} concentrations in solution respectively; V (L) is the solution volume; and m (g) is the mass of PE microbeads. Adsorption kinetics were assessed utilising the pseudo-first-order (PFO) and pseudo-second-order (PSO) models, with rate constants k_1 (h^{-1}) and k_2 (g mg^{-1} h^{-1}) respectively. Model parameters were obtained by nonlinear regression where applicable, and goodness-of-fit was assessed using R^2 and residual patterns. To describe equilibrium behaviour, the adsorption isotherm data were analysed using the Langmuir model (q_{max}, mg g^{-1}; K_L, L mg^{-1}) and the Freundlich model (K_F [(mg g^{-1}) (L $mg^{-1})^{1/n}$]; n, dimensionless). The Langmuir separation factor (R_L) was also calculated to evaluate adsorption favourability. All kinetic and isotherm models are treated as empirical descriptors of the data; therefore, mechanistic interpretations were made cautiously and supported by the material characterisation results.

3. RESULTS AND DISCUSSION

The UV-aged PE microbeads showed rapid Cd^{2+} uptake during the first few hours, followed by a slower approach toward equilibrium, with the final adsorption level increasing with the initial Cd^{2+} concentration. This two-stage uptake pattern is consistent with adsorption on a heterogeneous, oxidised PE surface formed during UV aging. However, kinetic trends alone are insufficient to confirm a single controlling mechanism. Therefore, the observed behaviour is interpreted as the combined effect of fast surface-site occupation and slower transport and/or surface-interaction processes on aged microplastics.

3.1 Characteristics of virgin and UV-aged PE microbeads

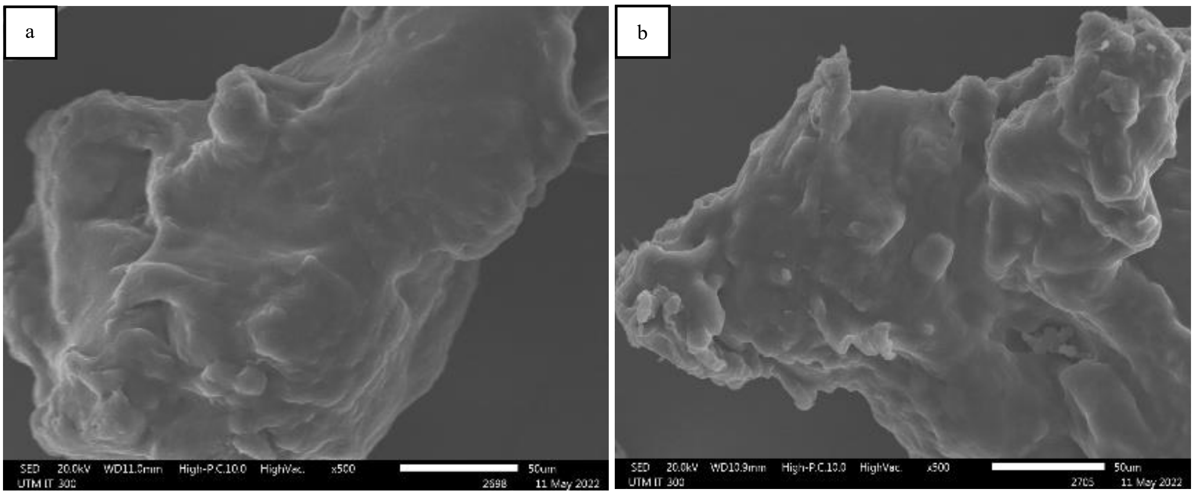

Fig. 1. SEM micrographs of PE microbeads: (a) virgin PE microbead and (b) UV-aged PE microbead after 3 months of exposure (×500). UV aging produced noticeable surface roughening with cracks and pit-like defects compared with the smoother virgin surface

Source: Author's own data

Fig. 1 shows that virgin PE microbeads exhibit relatively smooth, compact surfaces with only minor fissures, consistent with limited physical weathering in unaged microplastics[11,18]. After UV aging, the microbeads become visibly roughened and irregular, with cracks, pits, and hole-like defects that are commonly associated with embrittlement and surface abrasion during photo-oxidative degradation[9,10,15,18]. These surface defects can enlarge the effective surface area and create micro-asperities and niche regions that may promote contaminant retention compared with smoother virgin particles[9,13,18].

Overall, the SEM-observed morphological changes indicated increased surface heterogeneity following UV aging, which can enhance the interaction potential between PE microbeads and dissolved contaminants. This interpretation aligns with broader evidence that aged microplastics can act as auxiliary sorbent phases and mobile carriers (vectors) for heavy metals in aquatic systems[4,13].

3.2 Effect of contact time

The behaviour of Cd^{2+} adsorption on UV-aged PE microbeads, as depicted in Fig. 2, showed a rapid uptake during the first few hours followed by a slower approach to equilibrium; higher initial Cd^{2+} concentrations yielded higher adsorption capacities at all contact times. This two-stage uptake pattern is consistent with adsorption on aged, oxidised microplastic surfaces, where surface heterogeneity and multiple rate-influencing steps may contribute to the overall kinetics[10,13,16,17]. Across the tested concentration range (0.2–1.0 mg L^{-1}), the adsorption capacity increased steeply from zero to approximately 8 hours, indicating that a substantial fraction of q_e is achieved during the early stage. The initial rapid phase is commonly attributed to external mass transfer (film diffusion) and the occupation of readily accessible, higher-affinity surface sites generated by UV aging, including oxygen-containing functional groups (e.g., carbonyl, carboxyl, hydroxyl) and enhanced surface roughness[10,11,15,16,18]. Similar rapid uptake behaviours for divalent metals (Cd^{2+}, Pb^{2+}, Cu^{2+}) on aged PE and other microplastics have been reported, often showing that PSO can provide a good empirical fit to early time adsorption data[7,16,17,20].

After about 8 hours, the slope of the adsorption curves decreased, and only small increases in q_t occurred between eight and 32 hours, suggesting that many readily accessible sites became progressively occupied and that slower transport and/or surface interaction steps increasingly influenced the uptake rate. In such systems, the later stage was frequently discussed in terms of diffusion-related limitations (e.g., transport into/along surface defects created during aging) and heterogeneous surface interactions, rather than a single simple rate-limiting process [10,13,23,24]. The curves then approached a near-plateau between 32 and 96 hours, indicating that equilibrium is reached at approximately

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24–32 hours. Comparable equilibrium timescales (typically tens of hours to about 48 hours, depending on polymer, aging, and solution chemistry) had been reported for metal adsorption on aged PE and mixed microplastics[7,16,17,20].

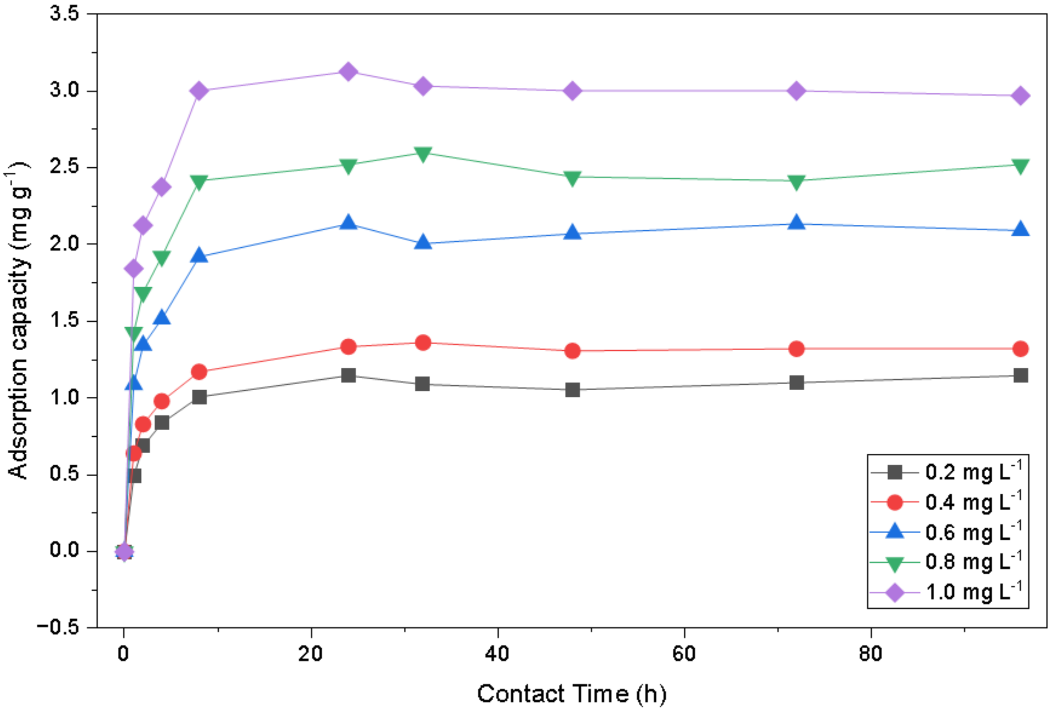

Fig. 2. Adsorption capacity (q_t, mg g^{-1}) of Cd^{2+} on UV-aged PE microbeads as a function of contact time for different initial Cd^{2+} concentrations ($C_0 = 0.2–1.0$ mg L^{-1})

Source: Author's own data

At any given contact time, higher initial Cd^{2+} concentrations produce higher q_t values (e.g., $C_0 = 1.0$ mg L^{-1} approaches about 3.0 mg g^{-1}, whereas $C_0 = 0.2$ mg L^{-1} approaches about 1.1–1.2 mg g^{-1} at longer time). This trend reflected a stronger concentration driving force for mass transfer and was consistent with many reports of favourable adsorption behaviour for metals on microplastics, where greater solute availability can promote progressive occupation of sites spanning a range of affinities on heterogeneous surfaces[4,7,8,13].

3.3 Adsorption kinetics

The kinetic parameters in Table 1 show that Cd^{2+} uptake by UV-aged PE microbeads is better described by the PSO model than by the PFO model, as reflected by higher PSO R^2 values (0.941–0.981) compared with PFO R^2 values (0.001–0.39) across all initial concentrations. Similar trends, where PSO provided a better empirical description than PFO for metal uptake by microplastics, have been widely reported for PE and other polymer microplastics, including systems involving Cd^{2+}, Pb^{2+}, and Cu^{2+} [7,8,16,17,23]. However, consistent with adsorption-modelling guidance, model agreement alone should not be treated as definitive proof of a specific adsorption mechanism (e.g., chemisorption vs. physisorption). Therefore, the PSO superior fit is interpreted here as an empirical descriptor of the observed kinetics rather than a mechanistic confirmation[10,13,24].

As shown in Table 1, the PSO estimated equilibrium capacity q_e increases from approximately 1.15 mg g^{-1} at $C_0 = 0.2$ mg L^{-1} to approximately 3.08 mg g^{-1} at $C_0 = 1.0$ mg L^{-1}, indicating that higher initial Cd^{2+} concentrations resulted in higher equilibrium loading on the microbeads. This concentration dependence is consistent with previous reports that metal uptake by aged or oxidised microplastics can increase with concentration due to a stronger driving force and progressive occupation of sites with different energies on heterogeneous surfaces[4,7,8,13]. The PSO rate constants k_2 (0.41–0.65 g mg^{-1} h^{-1}) remained within the same order of magnitude as C_0 increases, suggesting broadly similar apparent uptake rates under the experimental conditions. The relatively small variation in k_2 with C_0 may reflect the fact that UV aging increases surface heterogeneity and incorporates oxygen-containing functional groups (e.g., carbonyl, hydroxyl), which can influence the kinetics through surface interactions and are transported to less accessible regions such as cracks and pits. Such UV-induced oxidation and morphological changes have been consistently documented for PE and related polymers and are known to affect pollutant uptake behavior[10,11,15,16,18,20].

Table 1. Kinetic parameters for Cd^{2+} adsorption onto UV-aged PE microbeads using the PSO model (non-linear regression) and the PFO model (linear regression)

Initial Concentration (mg L^{-1})	PSO q_e (mg/g)	PSO k_2 (g mg^{-1} h^{-1})	PSO R^2	PFO k_1 (h^{-1})	PFO R^2
0.2	1.145	0.6517	0.977	0.1313	0.283
0.4	1.362	0.5941	0.981	0.0282	0.023
0.6	2.138	0.4103	0.962	0.0401	0.39
0.8	2.556	0.4297	0.941	0.0264	0.019
1.0	3.084	0.4103	0.927	0.0057	0.001

Kinetic parameters: Pseudo-second-order (PSO) equilibrium capacity (q_e), PSO rate constant (k_2), Pseudo-first-order (PFO) rate constant (k_1), and the PFO coefficient of determination (R^2)

Source: Author's own data

Accordingly, the overall kinetic pattern may reflect a combination of rapid initial uptake and a slower stage influenced by transport and heterogeneous surface interactions rather than a single rate-limiting step[10,13,23,24]. In contrast, the PFO model yielded small rate constants (~0.0057–0.1313 h^{-1}) and very low R^2 values, indicating that it does not adequately reproduce the measured q_t–time curves. This outcome is consistent with prior adsorption studies and methodological discussions showing that PFO may provide a poorer description when adsorption proceeds via more than one rate-influencing step and involves heterogeneous surfaces[23,24]. Therefore, while PSO offered a superior alignment with the current data, the kinetic results should be interpreted cautiously, and mechanistic claims should be supported by complementary evidence (e.g., surface characterisation, solution chemistry effects), rather than inferred solely from model selection[10,13,24].

3.4 Adsorption isotherm

The equilibrium adsorption of Cd^{2+} on UV-aged PE microbeads was assessed using Langmuir and Freundlich isotherm models, as presented in Table 2. Over the tested concentration range (0.2–1.0 mg L^{-1}), both models described the data well, and the difference in goodness-of-fit was marginal ($R^2 = 0.95$ for Langmuir vs. 0.96 for Freundlich). Given this small difference and the limited concentration window, the present dataset did not provide strong evidence to unambiguously favour the Freundlich model. Therefore, the isotherm fits were treated here as empirical descriptors of the observed equilibrium behaviour rather than as definitive proof of a single adsorption mechanism[10,13,24].

Table 2. Equilibrium isotherm parameters for Cd^{2+} adsorption on UV-aged PE microbeads

Equilibrium model	Parameter	Value
Langmuir	q_{max} (mg/g)	0.0060
	K_L (L/mg)	0.95
	R^2	0.95
Freundlich	K_F ((mg/g)(L/mg)$^{1/n}$)	0.0030
	n	1.56
	R^2	0.96

Note: q_{max} and K_L are Langmuir constants; K_F and n are Freundlich constants; R^2 is the coefficient of determination (dimensionless)

Source: Author's own data

The Langmuir parameter q_{max} (0.0060 mg g^{-1}) indicated an extremely low maximum adsorption capacity, corresponding to only a few micrograms of Cd per gram of microbeads at theoretical monolayer coverage. This confirms that UV-aged PE microbeads are low-capacity sorbents compared with engineered adsorbents such as activated carbon or mineral sorbents, which can exhibit adsorption capacities orders of magnitude higher under comparable conditions[6,25]. From an environmental perspective, the implication is that aged PE microbeads are more relevant as additional sorbent phases and potential vectors for Cd^{2+} transport than as practical materials for intentional water treatment[4,13].

The Langmuir affinity constant K_L (0.95 L mg^{-1}) yielded separation factors $0 < R_L < 1$ across the investigated C_0 range, indicating favourable adsorption under the studied conditions. However, because the experiments were conducted within a narrow and relatively low equilibrium concentration range, the Langmuir fit may largely reflect the near-linear portion of the isotherm rather than a fully developed saturation plateau. Consequently, q_{max} should be interpreted as an apparent capacity estimate within the tested domain, not necessarily as a definitive monolayer limit for broader conditions[10,24].

The Freundlich parameters $K_F = 0.0030$ (mg g^{-1}) (L $mg^{-1})^{1/n}$, n=1.56, suggested adsorption on a heterogeneous surface with favourable intensity (typically $n > 1$). This is consistent with UV-aging induced surface oxidation and the emergence of oxygen-containing functional groups on PE microplastics, as widely reported in aging and photo-oxidation studies[10,11,15,18,20]. Similar increases in surface oxidation and enhanced metal uptake on UV-aged PE and other microplastics were also been reported in adsorption studies[7,16,17]. Nevertheless, due to the minimal difference in R^2 and the limited data range, Freundlich behaviour cannot be conclusively asserted; instead, the parameters collectively support the interpretation of weak but favourable adsorption on heterogeneous, oxidised PE surfaces[10,13,24].

3.5 Environmental relevance: Pollutant vector versus engineered sorbent

Despite the observed enhancement of Cd^{2+} uptake after UV aging, the very low Langmuir q_{max} indicated that UV-aged PE microbeads are not effective engineered sorbents for water treatment. Specifically, Table 2 reports $q_{max} = 0.0060$ mg g^{-1} (≈6 µg g^{-1}), which corresponds to only ~0.03 µg Cd per 5 mg of microbeads even at theoretical monolayer coverage, highlighting the limited mass of Cd that can be removed under the present experimental conditions. Their primary environmental relevance, therefore, lies in their role as auxiliary sorbent phases and mobile pollutant vectors: even limited sorption per unit mass may still contribute to cadmium redistribution because microplastics are persistent and transportable, and aging can increase surface heterogeneity and interaction potential in aquatic environments[4,13,25].

4. CONCLUSION

Controlled UV exposure altered the surface properties of PE microbeads, producing a roughened morphology with cracks and pits, as reported in prior literature on UV-aged PE, likely promoting oxygen-containing functional groups (e.g., carbonyl and hydroxyl). Together, these changes increased surface heterogeneity and potential interaction sites for Cd^{2+}, but the overall adsorption capacity remained very low compared with engineered adsorbents, indicating that UV-aged PE is not a competitive material for intentional water treatment.

Batch adsorption results showed a rapid initial uptake of Cd^{2+} during the first few hours, followed by a slower approach to equilibrium at approximately 24–32 hours. Kinetic modelling demonstrated that the PSO model substantially better described the time-dependent data than the PFO model across all initial concentrations ($R^2 \approx 0.94$–0.98 for PSO vs. 0.00–0.39 for PFO). Nevertheless, PSO agreement is treated here as an empirical description of the observed kinetics rather than definitive proof of chemisorption. The two-stage uptake pattern more plausibly reflects multiple rate-limiting steps, including rapid surface adsorption followed by a slower, transport-controlled stage involving diffusion into UV-generated surface defects and heterogeneous surface interactions.

Equilibrium modelling using Langmuir and Freundlich isotherms yielded comparable fits over the tested concentration range, with only a marginal difference in R^2 (0.95 vs. 0.96). Therefore, the present results do not support a definitive conclusion that the adsorption strictly follows the Freundlich isotherm. Instead, the fitted parameters collectively indicated favourable but weak adsorption on a heterogeneous surface, alongside an extremely low apparent Langmuir capacity (q_{max}) in the microgram-per-gram range, reinforcing that the overall sorption potential is limited.

Overall, this study demonstrates that UV aging can measurably increase Cd^{2+} interaction with PE microbeads by modifying surface morphology and chemistry, but the adsorption capacity remains too small for engineered remediation applications. Under environmentally realistic conditions, UV-aged PE microbeads are therefore better viewed as mobile vectors and auxiliary sorbent phases that may contribute to the transport and redistribution of Cd^{2+} in aquatic systems, rather than as “high-performance” adsorbents. This study contributes to the plastics, waste management, and environmental monitoring sectors by demonstrating that UV-aged PE microbeads can act as mobile carriers of Cd^{2+} in aquatic systems. The findings support global plastic-pollution prevention agendas and are particularly relevant to SDG 14 (Life Below Water), especially Target 14.1 on reducing marine pollution from land-based sources, by improving understanding of how weathered microplastics may redistribute contaminants and threaten aquatic ecosystem health. Recommended future work includes extending equilibrium testing across a wider concentration range to strengthen isotherm discrimination (beyond small R^2 differences) and incorporating additional diagnostics (e.g., residual / error-function analysis, competitive ion effects, and porosity / surface area measurements) to better resolve rate-limiting steps and adsorption mechanisms.

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6. CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts, and declare the absence of conflicting interests with the funders.

7. AUTHORS’ CONTRIBUTIONS

Conceptualization: S. Jumali & S. Azman
Data curation: S. Jumali., S.S. Sharipudin & M.J. Mohamed Ibrahim
Methodology: S. Jumali
Formal analysis: S. Jumali
Visualisation: S. Jumali
Software: S. Jumali
Writing (original draft): S. Jumali
Writing (review and editing): S. Jumali, S.S. Sharipudin & M.J. Mohamed Ibrahim
Validation: S. Azman
Supervision: S. Azman
Funding acquisition: S. Jumali, S.S. Sharipudin & M.J. Mohamed Ibrahim
Project administration: S. Jumali

8. DECLARATION OF GENERATIVE AI IN THE WRITING PROCESS

During the preparation of this work, the authors used Microsoft 365 Copilot and ChatGPT for idea generation, language refinement, and argument structure improvement. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

9. DATA AVAILABILITY/SUPPLEMENTARY MATERIALS

The datasets used and analysed during the current study are available from the corresponding author on reasonable request.

10. ETHICS STATEMENT

The authors declare that this research did not involve human or animal subjects. All experimental procedures were performed in accordance with the institutional Safety, Health, and Environmental (HSE) protocols of Universiti Teknologi MARA and Universiti Teknologi Malaysia.

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