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ORIGINAL ARTICLE

Microplastic pollution patterns in aquaculture ponds: A comparative study from Rasht, Iran

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Abstract
Microplastic (MP) pollution in water bodies has been increasing rapidly. This study investigated spatial variation in microplastic abundance and trait composition in two adjacent freshwater aquaculture ponds in Rasht, Iran, to evaluate differences in MP distribution and particle characteristics under similar management conditions. Although the ponds are operated in much the same way and receive water from the same source, their MP patterns were not identical. In total, 158 microplastic particles were recovered and classified according to color, shape, and size. Pond A contained 117 MPs, whereas Pond B contained 41. The composition of MP morphotypes, including fibers, films, fragments, and foam, was similar between the two ponds (P= 0.18), suggesting shared sources or comparable transformation pathways. In contrast, clear differences were observed in MP color composition (χ^2= 43.28, P<0.001; Cramér's V= 0.523). Particle size alone did not differ significantly between ponds (Wilcoxon test, P= 0.297); however, its interaction with pond identity significantly improved the explanation of color variation (Likelihood Ratio test, P< 0.001). Overall, the results demonstrate that adjacent aquaculture ponds receiving comparable external inputs may nevertheless develop distinct microplastic assemblages because of pond-specific ecological processes. These findings emphasize the importance of considering multiple microplastic traits simultaneously rather than relying solely on abundance estimates when assessing microplastic pollution in managed freshwater ecosystems.

Keywords: Microplastics, Aquaculture, Particle characterization, Multinomial logistic model, Environmental pollution

INTRODUCTION

Plastic pollution has increasingly come to be seen as one of the defining environmental issues of the Anthropocene. Since industrial-scale plastic manufacturing began in the 1950s, roughly 9.2 billion tonnes of these materials have been produced, and a significant share has eventually made its way into the waste stream and, from there, into natural environments (Geyer et al. 2017). Within this broader issue, microplastics (MPs; particles smaller than 5mm) have drawn particular attention because they persist, spread widely, and have been shown to affect a range of organisms across different ecosystems (Rochman et al. 2016). While much of the early work in this field focused on marine environments, freshwater systems (including rivers, lakes, and reservoirs) are now known to play a major role in both transporting and storing plastic debris (Li et al. 2018).

Macroplastics gradually weather into MPs through a mix of photodegradation, abrasion, and biological activity (Andrady 2017). This breakdown produces a mixture of particles that can differ quite substantially in size, shape, color, and chemical composition. These traits influence how MPs behave in the environment, their transport, their buoyancy, and the likelihood that they will be ingested by aquatic organisms. Common forms, such as fibers from textiles, fragments from consumer packaging, or thin films from agricultural plastics, each behave differently in water and differ in their accessibility to organisms (Crawford & Quinn 2017). Because of their small size, MPs are readily consumed by many species and have been linked to physical harm, oxidative stress, and altered feeding (Wright et al. 2013; Rasta et al. 2024). In addition, MPs can carry persistent organic pollutants, heavy metals, and even pathogens, introducing further layers of ecological and toxicological complexity (Rasta et al. 2021; Hedayati et al. 2022; Vayghan et al. 2022).

Although research on MPs in freshwater systems has expanded rapidly, aquaculture ponds remain comparatively understudied, despite being among the fastest-growing and most intensively managed freshwater environments. Global aquaculture production now exceeds 120 million tonnes annually and supplies over half of all seafood consumed by humans (Wu et al. 2020). The way these ponds are designed and operated, dense fish populations, heavy feeding, frequent management interventions, and widespread use of plastics, create conditions that may encourage MP accumulation and even transformation (Ory et al. 2018). Several potential MP sources can contribute to these systems, including degraded farm infrastructure, atmospheric fallout, incoming water, aquafeeds, and everyday operational activities (Lin et al. 2022; Kristanti et al. 2022). Moreover, the ecological characteristics of aquaculture ponds, high nutrient loads, restricted hydrology, and manipulated biological communities, may shape how MPs are retained, sorted, or broken down, in ways that differ from natural lentic systems (Song et al. 2017; Nejat et al. 2024).

Even with increasing recognition of aquaculture ponds as potential MP hotspots, a consistent challenge in the literature is the assumption that freshwater habitats behave more or less uniformly. This viewpoint can overlook fine-scale spatial differences and the ecological processes that determine how MPs move and transform within a system. Many studies also analyze only a single MP trait (for example, size) even though it is the interaction among several traits, such as color, morphology, and size that often determines environmental fate. While MP contamination has been documented in various aquaculture settings worldwide (Liu et al. 2019; Ma et al. 2020; Sanabila et al. 2022), and recent work in Iranian freshwater environments points to substantial contamination levels (Khoshnood 2024; Naz et al. 2024), the internal filtering and sorting processes within small, highly managed ponds remain poorly characterized. Despite the growing number of studies on microplastic contamination in freshwater ecosystems, most investigations have focused primarily on reporting abundance or individual particle characteristics, with limited attention to the combined influence of multiple particle traits under comparable environmental conditions. Consequently, it remains unclear whether adjacent aquaculture ponds receiving similar external inputs exhibit comparable microplastic assemblages or whether internal ecological processes generate distinct trait-specific patterns. Addressing this knowledge gap is essential for improving ecological interpretation of microplastic dynamics in managed freshwater systems. In this study, we suggest that aquaculture ponds do not simply collect MPs passively; rather, they operate as active ecological filters, where local physicochemical conditions and biological activity can selectively retain or alter MPs based on their traits, even when external inputs and management practices are nearly the same. Therefore, the present study aimed to compare microplastic abundance and trait composition between two adjacent aquaculture ponds sharing similar water sources and management practices, and to evaluate whether pond-specific ecological processes influence microplastic distribution beyond differences in external inputs.

MATERIALS AND METHODS

Study area: The study was conducted in two adjacent freshwater aquaculture ponds located in Rasht, Guilan Province, northern Iran. The ponds receive water from a common surface source and are operated under identical aquaculture practices. The geographical coordinates of Pond A and Pond B are 37.192281°N, 49.631406°E and, respectively (Fig. 1). Both ponds are used for intensive carp cultivation and feature semi-static water renewal, routine aeration, and high nutrient loading due to feeding practices.

Sampling procedure: Sampling was carried out in May 2025, when activity in the ponds was at its highest. In each pond, we collected three separate surface-water samples, and for every replicate we took roughly 20 liters of water using a stainless-steel container that had been cleaned beforehand. To make sure larger debris

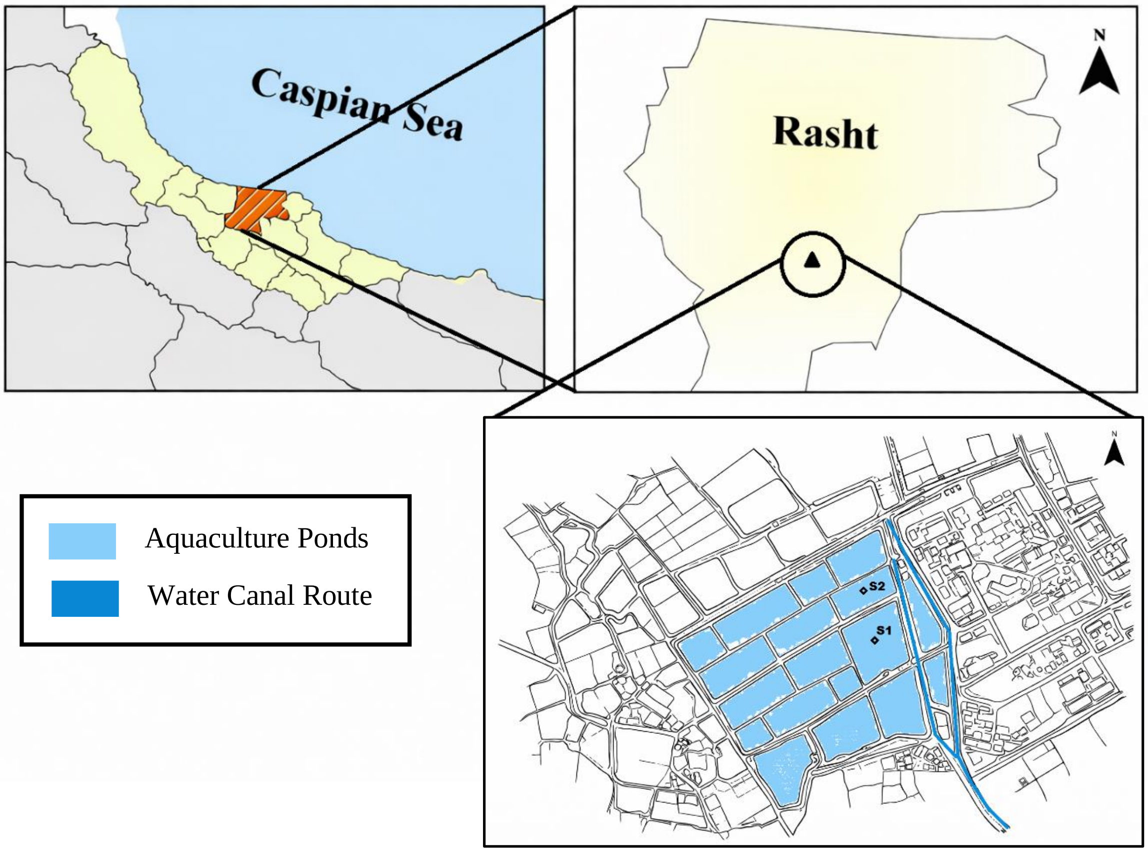

Fig.1. Geographic location of the study area showing the aquaculture ponds and their water canal route in Rasht, Iran.

did not enter the samples, the water was first poured through a 5-mm stainless-steel sieve right at the site. Whatever passed through this sieve was then filtered again through a much finer 20-µm mesh so that the microplastic particles could be held back. Surface water was sampled because floating and near-surface microplastics represent the most environmentally relevant fraction for evaluating recent inputs and water-column transport. Any material left on the mesh was gently washed off with filtered distilled water and transferred into amber glass bottles that had aluminum-lined caps. After finishing the fieldwork, we placed all bottles in insulated coolers and brought them to the laboratory within about four hours so the samples would remain as intact and uncontaminated as possible.

Laboratory analysis: Organic material present in the samples was digested with 30% hydrogen peroxide, which was heated to about 60°C and left to react until the organic matrix was no longer visible. After digestion, the remaining material was filtered under vacuum through 20µm glass fiber filters (Whatman GF/B). The filters were then allowed to dry naturally inside a closed desiccator and were kept in covered glass petri dishes until the samples were examined.

Microplastic particles were later identified under a stereomicroscope (Leica M80) using magnifications between 40× and 80×. Each particle was described according to its color, overall shape, and size. For size measurements, photographs of the particles were taken using the microscope after calibrating the imaging system with a 1-cm reference scale. These images were then analyzed using Digimizer, which allowed the maximum linear dimension of each microplastic to be measured in micrometers. Colors were recorded as they appeared in the field of view, while morphotypes such as fibers, fragments, films, and foam were distinguished based on their visible structure and texture.

Quality control (QC) and contamination prevention:

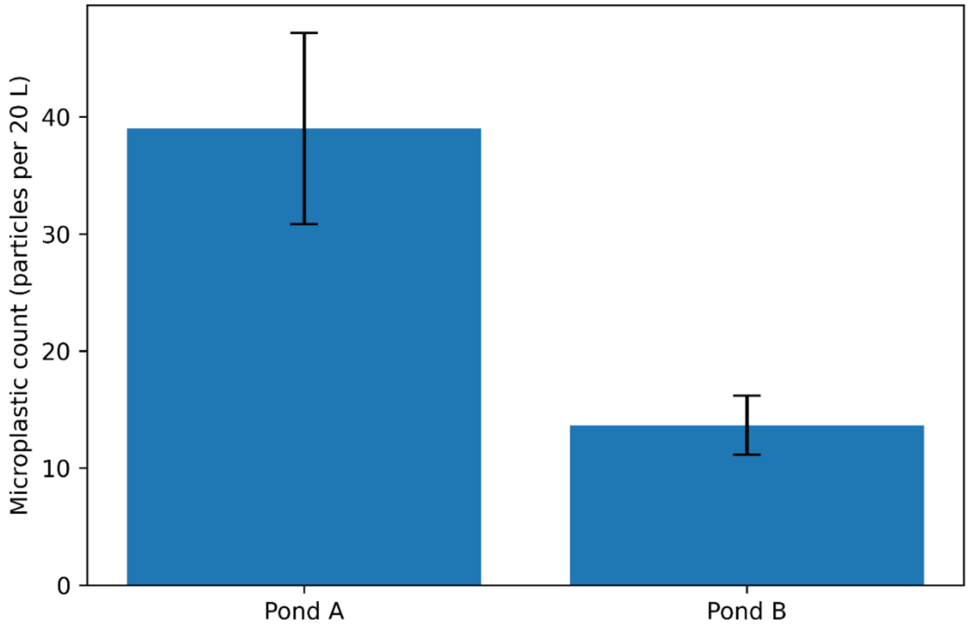

Fig.2. Mean microplastic counts (particles per 20L; mean±SD) in the two aquaculture ponds.

To prevent airborne or process-related contamination, all laboratory procedures were conducted in a clean air cabinet under controlled airflow. Cotton laboratory coats and nitrile gloves were worn during sample handling. Only glass and metal instruments were used throughout the study; no plastic tools or containers were introduced during any step of sampling or analysis.

All surfaces were cleaned with filtered ethanol (70%) and rinsed with particle-free distilled water before use. Procedural blanks consisting of 20µm filtered deionized water were prepared and processed alongside each batch of samples to monitor lab-based contamination. Blank filters were examined under the microscope before every analysis session. Fibers found in blanks (if any) were characterized and compared against field samples. Only particles not matching blank profiles (in color, shape, or size) were included in the final dataset. No polyester laboratory garments or wiping tissues were used to avoid contamination from synthetic fibers.

Statistical analysis: Each microplastic particle detected in the samples was treated as an individual observation and assigned its corresponding attributes, including pond of origin, color, morphology, and measured size. All statistical analyses were carried out in R (version 4.3.1). To examine whether the two ponds differed in the distribution of particle colors or morphotypes, chi-square tests were applied. Particle size was compared between ponds using the Wilcoxon rank-sum test, since the data did not meet normality assumptions based on the Shapiro–Wilk test ($P<0.05$). To explore how multiple particle traits interacted with pond identity, a multinomial logistic regression model was fitted using the *nnet* package. Model fit and performance were evaluated through AIC values together with McFadden's pseudo-R^2, which provided an indication of how well the model captured variation across the different microplastic categories.

RESULTS

General overview of microplastic pollution in aquaculture ponds: A total of 158 microplastic particles was obtained from 120-liter surface water samples taken from two aquaculture pond systems. The concentration of microplastic particles in two aquaculture ponds was not equal, with Pond A providing 117 microplastic particles for every 60-liter water sample and Pond B providing 41 for an equal volume of water (Fig. 2). In three replications of 20L each, in Pond A, the microplastic concentration varied from 1.60 to 2.40 items L^{-1}, with mean values of

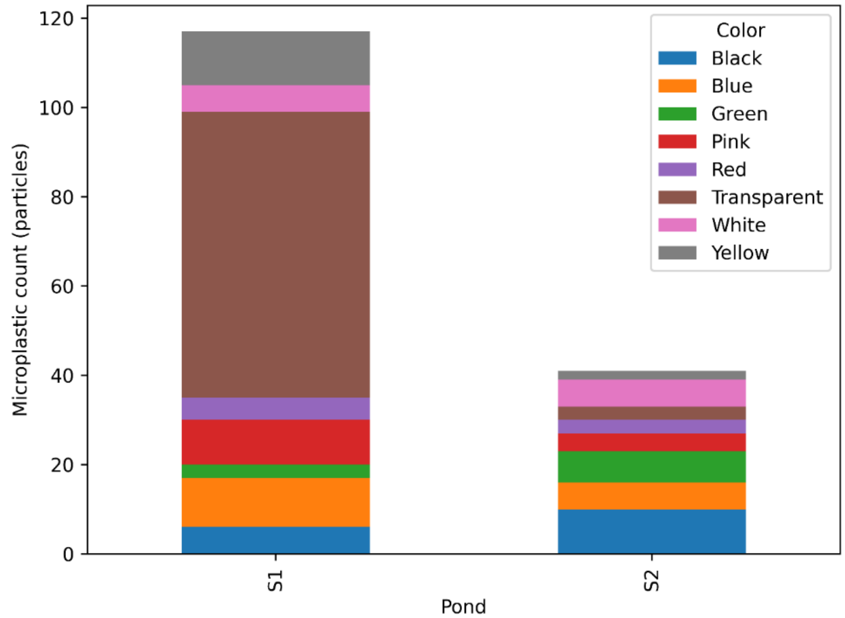

Fig.3. Color-based distribution of microplastic particles (counts) in Pond A (S1) and Pond B (S2).

Table 1. Color × Pond frequency matrix.

color	S1	S2
Black	6	10
Blue	11	6
Green	3	7
Pink	10	4
Red	5	3
Transparent	64	3
White	6	6
Yellow	12	2

1.95±0.41 items L^{-1} (mean±SD; n= 3). In Pond B, the microplastic concentration was relatively low, ranging from 0.55 to 0.80 items L^{-1}, with mean values of 0.68±0.13 items L^{-1} (n= 3). When the data from both ponds is combined, the average value of microplastics present per liter of water was 1.32 items L^{-1}. Overall, higher microplastic abundance was consistently observed in Pond A than in Pond B across all sampling replicates.

Color distribution: a divergent pattern revealed through statistical and visual analysis: Microplastics collected from both aquaculture ponds varied in colors, which included blue, black, transparent, and white. The combination of these colors in Pond A and Pond B differed, which indicated that their composition was distinct between the two systems (Table 1; Fig. 3). The statistical test indicates a significant relationship between color distribution and the sampling pond (χ^2= 43.28, P<0.001). The strength of association between color composition and sampling pond is moderate to strong with a value of 0.523. The presence or absence of certain colors is significantly higher in one pond than the other based on their color composition (Table 1). Overall, the color composition of microplastic particles differed significantly between the two ponds, indicating distinct color distributions.

Ptype morphology: lower variability and similarity across ponds: The MP particles we collected were grouped into four unmistakable shapes: fibers,

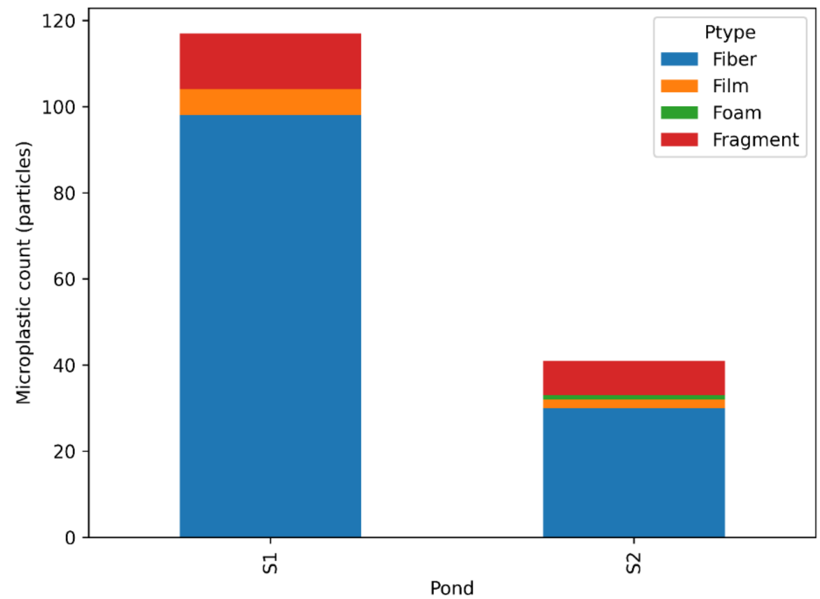

Fig.4. Distribution of microplastic morphotypes based on particle counts in Pond A (S1) and Pond B (S2).

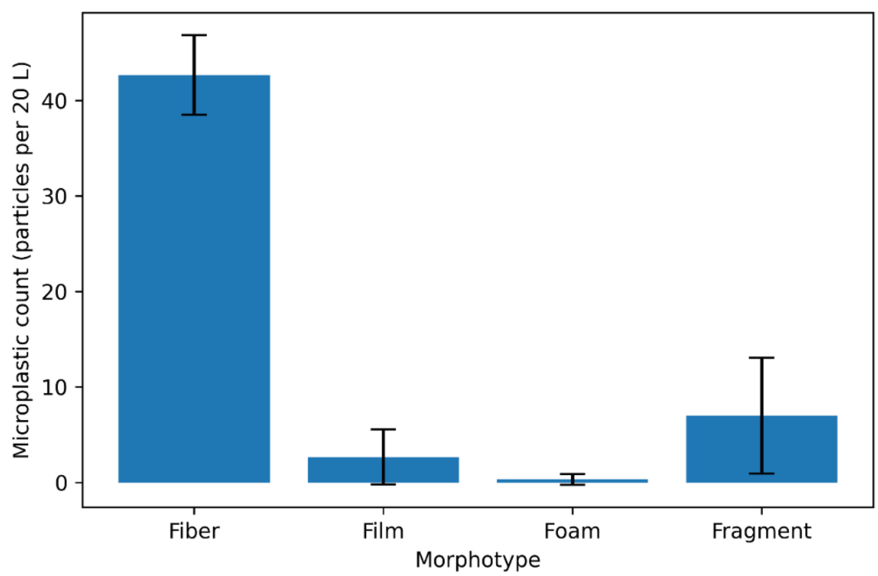

Fig.5. Overall distribution of microplastic morphotypes expressed as mean particle counts (± SD) across three 20-L replicates.

fragments, films, and foam. At first glance at Figures 4 and 5, one can tell all four morphotypes were found in every pond, though the counts for each were very different. To compare if the ponds were different in their general composition of shapes, a chi-square test was performed. The result was not significant χ^2 = 4.89, df = 3, P= 0.18), hence, pond identity failed to predict the distribution of morphotypes. In practical terms, the two systems carried a similar mix of shapes. Now, looking at the major players, most of the particles in both ponds were comprised of fibers and fragments, whereas films and foam made up the minor fractions. This was indeed the pattern across the entire study site. So, while there was some difference in raw count, the underlying profile of microplastic shape types-the ones common, the ones rare-was fundamentally the same in both Pond A and Pond B.

Size distribution: limited direct variability, but complex interactions with color and pond: The size of the microplastics in the two aquaculture ponds varied greatly, ranging from substances that measured less than 150μm to those that measured nearly 5000μm.

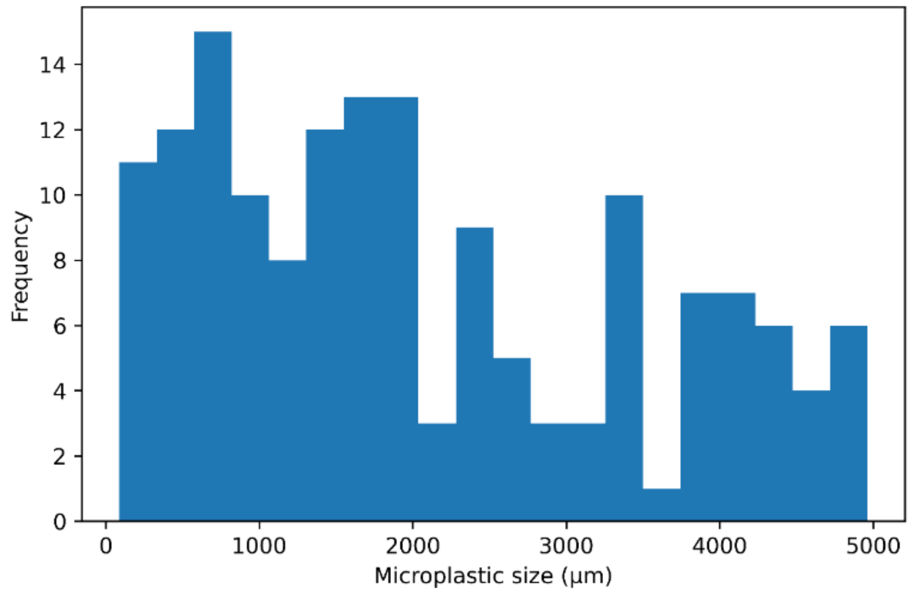

Fig.6. Size-frequency distribution of microplastic particles collected from the aquaculture ponds.

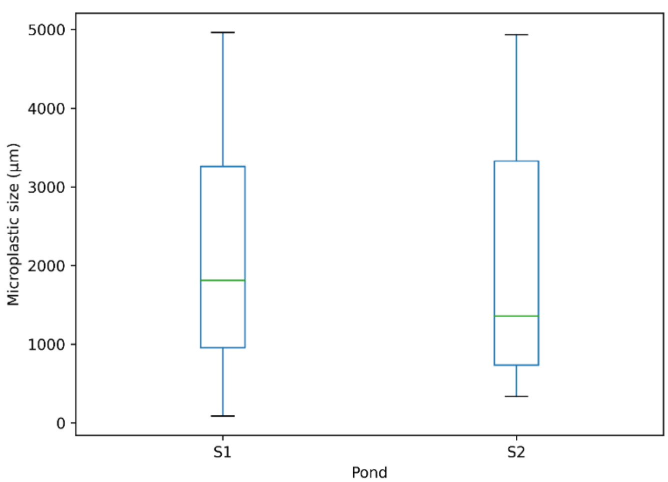

Fig.7. Comparison of microplastic particle sizes (µm) between Pond A (S1) and Pond B (S2).

The size of each particle was taken to be the longest dimension. Additionally, size could be measured as a continuum or in categories. To concisely describe, the particles were categorized into five classes depending on their sizes, which include <150µm, 150–300µm, 300–1000µm, 1000–3000µm, and 3000–5000 µm. Notably, the size frequency distribution depicts that the smaller particles, specifically those below 1000µm, dominated the two ponds, followed by the less frequent largest categories (Fig. 6).

The total size distribution is shown by the size histogram (Fig. 6), showing a right skewed distribution with a higher number of smaller particles. In comparing the size distributions, box plots showed overlapping size distributions and medians between the two ponds (Fig. 7). A test showed no significant difference in size to exist between the two ponds when taken as a single variable (Wilcoxon rank sum test, P=0.297). In conclusion, a comparative trend in microplastic size distribution was observed in both ponds under similar conditions, despite differences in microplastic size classes.

Integrative analysis via Multinomial Logistic Regression (MLR): To examine how microplastic color distributions are jointly influenced by particle size and pond identity, a multinomial logistic regression model was fitted, treating color (eight categories) as the response variable. Predictor variables included particle size (Z-standardized), pond identity (S1 and S2), and their interaction.

Model fit statistics supported the inclusion of interaction terms. The likelihood ratio test indicated that the full model provided a significantly better fit than the null model (χ^2= 50.42, df= 14, P< 0.001). McFadden's pseudo-R^2 was 0.089, indicating a modest model fit consistent with the complexity of environmental field data. Because direct interpretation of logit coefficients is not straightforward, model estimates were expressed as odds ratios (ORs) with

Table 2. Odds ratios (ORs) and 95% confidence intervals from the multinomial logistic regression model evaluating the effects of particle size and pond identity on microplastic color categories.

Comparison_vs_ref_color	term	odds_ratio	ci95_low	ci95_high
Blue	const	0.172999	0.091177	0.328251
Blue	size_z	0.094367	0.040844	0.218028
Blue	pond_S2	0.136459	0.065295	0.285186
Black	const	0.864136	0.494876	1.508926
Black	size_z	0.865594	0.472928	1.584286
Black	pond_S2	0.498278	0.241942	1.0262
Pink	const	11.46722	2.487186	52.86988
Pink	size_z	35.04501	7.517639	163.3695
Pink	pond_S2	7.917743	1.50852	41.55772

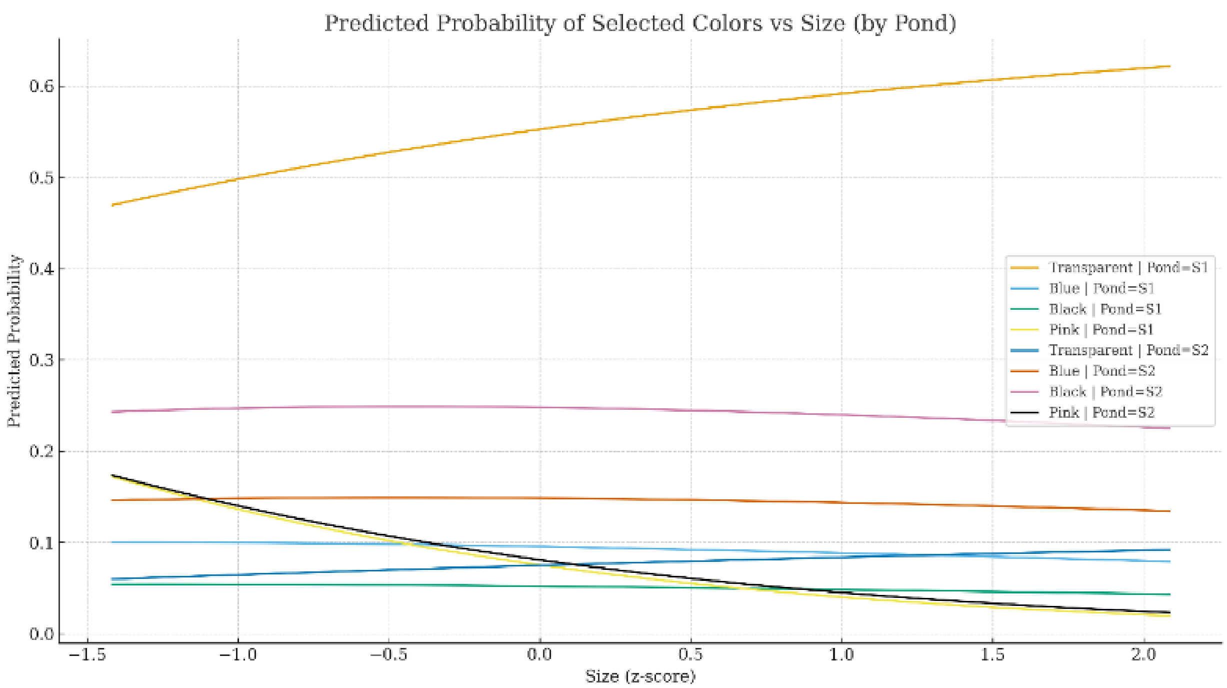

Fig.8. Predicted probabilities of selected microplastic color categories as a function of particle size (z-score) in the two aquaculture ponds.

95% confidence intervals (Table 2). Several color categories showed size- and pond-dependent patterns. In particular, increases in particle size were associated with higher odds of classification into certain color categories relative to the reference color. Pond identity also influenced color occurrence probabilities, with some colors being more likely in Pond S2 after accounting for particle size effects.

To visualize these patterns, model-based predicted probability curves were generated across a range of particle sizes for both ponds (Fig. 8). The curves illustrate how the probability of different color categories changes with particle size under each pond condition. For example, transparent particles showed consistently high probabilities at smaller sizes, whereas other color categories increased in probability with particle size in a pond-specific manner. Together, these results indicate that microplastic color composition is not determined by particle size alone, but reflects the combined influence of size and pond context within the studied aquaculture systems.

DISCUSSION

Color as an Integrative tracer: pond-specific sorting of microplastics driven by ecological mechanisms: The present study suggests that aquaculture ponds may function as dynamic micro-ecosystems in which microplastic assemblages are influenced by internal ecological processes rather than acting solely as passive accumulation zones. The pronounced divergence in MP color distribution observed between two adjacent ponds operating under identical management conditions (χ^2= 43.28, P<0.001; Cramér's V= 0.523) highlights the importance of pond-specific controls on MP fate. Such differences, emerging over a sub-kilometer spatial scale, challenge simplified source-to-sink assumptions and indicate that intrinsic pond characteristics can generate distinct MP assemblage signatures. Color-based sorting of MPs in this context can be interpreted as the integrated outcome of multiple, interacting ecological mechanisms operating within the pond environment. These mechanisms likely reflect the combined influence of biological interactions, physicochemical degradation processes, and hydrodynamic conditions, which together regulate the retention, transformation, and redistribution of MPs. In the following sections, we examine three key pathways through which these processes may contribute to pond-specific color differentiation.

The biological filter: selective ingestion and trophic transfer: Aquaculture pond ecosystems feature a high degree of biological activity with tightly linked food webs, and these features may serve as an important biological filter on MP assemblages. There are an increasing number of findings that indicate that interactions between aquatic biota and MPs are not random, but are determined through visual and behavioral interactions, in which the color of MPs proves to be particularly important. The choice of MP color preferred in ingestion, determined through experiments, has been found to consist of blue, black, and red, most likely because they resemble plankton, algae, or detrital particles (Ory et al. 2018; Mao et al. 2020; Wang et al. 2020).

In intensively managed aquaculture systems, due to enhanced feeding intensity and biological assemblage composition shaped by fish stocking regimes, such selective feeding has been proposed as one possible mechanism that may contribute to shaping microplastic color composition in aquaculture systems. Small differences in fish assemblage structure, feeding patterns, or zooplankton assemblages between water bodies can result in different levels of predation on particular color fractions of MPs. Comparable patterns of color-selective MP ingestion have been reported for freshwater fishes as well as invertebrates inhabiting both natural systems and water bodies under controlled regimes. Moreover, biological filtering mechanisms may operate beyond the point of ingestion. This occurs through the transfer of MPs across trophic levels and their subsequent return to the environment via egestion. Biologically aggregated particles and fecal pellets are often denser or display sinking behaviors that differ from those of individual MPs, facilitating the selective retention of certain MP colors within the water column or sediments (Welden & Cowie 2016; Wang et al. 2020). This process can further influence the relative proportions of MP colors retained within individual ponds. Taken collectively, these observations suggest that biological interactions in aquaculture ponds function as an active, color-sensitive filter. Through selective ingestion and trophic processing, individual ponds may develop distinct MP assemblages that are reflected in differences in color composition.

The photochemical gateway: differential degradation and fragmentation: Photochemical degradation is a nonbiological pathway through which microplastic communities in aquaculture ponds can be differentially modified. Sunlight exposure, in particular ultraviolet light, promotes the weathering of polymers-surface oxidation, embrittlement, and eventual fragmentation into smaller pieces. These effects have been shown by experiments to not be uniform across all particles, instead depending greatly on how the plastics interact with light-pigment type and color (Song et al. 2017; Mao et al. 2020). The dark-coloured microplastics-black or deep blueacquire a higher proportion of the incoming radiation and age quicker in the sun than lighter-coloured or transparent particles. This increased light absorption accelerates polymer degradation and fragmentation, which promotes the particles into successively smaller size fractions (Song et al. 2017; Wang et al. 2020). Light-coloured or transparent MPs, inversely, tend to have lower interaction with the incoming radiation and degrade slower, and therefore remain in the water column for longer. But in natural freshwater, the process of photochemical degradation does not act in isolation. The speed and effectiveness with which this takes place are mediated by site-specific conditions like water depth, amount of suspended material, and shading by phytoplankton or biofilms. Studies conducted in freshwater ponds and lakes have demonstrated that increased turbidity and greater biological shading can substantially reduce UV penetration, which significantly slows photodegradation and prolongs the residency time of colorant-bearing MPs in the environment (Xiong et al. 2021; Lin et al. 2024; Huang et al. 2024). Brighter systems can promote more rapid fragmentation, particularly for pigments that enhance light absorption. In this way, light-driven degradation acts as a kind of selective filter, which may gradually alter MP assemblages through changes in particle size and color over time. It does not just decrease overall MP numbers; it tends to preferentially remove or transform specific color fractions, potentially creating pond-specific MP signatures when considering biology and water movement (Huang et al. 2024; Corcoran et al. 2025).

The hydrodynamic sink: biofouling-mediated sedimentation: The third mechanism that affects MP assemblages in aquatic culture ponds is the hydrodynamic process, which is heavily influenced by biofouling. Microbial biofilm formation on MP changes the density, roughness, or settling velocities of the MP, which influence their tendency to remain or leave the water body. Several studies have indicated that this mechanism is highly effective for particles with high surface area to volume ratio, for example, fibers, which easily serve as substrates for biofouling (Kooi et al. 2017; Xiong et al. 2021; Yu et al. 2024).

In nutrient-dense aquatic systems like freshwater ponds for aquaculture, biofouling has been shown to increase the density of MPs to increase quickly, leading to changes in their buoyancy from positive to neutral or negative. The observed effect in these systems helps to facilitate the sinking of the MPs to the sediments or the benthic biofilms, which in effect creates a hydrodynamic sink for the particles (Yu et al. 2024; Wang et al. 2020). It is essential to examine that the removal rate from the environment is not dependent on any single attribute possessed by an MP. In these circumstances, observed color-related patterns in the water column could then emerge indirectly as a result of their link with morphotypes that are more prone to settling due to biofouling. This could be the case with MPs with a fibrous morphology, which have been seen to be the most prevalent type of MP in aquaculture and freshwater environments. Such MPs are shown to be highly prone to biofouling aggregation and thus are readily removed from the water column due to their aggregation (Xiong et al. 2021; Rasta et al. 2023).

This has implications that stress the significance of MPs being considered as multi-trait particles, which are characterized, from an environmental perspective, by complex physical, biological, and hydrodynamic interactions (Corcoran et al. 2025). In the case of aquaculture ponds, biofouling-induced sedimentation may thus function as a selective sink that preferentially affects MP assemblages (Yu et al. 2024), which enhance pond-specific characteristics through a combination of biological retention (Xiong et al. 2021) and photochemical degradation (Razeghi et al. 2021).

Synthesis: an integrated view of pond as a selective ecosystem: The fact that the MP morphological distribution appears so similar for the two ponds represents an initial indication of shared sources of contamination (Xiong et al. 2021; Huang et al. 2024). On this background, the strong difference in the distribution of MP color represents an important case study finding because it reveals that despite the fact that pathways of input could be similar, the dynamic patterns of MPs within the ponds are far from random (Razeghi et al. 2021). On the contrary, internal dynamics function selectively, influencing MP assemblages after their arrival within the system (Huang et al. 2024). Similar patterns of trait-specific sorting have also occurred at much larger spatial scales in freshwater systems, where patterns of particle distribution are affected along pathways of transport because of the joint action of both physical and biologic processes rather than the effects of source material variations alone, as Mani et al. (2015) suggested in their study.

Taken together, these data point to a role for biological filtration, photochemical breakdown, and hydrodynamic removal as interrelated processes, not independent ones, in determining MP fate in aquaculture ponds (Fig. 1) (Huang et al. 2024). A particle surviving in the water column due to reduced rates of photochemical breakdown, for example, could still be selectively removed via consumption, while further biological processing could influence its settling properties (Yin et al. 2019). Particles escaping biological filtration could, in turn, be progressively changed in physical properties or chemistry, making them more or less susceptible to aggregation and settling (Wang et al. 2020).

Consequently, the resulting MP color pattern seen in each pond is better considered the result of these interrelated processes rather than the effect of a single one (Rasta et al. 2025). The recognition of aquaculture ponds as selective ecosystems, rather than passive sinks, offers a consistent way of understanding how a same external environment stimulus can create a particular internal MP community (Huang et al. 2024). Such a holistic view points out the necessity of taking into account interrelated particle characteristics while evaluating the microplastic environment in controlled freshwater ecosystems (Shamim et al. 2025).

Implications for monitoring and risk assessment: This paradigm shift has several implications with regard to MP monitoring and risk evaluation in aquaculture systems (Huang et al. 2024). Methods relying solely on single-point water sampling in aquaculture ponds cannot fulfill the monitoring requirements with regard to the internal transfer processes of MPs (Yin et al. 2019; Corcoran et al. 2025). This should instead involve a multi-compartment approach where the water column and biological components can also be considered, allowing the evaluation of transfer processes between the compartments (Rasta et al. 2026; Rasta et al. 2023).

From a risk perspective, the selective enrichment of particular MP traits, specifically color, within a pond implies a non-uniform exposure, even for ponds under the same level of management and input (Rasta et al. 2025; Huang et al. 2024). Such non-uniformity can lead to a targeted exposure level of the cultivated organisms to specific MP fractions, potentially more prone to the presence of chemical additives or sorbed contaminants, accordingly raising the level of toxicological significance above the value posed by their abundance (Rasta et al. 2026; Rasta et al. 2023; Corcoran et al. 2025).

In summary, the current results clearly indicate the presence of selective ecological filtering in aquaculture ponds, contradicting the assumption of microplastic passive accumulation (Huang et al. 2024). As indicated, the synergy between food web dynamics, photochemical degradation, and sedimentation processes demonstrates the active modification of the physical properties of MP aggregates within the pond (Wang et al. 2020). Understanding such ecological phenomena within the pond is important for enhancing the accuracy of the monitoring schemes, in addition to informing the appropriate management strategies for the health of the species within the microplastics-contaminated freshwater environment (Vayghan et al. 2022).

Particle size as an interactive and context-dependent variable: Particle size did not have a significant difference between the two ponds when considered independently (P= 0.297). However, the role of particle size became apparent only after we took into account its relationship with the pond we were in, using the multinomial regression analysis. In simple terms, the size of particles is not a factor that by itself defines the microplastic outcome. Rather, size is a relative property that only has meaning given the local environment and conditions. In this sense, size matters only as it relates to pond processes, and not as a universal constant for every situation.

One key shaper of how this context unfolds is the differential bioavailability brought on by which organisms are selective about what they consume (Yin et al. 2019; Rasta et al. 2025). Particle size serves as a powerful gateway to who eats what, because different guilds of aquatic life interact with different particle sizes; the stage for trophic interactions is set by size (Yin et al. 2019; Shamim et al. 2025). A great volume of research indicates that freshwater invertebrates and zooplankton are selective to ingest microplastics within limited size ranges (Yin et al. 2019; Rasta et al. 2025), while larger particles are more often within the reach of visually guided predators such as fish (Yin et al. 2019; Rasta et al. 2023). Because ponds can differ even subtly in which species are present or how they feed, they can create opposite size-based pressures on MP particles (Huang et al. 2024; Corcoran et al. 2025). That means the same external input can yield various size-trait patterns among different communities. Across freshwater systems, these size-dependent biological interactions are well documented and are widely viewed as a central force reshaping how microplastics move through and become distributed among trophic levels (Yin et al. 2019; Rasta et al. 2025; Corcoran et al. 2025).

Aside from biology, the interaction between particle size and pond identity functions to vary particle trajectories and deposition (Yu et al. 2024). The time MPs spend suspended within ponds depends on how their characteristics influence hydrodynamics, but biofouling upsets that connection altogether (Wang et al. 2020). As biofilms form on MPs, particles increase in mass and accumulate sediment at a different rate, effectively altering the cutoff length at which MPs transition from floating to sinking (Xiong et al. 2021; Yu et al. 2024). The rate and degree to which biofouling proceeds are heavily influenced by locale-specific conditions such as nutrient availability, temperature, and biological activity (Corcoran et al. 2025). Thus, MP samples of identical size can have strongly differing fates within different ponds, sinking more quickly where biofouling rates are higher. This provides a possible explanation for the interaction between size and pond identity that the model distinguishes.

The correlation between the size and color of particles serves as a constant reminder that MP fate cannot be dictated by a single parameter but by a combination of factors (Rasta et al. 2025). Size might impact their vulnerability to predators, their chances of complying with photochemical reactions, and their aggregating abilities, to name a few (Yin et al. 2019). However, color behaves in a decidedly different manner, as it influences either the reaction of light with the particles or their reaction with biological processes (Razeghi et al. 2021; Rasta et al. 2025). When taken together, they generate a multi-layered filter for each pond, depending on biological, UV, and sedimentation factors, which determine the amount of particles present in each pond and which particles become removed or modified (Huang et al. 2024; Yu et al. 2024; Corcoran et al. 2025).

In other words, the absence of a strong, independent size effect does not diminish the realized role of particle size in ecosystems. Instead, size is a mediating factor that depends on the environment; it influences transport, bioavailability, and ultimately exposure (Rasta et al. 2025; Shamim et al. 2025). When we present the size distributions of microplastics without relating them to the environment near the location being measured, we are likely overlooking the crucial parameters that govern the fate of microplastics. It's simple: we require environment-dependent interpretations of particle size measurements when we examine ecosystems for risks (Shamim et al. 2025).

Morphological consistency as a fingerprint of common sources and fate pathways: Unlike the great variation known in the case regarding the colors of the microplastics and the size that matters depending on the situation, the composition regarding the morphotypes, including fibers, fragments, films, and foam, remains the same in the two ponds with little significance, $P = 0.18$. Just because the variation in morphotypes remains constant, in spite of the clearly different characteristics of the particles, this provides an important indication regarding the origin and the processing procedure regarding the MPs (Corcoran et al. 2025).

In both freshwater and aquaculture, the presence of fibers is most characteristic of microplastic pollution, and this is not surprising given the wide human use that leads to their distribution (Vayghan et al. 2022; Huang et al. 2024). From the present study, it is clear that fibers continue to represent the most abundant type in both ponds and support the general trend here as evident in aquaculture and freshwater systems (Huang et al. 2024). In aquaculture, this is probably because there are several overlapping sources: the degradation of plastic infrastructure such as nets, ropes, and plastic films, the transport of textile fibers in the air, and the shared source of water with a prevailing microplastic background level in the catchment area (Vayghan et al. 2022; Huang et al. 2024; Rasta et al. 2026). The presence of comparable morphotype proportions in both ponds indicates that both sources are being distributed in approximate measure.

The fact that this morphological signal is constantly of this shape indicates that what is happening in the ponds is able to fine-tune the adjustment of these secondary traits (such as color and size) without necessarily causing the proportional representation of the dominant morphotypes to fluctuate wildly (Corcoran et al. 2025). Overall, it appears that the ponds are recruiting MPs proportionally across these dominant categories, despite the finer level of sorting continuing to occur at the level of the sub-populations within these categories (Nava et al. 2023). That is, certain subsets of fiber (based on either color or size) could be preferentially depleted, or reduced, while the same processes of retention and removal are occurring due to this morphotype in both of these ponds (Mao et al. 2020; Rasta et al. 2025).

There seems to be a tiered understanding implied in this text regarding the stratification pattern that MPs follow in aquaculture ponds. On first strata, there's been a natural setting of who's in the basic structure and morph types that enter into this environment from outside (Corcoran et al. 2025). Once inside this environment, natural systems and physical-chemical processes fine-tune those traits that are relatively easy to change (Mao et al. 2020; Wang et al. 2020), the ones that are reflected in traits like properties of light absorption or reflects coat patterns and sizes, in a way that doesn't result in MP populations unmaking their basic morph structure but creating a community difference instead (Corcoran et al. 2025).

These patterns are also present in larger freshwater systems: the combination of morphologies remains relatively constant even when the density of particles or the types of polymers change over the landscape (Yin et al. 2019; Corcoran et al. 2025). Over rivers and lakes, assemblages with high levels of fibers remain relatively constant in different types of environmental settings (Wang et al. 2020; Vayghan et al. 2022), supporting the proposal that morphology is used as a marker for the origin of plastics, but with other properties changing depending on the local environment (Mao 2020). Together, these findings point to morphology as an established, fixed descriptor for microplastic pollution, and, indeed, morphology should be interpreted in the context of more dynamic properties for an accurate understanding of how microplastic pollution behaves in managed freshwater systems (Corcoran et al. 2025).

Implications for source apportionment and mitigation: The presence of the P-type stable morphological pattern in the ponds is more than an interesting phenomenon. It is also important for understanding where we might actually look. A pattern that remains relatively constant is more than just descriptive information. It actually offers us the key we need to identify where the source of the microplastics is, at least in the sense that the external source is the primary source. The microplastics' morphological pattern is like the positive fingerprint telling us where the pollution is coming from.

Fibers are the prevailing type in both locations, and the conclusion is simple: mitigation efforts must target the reduction of these high-fiber sources at the source. In aquaculture, this means hardening plastic infrastructure and reducing the amount of fibers inadvertently released during normal production activities. Add a filtering system at water intake points to limit the amount of backgrounds sourced microplastics entering the facility, and target the broader sources of fibers in the air and watersheds (Huang et al. 2024).

Most importantly, the morphological composition resilient to the internal pond processes indicates that a reduction of the inputs aimed at the morph types present in the system would result in a predictable decrease. This is not the same when it comes to characteristics such as color or size, which are more dominantly affected by the in-pond processes. It is hereby that morphology appears very stable to use in determining the efficacy of mitigation (Corcoran et al. 2025).

Altogether, whereas color and size information do point to the influence of local ecological filtering, morphotype is a more robust diagnostic to locate source dominance as well as success regarding mitigation. In controlled aquatic environments such as aquaculture ponds, morphotype information may prove beneficial to monitor sources as well as assess success regarding mitigation.

Study Limitations

This study has several limitations that should be considered when interpreting the findings. First, microplastic identification was based on established visual microscopic criteria without spectroscopic confirmation (e.g., FTIR or Raman spectroscopy). Although this approach is widely used in exploratory studies, it may result in occasional misclassification of visually similar non-plastic particles and therefore influence absolute abundance estimates. Nevertheless, because identical sampling, processing, and identification procedures were applied consistently to both ponds, the comparative differences observed between ponds remain robust. Second, sampling was limited to the surface water column and did not include sediment or deeper water layers. Consequently, the present findings should be interpreted as representing surface-water microplastic assemblages only. Since sedimentation and biofouling may alter particle composition below the surface, future investigations integrating both water-column and sediment compartments would provide a more comprehensive understanding of microplastic dynamics in aquaculture ponds.

Recommendations and Conclusion

Recommendations

Practical recommendations for aquaculture management

- **Source Control:** Focus mitigation actions on reducing the usage of raw material inputs through the use of more hard-wearing aquaculture fabric; establish a maintenance and replacement regimen for nets and ropes; and install appropriate filtration at water intake points.
- **Pond Management Optimization:** To abate the cycle of microplastics in the system, optimize water exchange rates and aeration patterns to enhance the flushout of particles and decrease conditions that contribute to fouling and suspension.
- **Comprehensive Monitoring:** Call for the implementation of multi-compartment monitoring, where the concentrations of microplastics in the water column, sediment, and lipid tissues of cultivated species are to be monitored consistently. A comprehensive understanding becomes imperative for effectively estimating the risk of exposure.

Recommendations for future research

- **Mechanistic Studies:** Going forward, we should quantify the central processes identified herein. That is, the rate at which different microplastic types are ingested by diverse species, and biofouling and photodegradation actually occur under natural conditions in ponds.
- **Trophic Transfer and Risk:** Mapping how microplastics and their associated contaminants move through the entire aquaculture food web-from the tiniest base organisms up to the commercially valuable species-will truly provide an accurate degree of exposure risk to humans.
- **Predictive Modeling:** Such work will be necessary in constructing integrated hydro-ecological models that weave in particle properties with ecosystem

variables. These models will be required to predict the fate of microplastics with a view to informing the design of safer aquaculture systems.

CONCLUSION

The present study suggests that aquaculture ponds function as more than passive recipients of microplastics, acting instead as ecological systems that may selectively influence microplastic assemblages after their introduction into the aquatic environment. Rather, they are active ecological systems with the capacity to selectively affect the composition of the microplastics once they have entered the environment. The two neighboring ponds that we studied, yet which have almost the same management practices, have distinctly different microplastic compositions.

By pond, there was not a significant change in the composition of the types of microplastic shapes, indicating the size types essentially reflect the prototypical pollution sources and entry routes. However, there were significant differences in the composition for color, suggesting that pond-specific ecological processes may contribute to differences in particle characteristics. Size, on the other hand, was not significant on its own for the ponds but significant when considered in the context of each pond's conditions, referring to the size being significant but in the appropriate context of size.

Taken together, these findings suggest that different microplastic traits provide complementary ecological information. While similarities in morphotype composition may reflect comparable input sources, differences in color distribution indicate that internal pond conditions may further modify microplastic assemblages after their entry into the system.

More generally, the results challenge us to look beyond the simple enumeration of microplastics. If we are to effectively evaluate exposure, ecological risk, and the effectiveness of mitigation in aquaculture, we need to employ a multi-trait methodology that takes into account the characteristics of particles as well as the unique dynamics of each particular ecosystem. Viewing aquaculture ponds as selective ecological filters provides a more comprehensive framework for understanding microplastic dynamics in managed freshwater ecosystems and may support the development of more effective monitoring and management strategies.

By integrating conventional descriptive analyses with multinomial logistic regression, this study demonstrates the value of a trait-based analytical framework for investigating microplastic heterogeneity in managed freshwater environments.

Future studies should incorporate spectroscopic polymer identification (e.g., FTIR or Raman spectroscopy), include sediment and deeper water compartments, and evaluate seasonal variation to better understand the ecological mechanisms governing microplastic transport and transformation in aquaculture systems.

ETHICAL APPROVAL

This study was conducted in accordance with national and institutional guidelines for research involving aquatic organisms. All sampling, handling, and laboratory procedures were carried out using non-invasive methods and did not involve any harm or experimental manipulation of live animals beyond routine aquaculture practices. Ethical approval for the study was granted by the appropriate institutional review committee under the code: IR.GUILAN.REC.1403.189.

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مقاله کامل

آلودگی میکروپلاستیک در استخرهای پرورش ماهی: یک مطالعه تطبیقی در رشت، ایران

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چکیده: آلودگی میکروپلاستیک‌ها در محیط‌های آبی به‌سرعت در حال افزایش است، با این حال رفتار این ذرات در سامانه‌های کوچک و مدیریت‌شده آب‌های شیرین هنوز به‌خوبی شناخته نشده است. در این پژوهش، رفتار و الگوی توزیع میکروپلاستیک‌ها در دو استخر مجاور پرورش آبزیان در شهر رشت، ایران، بررسی شد. با وجود آنکه این دو استخر تحت شرایط مدیریتی مشابهی اداره می‌شوند و از یک منبع آبی مشترک تغذیه می‌کنند، الگوهای آلودگی میکروپلاستیکی آنها یکسان نبود. در مجموع، ۱۵۸ ذره میکروپلاستیک از نمونه‌های آب استخراج و براساس رنگ، ریخت‌گونه و اندازه طبقه‌بندی شدند. تعداد میکروپلاستیک‌ها در استخر A برابر با ۱۱۷ ذره و در استخر B برابر با ۴۱ ذره بود. ترکیب ریخت‌گونه‌های میکروپلاستیک شامل الیاف، فیلم‌ها، قطعات و فوم بین دو استخر تفاوت معنی‌داری نشان نداد (*P*=۰/۱۸) که بیانگر منابع مشترک یا مسیرهای تبدیل محیطی مشابه است. در مقابل، توزیع رنگ میکروپلاستیک‌ها تفاوت معنی‌داری بین دو استخر داشت (χ^2=۴۳/۲۸ ، *P*<۰/۰۰۱، Cramér’s V=۰/۵۲۳). اندازه‌ی ذرات به‌تنهایی تفاوت معنی‌داری بین دو استخر نشان نداد (*P*=۰/۲۹۷)، اما زمانی که همراه با هویت استخر در نظر گرفته شد، نقش معناداری در تبیین تفاوت میان گروه‌های رنگی ایفا کرد (آزمون نسبت درست‌نمایی، *P*<۰/۰۰۱). در مجموع، نتایج نشان می‌دهد که حتی با وجود ورودی‌ها و مدیریت مشابه، فرآیندهای زیستی و شرایط محیطی هر استخر می‌توانند به‌صورت متفاوتی بر تجمع و ویژگی‌های میکروپلاستیک‌ها اثر بگذارند. این یافته‌ها نشان می‌دهد که اتکا صرف به شاخص‌های مبتنی بر فراوانی برای توصیف الگوهای آلودگی میکروپلاستیک‌ها کافی نیست.

کلمات‌کلیدی: میکروپلاستیک، آبزی‌پروری، ویژگی‌های ذره، توزیع رنگ، مدل لجستیک چندگانه، آلودگی محیط‌زیست