Understanding the Characteristics, Origins, Potential Impacts, and Removal Efficiencies of Microplastics in Wastewater Treatment Plants in Southeast Asia

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Abstract

Microplastics, or fragments of plastic smaller than 5 millimeters in size, have received considerable attention in recent years. As these microscopic particles enter our oceans, water sources, and even the air we breathe, concerns about their impact on human health have increased, particularly in Asia, a region experiencing rapid industrialization and urbanization. This study provides an up-to-date review of the current state of knowledge regarding microplastic pollution, with a particular focus on the Southeast Asia (SEA) region. It encompasses an evaluation of microplastic origins, characteristics, removal efficiencies in wastewater treatment plants and potential impacts of microplastic pollution. The findings of this review reaffirm that microplastic pollution is a widespread issue in the region, with the Philippines and Vietnam having the most contaminated rivers. The prevalent microplastic shapes found in fresh water in SEA are fibers and fragments, with PP and PE being the most common polymer types. Moreover, blue and transparent microplastics are observed in nearly all the studies. Microplastic sizes exhibit variations due to different collection methods. Notably, there is a significant lack of studies concerning the impacts of microplastic pollution on humans and aquatic organisms. This study underscores the need for more comprehensive and proactive approaches to microplastic management. These include implementation of designated policies for microplastic management, adoption of standardized sampling methods and initiation of more extensive research endeavors aimed at addressing this form of pollution in freshwater environments.

Key words: abundance, microplastic, pollution, review, SEA

1. Introduction

Plastic waste, an artificial pollutant, is a pressing environmental issue worldwide. Particles smaller than 5 mm are classified as microplastics (Ashrafy *et al.*, 2023) and are recognized as emerging pollutants that pose a threat to aquatic environments and, potentially, to human health (Osman *et al.*, 2023).

Among the 11 Southeast Asian (SEA) nations, Indonesia, Thailand, Vietnam, the Philippines and Malaysia have especially remarkable municipal solid waste production, averaging 1.14 kg per capita per day, ranking these countries the top five producers of such waste in the world (Arumdani *et al.*, 2021). Notably, the Philippines holds the third position globally for plastic waste emissions into the ocean and is a leading contributor to plastic emissions from river sources (Meijer *et al.*, 2023).

Microplastic pollution in marine environments is relatively well understood and documented, with a wide range of studies conducted worldwide. A comparable level of understanding does not yet exist for fresh water. Even though there has been an increasing amount of work performed that confirms microplastic contamination in freshwater environments, very little of it has been conducted in SEA, resulting in a dearth of comprehensive understanding on the current state of microplastic-induced issues in the region.

This study aims therefore to provide a regional perspective on the most updated state of microplastic pollution in SEA countries, with a special focus on river environments, through conducting a comprehensive review of publications as well as government and project reports. It covers microplastic origins, characteristics, removal efficiencies in wastewater treatment plants (WWTPs), and potential impacts of this emerging waste in the region. The evaluated microplastic characteristics include shape, size, color, and abundance level in surface water, wastewater and stormwater.

2. Research Methodology

This review was accomplished by scrutinizing two primary data sources: journal articles and project reports. Multiple scientific databases were employed through systematic search tools such as Web of Science, Scopus and Google Scholar.

The highest priority was given to journal articles that were recently published by esteemed academic publishers. In instances where necessary information gaps required filling, conference papers were included. Individual searches were carried out for all eleven Southeast Asian countries, using keywords such as "microplastic," "microplastic pollution," "freshwater," "river," "characteristics," "origin," "wastewater treatment plants" and the specific name of each country.

3. Results

3.1. Microplastic Origins

There are several ways to categorize microplastics. Based on their characteristics, microplastic origins can be divided into point and non-point (diffuse) sources (Chen *et al.*, 2021; Nguyen *et al.*, 2023). Based on their nature, they can be divided into primary and secondary sources. The latter type of categorization is dominantly applied in the current studies in this field (e.g., Chen *et al.*, 2021; Su *et al.*, 2016).

Primary microplastics are specifically and industrially manufactured for a wide range of uses, including microbeads in cosmetics, abrasive materials in personal care products, sandblasting media, and large plastic pellets for industrial processes (Browne *et al.*, 2011). Secondary microplastics, on the other hand, are produced when larger plastic and synthetic materials fragment due to processes such as UV degradation and machine washing (Nguyen *et al.*, 2023). Examples of secondary microplastics include fibers from polyester, acrylic and polyamide clothing, as well as remnants of post-use agricultural mulch films in fields (Fendall & Sewell, 2009).

Studies on microplastics in freshwater systems in SEA reported secondary plastics as the principal contributors to the widespread presence of microplastics in the environment. Observed activities that induce microplastic pollution vary, from residential to industrial activities (Table 1). The presence of plastic manufacturing industries have often been witnessed when the contamination level (microplastic abundance) was remarkably high, such as in the Meycauayan River in the Philippines (Osorio *et al.*, 2021) and the Saigon River in Vietnam (Lahens *et al.*, 2018). Noteworthily, a recent study conducted by IGES (2022) on the Marikina River in the Philippines determined that vehicle tire abrasion and other microplastics generated from traffic roads are another substantial and alarming source of microplastic pollution in freshwater environments.

3.2. Microplastic Characteristics in SEA

a. Abundance

Microplastic abundance refers to the quantity of microplastic particles in a given unit. The average abundance of microplastic in rivers in SEA ranges from 0.0070 particles/m^3 in the Cherating River, Malaysia (Pariatamby *et al.*, 2020) to 259,505 particles/m^3 in the Saigon River in southern Vietnam (Lahens *et al.*, 2018) (Table 1). Among the 11 SEA countries, Vietnam and the Philippines seem to experience the worst microplastic pollution in rivers. The Meycauayan River in the Philippines was the second most contaminated river, with approximately 57,665 particles/m^3 (Osorio *et al.*, 2021).

These high values were attributed to the presence of textile and plastic manufacturing industries as well as residential activities in both countries (Lahens *et al.*, 2018; Osorio *et al.*, 2021). Also in the Philippines, stormwater collected from an under-bridge drain that flows directly into a tributary of the Marikina River exhibited an abundance level of 19,022 particles/m^3, which is 38 times higher than that in the river surface water (485 particles/m^3) (IGES, 2022).

b. Shape

Microplastic particles come in various shapes, including fragments, films, pellets/granules, filaments/fibers, sheets and foam (Zhang *et al.*, 2018). The morphology of microplastic particles can serve as an indicator of potential contamination sources (Wu *et al.*, 2018). For instance, fragments often result from the degradation of different plastic products such as packaging materials, plastic containers and household products (Osorio *et al.*, 2021; Thompson *et al.*, 2004). Fibers are typically associated with the weathering of fishing lines and nets, as well as the release of synthetic textile fibers from household laundry wastewater (Eo *et al.*, 2019; Wu *et al.*, 2018). Pellets, on the other hand, are regarded as primary microplastics and used as raw materials for manufactured plastic products (McDermid & McMullen, 2004).

The predominant microplastic shapes discovered in fresh water in SEA were fibers and fragments (Table 1). Reports of films, foams, cylinders, pellets and spheres were infrequent. Consequently, it is possible to conclude that the microplastics identified in this region are primarily secondary microplastics resulting from the breakdown and deterioration of plastic items. Microplastic-inducing activities were reported to be both

Table 1 Microplastic characteristics in SEA.

Country	Location	Sample	Methods	Abundance (particles/m^3)	Average abundance (particles/m^3)	Size range* (µm)	Color	Shape	Polymer type	Origin	Reference
Indonesia	Citarum River	Surface water	Sample collection: Manta trawl method. Sample pretreatment: net screening, oven drying, Fenton oxidation method. Microplastic visualization: microscope, Fourier transform infrared spectroscopy (FTIS).	0.0574 ± 0.025	0.0574	125–5,000	Blue, red, green, white, black, brown, and transparent	Fragment, fiber, film, monofilament, foam	PE, PP	Residential activities	Sembiring *et al.* (2020)
	Ciwalengke River	Surface water	Sample collection: grab sampling method. Sample pretreatment: filtering, oven drying. Microplastic visualization: binocular microscope, Raman spectroscopy.	5,805 ± 3,280	5,805	50–2,000	Red, green	Fiber, fragment	Polyester, nylon fiber	Direct clothing, fabric washing of textile industries	Alam *et al.* (2019)
	Surabaya River	Surface water	Sample collection: modified Manta trawl net. Sample pretreatment: oven drying, wet peroxide oxidation method. Microplastic visualization: stereo microscope, FTIS.	1.47–43.11	22.29	333–5,000	Transparent, white, blue, black, yellow	Fiber, fragment, film, foam, pellet	LDPE, PP, PS, PE, PET	Domestic and industrial activities	Lestari *et al.* (2020)
Malaysia	Cherating River	Surface water	Sample collection: conical nylon plankton net. Sample pretreatment: sieving. Microplastic visualization: binocular microscope.	0.0070 ± 0.0033	0.0070	100–5,000	Transparent, black, blue, red, yellow, white	Fiber, fragment, film, foam, pellet	Not reported	Intense fishing and tourism activities	Pariatamby *et al.* (2020)
	Dungun River	Surface water	Sample collection: bucket. Sample pretreatment: filtering, oven drying. Microplastic visualization: stereomicroscope, FTIS.	38.7–300.8	169.75	60–5,000	Black, transparent, blue, red, brown, green, purple, white	Fiber, fragment	PAN, RY, PP	Potentially household sewage, fishing	Hwi *et al.* (2020)
Philippines	Cagayan de Oro River	Surface water	Sample collection: bucket. Sample pretreatment: oven drying, digestion, density separation, filtering. Microplastic visualization: stereomicroscope, FTIS.	300	300	300-5,000	Blue, red, white, transparent, brown, black	Fiber, filament, fragment	PA, PU, PET	Residential activities	Gabriel (2023)
	Cañas River	Surface water	Sample collection: bucket. Sample pretreatment: oven drying, wet peroxide oxidation method, density separation, filtering. Microplastic visualization: microscope, Raman spectroscopy.	1,580	1,580	300–5,000	White, black, red, green, blue, yellow, orange, transparent, others	Fragment, film, pellet, line, sheet, foam	PP, HDPE, LDPE, PS, PU, PET, PVAC	Plastic manufacturing industries	Osorio *et al.* (2021)
	Pasig River	Surface water		3,405	3,405	300–5,000					
	Parañaque River	Surface water		5,015	5,015	300–5,000					
	Tullahan River	Surface water		11,475	11,475	300–5,000					
	Meycauayan River	Surface water		57,665	57,665	300–5,000					
	Marikina River	Surface water	Sample collection: bucket Sample pretreatment: oven drying, wet peroxide oxidation method, density separation, filtering. Microplastic visualization: microscope, Raman spectroscopy.	485	485	75–5,000	Blue, black, red, white, yellow, green, orange, transparent	Fiber, fragment, film, foam, pellet	PP, TRWP, PS, LDPE, nylon	Residential and industrial activities	IGES (2022)
		Stormwater		19,022	19,022					Vehicle tire abrasion	
Thailand	Chao Phraya River Maeklong River	Surface water	Sample collection: container. Sample pretreatment: oxidation, filtering. Microplastic visualization: Raman spectroscopy.	400–2,400	140	50–1,000	Blue, red, yellow, green, transparent, white, black	Fiber, fragment	PE, PET, PP, PS, PVC	Disposal wastewater, illegal dumping of plastic wastes	Chanpiwat (2021)
Vietnam	Red River	Surface water	Sample collection: plankton net. Sample pretreatment: sieving, digestion, density separation, filtering. Microplastic visualization: microscope, FTIS.	2.3	2.3	80-~4,500	Not reported	Fiber, fragment	PE, PP, alkyd resin polyester, PO, PS, PA, additives	Residential activities, fishing, transportation	Strady *et al.* (2021)
	Nhue River	Surface water		93.7	93.7			Fiber, fragment		Residential activities, fishing, transportation	
	To Lich River	Surface water		2,533	2,533			Fiber, fragment		Residential activities	
	Saigon River	Surface water	Sample collection: bucket, plankton net. Sample pretreatment: digestion, density separation, filtering. Microplastic visualization: stereomicroscope, FTIS.	10–519,000	259,505	50–4,850	Blue, black, transparent, red, and others	Fiber, fragment	PET, PE, PP, PE-PP copolymer, rayon, PP-vistalon, viscose, acrylic	Textile and plastics industries, high macroplastic contamination	Lahens *et al.* (2018)

**Please see section (c) below for an explanation of size range.*

residential and industrial activities, including fabric washing from textile industries (Alam *et al.*, 2019), laundry (Alam *et al.*, 2019; IGES, 2022), intense fishing and tourism (IGES, 2022; Pariatamby *et al.*, 2020), household sewage (Hwi *et al.*, 2020), microplastic particles from tire and road wear (IGES, 2022), and disposal of wastewater, as well as the illegal dumping of plastic waste into the river.

c. Size

Size is considered one of the deciding factors in microplastic ingestion (Covernton *et al*., 2019). Organisms are more inclined to ingest what they view as smaller prey, such as microplastics, as their sizes closely resemble those of certain plankton (Cole *et al*., 2011; Wright *et al*., 2013).

Microplastic sizes reported in SEA studies range from 50 to 5,000 μm (Table 1), and significant variations are observed among these studies. These differences can be attributed, in part, to the collection methods used, including the size of the mesh. More specifically, whilst the upper size limit reported was the actual size of microplastics collected, the recorded lower size limit was often determined by the mesh size selection. There is also a lack of consistent categorization in terms of size, i.e., what size ranges are considered small, medium and large. For instance, Lestari *et al*. (2020) regarded small microplastics as those with a size of less than 1 mm, whereas the study by Chanpiwat & Damrongsiri (2021) considered a threshold of 300 μm. Such inconsistency hinders direct and accurate comparisons between studies, areas and countries.

d. Polymer type

The chemical composition of microplastics plays a vital role in pinpointing pollution sources (Wright *et al*., 2013). Plastic products are crafted from a variety of polymer types.

Types of polymers vary; the most frequently observed in SEA are polypropylene (PP) and polyethylene (PE) (Table 1). Both of these are low-density polymers, making them, regardless of their shape and size, buoyant and easily carried by water rather than likely to settle in sediments (Chanpiwat & Damrongsiri, 2021). They are the most commonly used and widely manufactured polymers globally (Zhang *et al*., 2018). PP is predominantly employed in the production of rigid plastic items and furnishings, including textile floor coverings and fishing equipment (Wang *et al*., 2018).

e. Color

While microplastic colors can be utilized as an indicator of potential pollution sources, the accuracy thereof can be questionable given that color tends to be unstable and susceptible to alterations caused by weathering and bleaching processes (Chanpiwat & Damrongsiri, 2021; Turner & Holmes, 2015). Colors are proven to be significant, however, when evaluating the potential accumulation of these particles in aquatic organisms. This is because such organisms may inadvertently ingest microplastic particles with coloration similar to that of their natural prey (Chanpiwat & Damrongsiri, 2021).

The colors of microplastics observed in SEA freshwater environments vary. They include blue, red, green, white, black, brown, transparent, yellow and purple, with blue and transparent being dominant (Table 1). In general, colored microplastics were more dominant in the region than non-colored microplastics. This suggests a significant ecological threat given that coloration renders microplastics more prone to ingestion by aquatic organisms (Lestari *et al*., 2020; O'Connor *et al*., 2020). Moreover, the colorants used to generate these colors contain chemical compounds that may be released into the environment through degradation processes, posing potential ecological and toxicological risks to aquatic organisms (Dimassi *et al*., 2022).

3.3. Removal Efficiencies of Microplastics in Wastewater Treatment Plants

The outflow (effluent) from wastewater treatment facilities has been recognized as a potential origin of microplastics in marine and freshwater ecosystems (Nguyen *et al*., 2023). Conventional WWTPs are not designed to treat small-sized plastic particles (Cristaldi *et al*., 2020; Tadsuwan & Babel, 2021). Since microplastics are lightweight, they can bypass the current treatment units through overflows and be released into receiving rivers or natural water bodies (Hongprasith *et al*., 2020). Nonetheless, recent research has demonstrated that these treatment plants play a substantial role in diminishing the presence of microplastics in the environment by extracting them from the inflowing waters (Chen *et al*., 2021).

Increasing efforts have been made to better understand and enhance the effectiveness of WWTPs in removing microplastics, which can be evaluated by calculating the percentage of microplastics removed by the end of the treatment process. Such efforts, however, are still limited in SEA; only a few studies assessed WWTPs' performance in microplastic removal (Table 2).

A WWTP in SEA typically consists of primary and secondary treatments; some also include preliminary and/or tertiary treatments (Table 2). Removals of microplastics were found to occur throughout these treatment processes, even though factors affecting such removal efficiency remain unclear (Le *et al*., 2023; Singh, 2022). The overall efficiency of microplastic removal in these plants varies; some achieved over 90% removal efficiency whereas others could remove less than half of the received microplastics. In Thailand, whilst Hongprasith *et al*. (2020) found secondary treatments played a much more significant role in removing microplastics in the surveyed WWTPs, Tadsuwan & Babel (2021) reported higher removal efficiency during the primary steps. Similar to Hongprasith *et al*. (2020), Le *et al*. (2023) observed that more microplastics were eliminated during the secondary than the primary

Table 2 Removal efficiencies of microplastics in wastewater treatment plants in SEA.

Country	Capacity (m^3/day)	Treatment processes	Microplastic concentration		Average removal efficiency	Reference
			Influent (particles /m^3)	Effluent (particles /m^3)		
Philippines	6,838	Primary: screening, removal of fats and oil, grease chamber, equalization tank. Secondary: activated sludge process, clarification tank, chlorination.	4,370	1,100	75%	World Bank (2021)
	520	Primary: screening, equalization tank. Secondary: activated sludge process, clarification tank, chlorination.	2,500	140	94%	
	10,400	Sequencing batch reactor (SBR) (operates in a batch mode and consists of several distinct phases, including filling, reacting, settling, decanting, idling).	1,000	200	80%	
	15,400	Primary: screening, removal of fats and oil, grease chamber, equalization tank. Secondary: activated sludge process, clarification tank, chlorination.	510	400	22%	
	567	SBR (operates in a batch mode and consists of several distinct phases, including filling, reacting, settling, decanting, idling).	3,860	760	80%	
	100,000	Primary: coarse and fine screening, grit and grease chamber, primary settler. Secondary: biotank, clarifier, chlorine contact tank, sludge treatment.	1,750	315	82%	IGES (2022)
Thailand	200,000	Primary: screening, grit chamber. Secondary: sequence batch activated sludge.	12,200	2,000	84%	Hongprasith *et al.* (2020)
	157,000	Primary: coarse and fine screening, grit trap. Secondary: aeration tanks, final clarifiers.	27	15	45%	Tadsuwan & Babel (2021)
Vietnam	17,000	Preliminary: coarse screen, grit chamber. Primary: oil and grease trap. Secondary: sequencing batch reactor, UV channel.	24,300	810	97%	Le *et al.* (2023)
	7,500	Preliminary: bar crack, grit chamber. Primary: Imhoff settling tank. Secondary: trickling filter, secondary clarifier. Tertiary: aerated lagoon, maturation pond, chlorine contactor.	125,250	140	100%	

processes in the four WWTPs they evaluated in Vietnam. The highest removal rate (99.9%) was observed in a WWTP making use of tertiary treatments (an aerated lagoon followed by a maturation pond) (Le *et al.*, 2023).

Several studies have recommended employing tertiary treatment technologies in addition to conventional treatment stages (Cristaldi *et al.*, 2020; Le *et al.*, 2023; Tang & Hadibarata, 2021). Suggested tertiary technologies include, but are not limited to, air flotation, electrocoagulation, membrane technologies, micromachines and advanced oxidation processes (Cristaldi *et al.*, 2020; Tang & Hadibarata, 2021). Since the characteristics of microplastics (abundance, morphology and nature) strongly influence the removal efficiency of the treatment processes (Yuan *et al.*, 2021), they should be fully taken into account when selecting removal technologies, along with other factors including environmental/health requirements, statutory requirements and cost efficiency (Sadia *et al.*, 2022).

3.4. Potential Impacts of Microplastic Pollution

Aquatic organisms exposed to microplastics exhibit five common responses, including reductions in consumption, growth, movement, reproduction and survival (Ma *et al.*, 2019). The extent of these effects can vary among different species. Through ingestion, chemical substances that are present in all plastic products, including styrene and toxic metals, are deposited in aquatic organisms and potentially further transferred, through a trophic food web, to humans (de Sá *et al.*, 2018).

There exist only two studies that have focused on organisms in SEA freshwater ecosystems. In one of them, Kasamesiri and Thaimuangphol (2020) investigated eight fish species and found that 72.9% of the collected fish were contaminated with microplastics, with a mean abundance of 1.76 particles per fish. The other study found an average abundance of 1.166 particles per milkfish (*Chanos chanos*) (Sembiring *et al.*, 2020). Neither of these studies addressed the impact of such contamination.

Even though further research is needed before the negative impacts of microplastics on human health can be fully understood, an increasing number of studies has confirmed such impacts (e.g., Bhuyan, 2022; Campanale *et al.*, 2020; Gallo *et al.*, 2018; WHO, 2022). Once ingested, microplastic particles can traverse the human digestive system and reach vital organs (Abeynayaka *et al.*, 2022). Given that microplastics contain various harmful substances, their effects on human health can be extensive and severe (Bhuyan, 2022; Campanale *et al.*, 2020; WHO, 2022). This encompasses inducing oxidative stress, cytotoxicity, neurotoxicity and immune system disruption, potentially leading to various diseases, including cancer, cardiovascular disease and diabetes (Bhuyan, 2022; Gallo *et al.*, 2018). No studies have been found in SEA that quantify the impacts of microplastic pollution on humans.

4. Discussion

Whilst increasing attention has been paid to microplastics in SEA, data on microplastic pollution, especially for freshwater environments, remain limited and unevenly provided among countries in this region. In Indonesia, Malaysia, Thailand, the Philippines and Vietnam, several studies addressing this type of pollution have been conducted in a variety of areas in the last five years. No such efforts, unfortunately, were observed in the remaining SEA countries, with hardly any data recorded in Brunei Darussalam, Myanmar, Cambodia, Timor-Leste, Laos and Singapore.

Based on the reported data, this study confirms microplastic pollution in freshwater environments as a prevalent issue in SEA. Among the 11 countries in this region, the Philippines and Vietnam appear to have the most contaminated rivers. The most common shapes of observed microplastic particles are fibers and fragments, indicating that secondary microplastics are the main pollutants. Since secondary microplastics are often generated from degradation of macroplastics (Chen *et al*., 2021; Lahens *et al*., 2018; Osorio *et al*., 2021; Strady *et al*., 2021), this finding signals a demand for more stringent methods of solid waste management.

Almost all studies have reported that residential activities play a significant part in microplastic contamination of fresh water. Given that SEA is still undergoing growth in its urban population, this signifies a need for aggressive policies and regulations designated for microplastic waste management.

Microplastic sizes reported in the existing studies vary, due mainly to the difference in sample collection methods, including the size of the mesh. This hampers accurate comparison between studied sites, making it challenging to identify areas of focus for intervention. Therefore, it is critical to develop a standardized method for microplastic sample collection.

The significant level of microplastic abundance in stormwater raises the alarm about the role that paved surfaces or traffic roads play in exacerbating microplastic pollution. Since there has been only one study evaluating stormwater, further efforts addressing this source are of great importance.

This study affirms the contribution of WWTPs in reducing the amounts of microplastics discharged into water bodies. What factors affect this contribution, and how, remains unclear. It is also worth mentioning that existing studies on microplastic control in wastewater treatment facilities have focused mainly on centralized WWTPs, which cover a limited portion of the populations in SEA. For instance, centralized WWTPs in Vietnam only respond to roughly 12.5% of the total domestic wastewater generation rate in urban areas (T.D. Nguyen, 2021). Evaluating decentralized WWTPs is therefore essential for a thorough understanding of microplastic removal efficiency of these facilities in this region. Future studies need to target these knowledge gaps and open the door to improved microplastic pollution treatment. Similarly, there remains a paucity of data on the impacts of this pollution on aquatic organisms and humans across SEA, highlighting the need for increased attention and research in this area.

5. Conclusion

SEA has experienced significant population and economic growth over the last ten years. Such growth, unfortunately, has given rise to a wide array of environmental issues, one of which is microplastic pollution, an emerging global concern. Limited attention has been paid to the issue of microplastic contamination in freshwater environments within this region, resulting in insufficient understanding. This study provides the most up-to-date review of the existing body of knowledge on this subject and consequently identifies knowledge gaps and necessary interventions. These interventions include the establishment of policies for microplastic management, the implementation of standardized sampling methods and a call for more research to address this form of pollution in freshwater ecosystems.

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