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Sources of Microplastic Contamination in PET Bottled Drinking Water: A Life Cycle Perspective

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Abstract. This essay explains how tiny plastic particles, called microplastics, get into bottled water. It starts with how plastic pellets used to make the bottles are often spilled into the ocean during shipping. Then, the process of manufacturing the bottles creates microplastic dust and fragments that would contaminate the water. The final steps of filling and capping the bottles, especially the act of screwing on the cap, are also major sources of these plastic particles. Storing and reusing plastic bottles makes the problem worse. Studies show that microplastics leak into the water from the bottle's inner walls, especially when bottles are reused multiple times or exposed to heat, such as in a hot car or microwave. This means that from the very beginning of making a plastic bottle to when we drink from it and reuse it, microplastics are constantly being released, creating a serious pollution problem.

Keywords: Microplastics, PET bottled water, Life cycle assessment, Nurdle pollution, Capping abrasion, Bottle reuse, Thermal degradation, Mechanical fragmentation, Recycling microplastics, Landfill leachate, Polyethylene terephthalate, Secondary microplastics, Cap-neck friction, Raman spectroscopy, Human exposure

1. Introduction

Known as one of the most pressing environmental and public health challenges of the 21st century, plastic pollution has emerged among the various forms of plastic wastes. Microplastics— [1] plastic particles smaller than 5 mm— have drawn particular concern due to their persistence, ability to infiltrate ecosystems, and potential toxicityto living organisms and humans [2,3]. The breakdown of larger plastics and direct release during manufacturing or product use are the two major sources of microplastics. Once released into the ecosystem, they can be ingested by wildlife, enter the food chain, and ultimately reach humans through multiple exposure pathways, including seafood [4,5], salt, air, and drinking water [6]. As plastic consumption continues to rise, single-use products, particularly bottled water, have become a major contributor to this problem.

Bottled water, widely marketed as a safe and convenient alternative to tap water, has become one of the fastest-growing beverage sectors globally. However, recent studies have detected significant concentrations of microplastics in bottled water [7] across multiple commercial brands and

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countries. A large percentage of these bottles are made from polyester plastic polyethylene terephthalate (PET) due to its excellent transparency, light weight [8], and strength. PET is a type of a thermoplastic produced by the polymerization of ethylene glycol (EG) and terephthalic acid (TA), forming long chains linked by ester functional groups [9]. These ester bonds are chemically reactive sites that make PET susceptible to degradation when exposed to environmental stressors mainly through hydrolysis, photodegradation, and thermo-oxidation [10]. Over time, this produces microplastic fragments and can release trace additives into the environment.

Current studies on PET bottles tend to focus narrowly on specific stages, such as chemical degradation or environmental impacts [11,12], often overlooking how microplastic contamination evolves across interconnected stages of a bottle's life span. To address this issue, researchers applied a more comprehensive method called Life Cycle Assessment (LCA) to evaluate environmental impacts across a product's entire lifespan, from material extraction to final disposal [13]. By identifying stages and processes that contribute the most to environmental harm, LCA supports more sustainable material and design choices. Applying LCA to PET water bottles is essential for understanding how microplastic pollution arises throughout their production, use, and disposal, enabling targeted strategies to reduce both particle release and associated chemical contamination.

In this work, we categorize contamination pathways into four key stages: (1) raw material and bottle manufacturing, where nurdles, additives, and mechanical abrasion can release particles; (2) packaging processes such as filling, capping, and shrink wrapping, where friction and heat can shed microplastics; (3) storage and handling, where temperature fluctuations, UV exposure, and physical stress accelerate PET degradation; and (4) end-of-life management, including both recycling and landfill disposal. In recycling, remelting and shredding can generate additional particles, while in landfills, prolonged weathering and leaching can release microplastics into surrounding soils and waterways.

We aim to support targeted mitigation strategies that outline distinct, stage-specific interventions tailored to each phase of the PET bottle life cycle. By addressing the unique contamination mechanisms at manufacturing, packaging, storage, and disposal or recycling, this review gives researchers and industry stakeholders actionable strategies to target microplastic release where it is most likely to occur.

2. Production

Nurdles are the second largest source [14] of primary microplastic pollution globally. With PET bottle production relying on these plastic pellets, large quantities are shipped by cargo ships across oceans. Each year, an estimated 230,000 tons [15] enter marine environments through unintentional spills, often from damaged or lost shipping containers [16]. The 2021 spill of roughly 1,680 tons [17] off the coast of Sri Lanka illustrates how a single shipping accident can release massive amounts of nurdles into the ocean. Once exposed to seawater, the salty and oxidative environment [18] accelerates surface weathering, causing the pellets to crack and fragment. Over time, this process breaks nurdles down into smaller particles that contribute directly to microplastic contamination.

Beyond large-scale transport spills, the manufacturing of PET bottles itself contributes to microplastic emissions through both chemical and mechanical pathways. During production, additives and plasticizers [19] such as stabilizers [20], slip agents, and colorants [21] are blended into PET resin to improve flexibility, durability, or aesthetics. However, chemical responses and effects may be generated by these additives that are usually low in molecular weight and not bound

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to the polymers [22]. They can migrate to the surface and create embrittlement or cracking [23], facilitating fragmentation into microplastics.

At the mechanical level, injection molding and blow molding—the core steps in bottle production—expose PET to high temperature, pressure, and shear forces. These conditions can induce polymer chain scission and oxidative degradation, reducing the structural integrity [24] of the final PET bottle. Surface imperfections that arise during molding, such as weld lines, flashing, or microvoids, can later serve as initiation sites for abrasion and delamination, releasing microplastic fragments into factory dust, wastewater, and the surrounding environment.

Importantly, cross-contamination within processing pipelines also introduces microplastics. Residual pellets or fragments from earlier production batches can accumulate in extrusion and molding equipment; over time, these residues break down under heat and shear, producing secondary microplastics.

In this way, PET manufacturing represents a chronic but under-recognized source of microplastic pollution, affecting the environment.

3. Packaging

The following stage that bottled water comes to is packaging. It typically involves three processes: filling, capping, and shrink-wrapping. Microplastics are likely to enter the water through all processes, but mostly during capping. Researchers reached this conclusion through different approaches:

In 2021, Weisser J. et al. [25] examined MP concentration in four bottling sites (A–D) in sequence during the early processes of bottled water treatment, from raw water to filled and capped bottles, finding the presence of MPs in every step of water bottling (Figure 1). Furthermore, a significant discrepancy in MP concentration was detected between “filled uncapped bottles” and “filled and capped bottles,” indicating that the capping process was likely to induce a significant amount of MPs released into the water. Indeed, compared to the third-to-last step (cleaned bottles), filled uncapped bottles even displayed less MP presence, suggesting that MPs in bottled water are not mainly from the filling process.

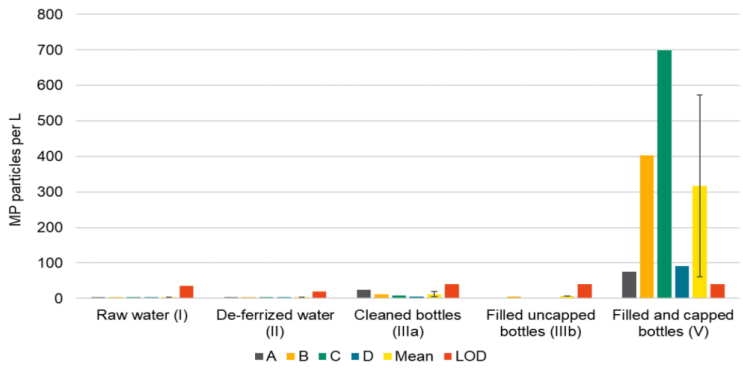

Figure 1. MP concentrations measured in four respective bottling sites, corresponding mean and LODs (limit of detection) for each sample type

In a 2019 study [26], Anna Winkler et al. investigated three different mineral water bottles (chosen by plastic thickness) and analyzed MP release on PET bottleneck surfaces and high-density polyethylene caps after numerous openings and closings, detecting a significant increase of MP occurrence, especially on caps. In addition, they applied mechanical stress to the body of bottles and

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found slight abrasion and an MP concentration increase compared to those of caps (Figure 2), implying that the inner wall is not as serious a source of MPs as the cap. Also, following the operations, they observed a great discrepancy in cap abrasion among the bottles, highlighting the difference in plastic behavior among brands.

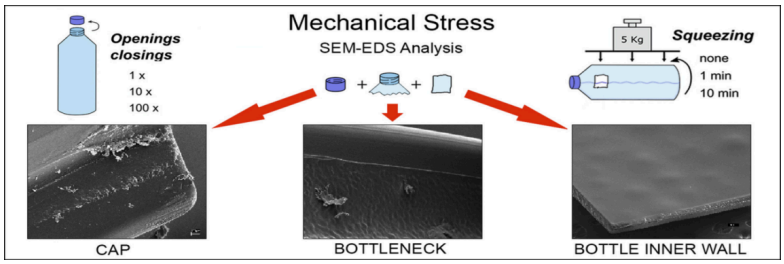

Figure 2. Observed abrasions on the cap, bottleneck and inner wall

In a 2023 study [27], Gambino et al. analyzed multiple PET bottles, rPET bottles, and glass bottles with their external labels removed through Raman spectroscopy and measured MP concentration (number of particles per liter) in the water. The results suggest that the bottle cap played a significant role in MP contamination. As can be seen from Figure 3, the bottle cap's spectrum closely resembled the spectra of the fragments detected in water. This result also suggests that the bottle cap is a likely source of the fragments released.

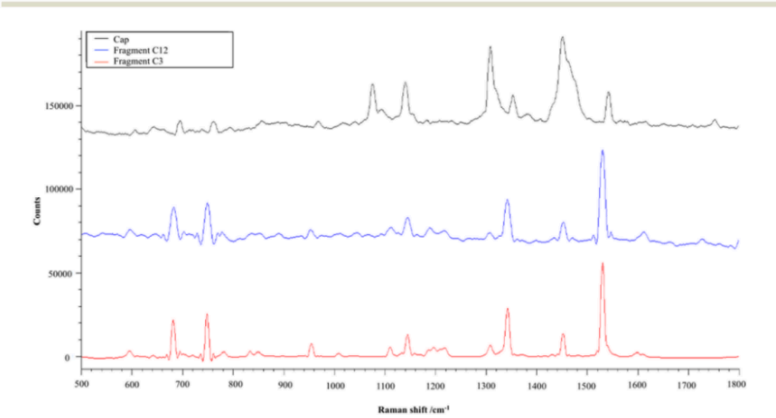

Figure 3. Raman Spectra of a bottle cap (black line) and two fragments found in water samples (blue and red lines)

Usually, bottled water comes across shrink-wrapping after being sealed; in turn, the chance for MPs to enter the water inside is relatively low. However, according to Sobhani et al. [28], MPs can be generated when we open plastic packaging such as tapes and caps through manual scissoring, tearing, cutting, or twisting. The graph below (Figure 4) shows that the mass of MPs rose significantly during the scissoring and tearing process, which suggests that MPs can be generated through artificial breaks of plastic films on the external surface of the bottle. We can infer that those MPs can accumulate and enter the water body when the cap is opened.

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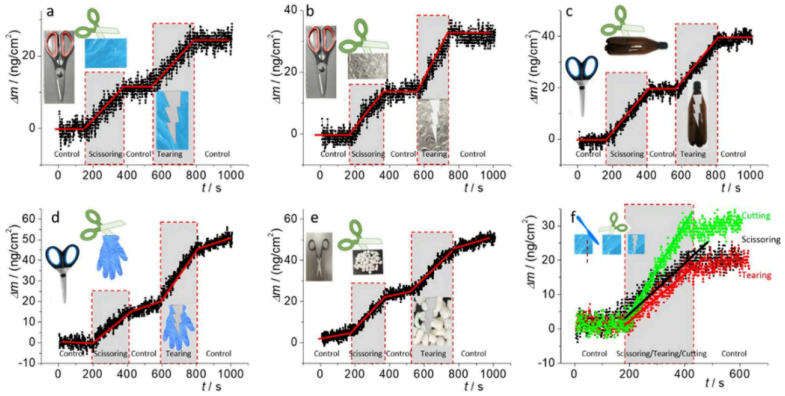

Figure 4. Mass change of MP monitored with quality control during scissoring, tearing, and cutting processes

4. Storage

In 2022 [29], scholars from university of Mosul, Iraq researched (topic)how tiny plastic particles, known as microplastics, detach from the bottle's interior and contaminate the water inside. The investigators specifically wanted to see if the way we store these bottles influences this process. To conduct this experiment, the researchers began by collecting 0.5-liter plastic water bottles from local markets in Mosul, Iraq, ensuring they were within their expiration date. These bottles were then separated into two groups for comparison: one group was carefully refilled with water that had been filtered to remove any pre-existing microplastics, which allowed the scientists to pinpoint new plastic particles coming solely from the bottle itself upon reuse. The second group was left as a control with its original bottled water to establish a baseline for comparison. Both of these groups were subsequently placed into three different storage environments to test several common real-world conditions: at room temperature in the shade (15–23°C), inside a refrigerator for cooling (4°C), and inside a freezer for freezing (–15°C). This process of reuse was repeated for each bottle up to 10 times over a time span of 30 days. Throughout the entire study, the team followed strict laboratory instructions—such as wearing special cotton coats and using sterilized equipment—to prevent any accidental contamination from the surrounding environment that could affect the results. Finally, to identify and count the microplastics, water samples were passed through extremely fine filters, and any captured particles were examined in detail under a microscope at high magnification. Then they got the results which showed a significant increase in microplastic concentration with repeated bottle reuse in all storage conditions. Under shade, the highest concentration reached 1050 particles per liter after the tenth reuse, compared to 120 particles per liter in single-use bottles. Under cooling, the maximum was 850 particles per liter, and under freezing, it was 648 particles per liter. The study observed that microplastic release became notably higher after the sixth reuse, showing structural degradation of the plastic bottles over time. The particles varied in form: fibers, fragments, flakes, and foam. These findings suggest that storage conditions and the reuse frequency strongly influence microplastic release, causing potential risks to human health and the environment.

In a 2022 study [30], researchers looked into how much microplastic comes out of everyday food and drink containers: like takeaway polystyrene boxes, polypropylene bowls, polyethylene bags, and reusable melamine bowls, under real-life conditions. They tested what happens when these containers are used with hot contents (like soups at 95°C) or cold drinks, reflecting how people actually use them in places like Southeast Asia. They also checked how washing affects microplastic release. Using methods like Nile Red staining and FTIR spectroscopy, the team found that all types

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of containers shed microplastics, anywhere from 10 to over 700 particles per litre. The results showed that hotter liquids and more washing led to more microplastic release. Interestingly, many of the plastic particles detected didn't match what the packaging claimed to be made of, which suggests labelling isn't always accurate. The study estimated that people that regularly eat takeouts could be swallowing up to 195,000 microplastic particles each year showing that food packaging is a significant and overlooked source of microplastics in our diets.

In a 2022 study [31], researchers investigated whether harmful chemicals can leak out of plastic water bottles and into the water we drink. The scientists were specifically interested in two types of plastic: polyethylene terephthalate (PET) which is used for most disposable water bottles, and polycarbonate (PC), which is often used for harder, reusable containers. The chemicals they tested for were phthalates which can come from PET, and bisphenol A which can come from PC, both of them were known as endocrine disruptors that can interfere with our hormones. To test this, the researchers stored water in many different PET and PC bottles under various conditions that mimic real life. Some bottles were left outside for a full year, others were left in a hot car, and some had boiling water poured into them or were heated in a microwave. Then they compared the water from these bottles to water from brand new, unused bottles. The results showed that the storage conditions make a big difference. Water in bottles that were left outside for a year had much higher levels of chemicals than the control group. And more bisphenol A and phthalates leak into the water when the bottles are heated, especially in microwaves. The conclusion is that while the levels of chemicals found were below official dangerous limits, they increased significantly under poor storage conditions [31].

5. Handling

Recycling is one of the most widely adopted methods of plastic bottle waste management; however, it poses significant challenges that can lead to microplastic generation. During the recycling process, there are two major stages that serve as the main sources of microplastic production.

5.1. Heat degradation during remelting

One frequent stage in recycling plastic is melting. Commonly used processes include gasification, pyrolysis, and other methods of valorization. Usually, these procedures are carried out under low pressure (1 atm) and high temperatures (300–1000 °C) [32].

Research has indicated that the heat decomposition of PET can result in the formation of microplastics. TGA and DTG analyses were employed in one such investigation to support this finding. The thermal degradation graphs in Figure 5 show the four different stages of PET disintegration. The breakdown of particular chemical fragments in the PET structure is correlated with each stage.

- The primary mass losses were due to the release of CO_2 and CO.
- In the second stage, losses were attributed to $C_2H_6O_2$ and C_2H_4O.
- In the third stage, C_4O_2 was released.
- In the final stage, losses were related to RCO–OR groups.

Furthermore, as the heating rate increased from 10 °C/min to 30 °C/min, the onset temperature of PET thermal degradation rose from 312 °C to 388 °C, indicating that higher heating rates lead to delayed but more rapid decomposition. At all these points, the residual mass of PET microplastics remained above 90%, suggesting that a significant portion of solid byproducts persisted—potentially in the form of microplastic fragments [33].

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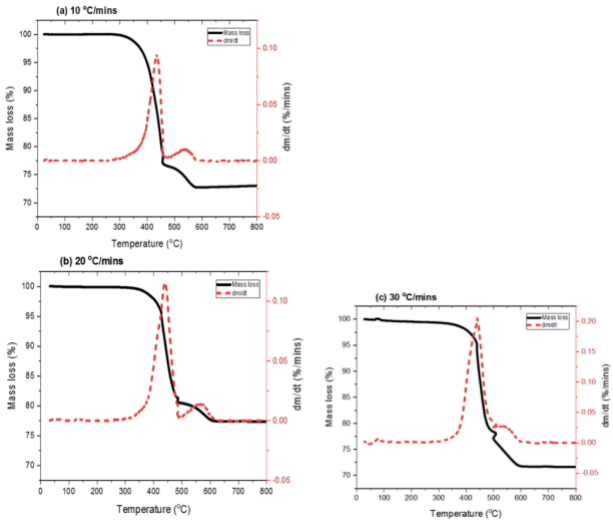

Figure 5. TGA and derivative thermogravimetric (DTG) thermogram of PET MPs at different heat-heating rates

5.2. Mechanical fragmentation during shredding

With PET and PE being the most often recycled materials, mechanical treatment is a well-liked method for both recycling and preparing solid plastic wastes for disposal. Plastics that can be used as fuels are separated from their recyclable components by mechanical treatment. Nevertheless, microplastics may be produced as a result of this process.

During mechanical-biological treatment (MBT) operations, a significant amount of microplastics has been discovered in the organic part of municipal solid waste, according to multiple scientific investigations [34]. Furthermore, studies carried out at plastic recycling plants have shown that between 14 and 5800 kg of microplastics are released into the environment annually.

In particular, plastic garbage that enters the facilities is sorted, cleaned, and shrunk in size. Impurities and pollutants are removed by washing the plastics after they have been shredded. According to a study, the wastewater released during washing releases microplastics into the environment, which are created during the shredding process.

The study employed a GP20 hybrid plastic shredder to replicate the real process that takes place during the recycling of plastic trash in order to calculate the quantity of microplastics produced during shredding. In accordance with ASTM D1921-01, a sieve analysis was carried out. The weight of the particles retained on each sieve was measured after shreds of plastic were run through a succession of sieves with sizes ranging from 6.7 mm to 0.106 mm. Moreover, using a high-resolution smartphone camera and the CountThis software, a particle count was performed using three particle size ranges: 0.212–0.500 mm, 0.500–0.850 mm, and 0.850–1.180 mm. The final microplastic loading rates were reported in two metrics: g/kg and particles/kg [35].

This experiment clearly mimics the conditions of industrial recycling and provides strong evidence that shredding is a significant contributor to microplastic release — both in the form of particles and through contaminated wastewater.

5.3. Landfill disposal

Landfill leachate generated from municipal solid waste disposal sites is a significant environmental pathway for microplastics to enter soils, surface water, and groundwater systems. From 1950 to

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2017, approximately 9.2 billion tonnes of plastic waste were produced, of which only about 25% was recycled. The remaining 75% was either disposed of in controlled or uncontrolled landfills.

Plastic waste buried in landfills is continuously affected by various environmental factors, including ultraviolet radiation, thermal cycling, microbial activity, and physical abrasion. These factors lead to the physical and chemical degradation of macroplastics, causing fragmentation into particles smaller than 5 mm, which are microplastics. In addition to primary microplastics already present in waste streams, secondary microplastics are generated over time through the ongoing breakdown of large plastic debris under favorable landfill conditions.

Another significant source of microplastic in landfill leachate is wastewater sludge, which may contain high concentrations of these particles. The leachate is a byproduct formed from waste decomposition and rainfall infiltration, which can carry microplastics into soil layers and water. This migration induced risks to both soil health and freshwater ecosystems due to the transportation of microplastics with other harmful substances [36].

A comprehensive review emphasized that landfills not only accumulate but also actively fragment and release microplastics into the environment [37]. In one study, leachate and groundwater samples were collected from various points along a transect extending upstream to downstream of a landfill in both March and June 2022. Microplastics larger than 25 μm were identified using micro-Fourier-transform infrared (μFTIR) imaging in transmission mode. All samples tested positive for microplastics, with concentrations range from 0.71 to 106.7 particles per liter. The data illustrated a trend of microplastic migration from leachate into alluvial groundwater systems. A total of 12 different polymer types were detected, with polyethylene (PE) and polypropylene (PP) being the most prevalent [38].

6. Conclusion

The method of Life Cycle Assessment (LCA) helps us to form a comprehensive view of the possible sources of MPs in bottled drinking water. Through LCA, we observed that microplastics in PET bottled drinking water tend to have originated from the entire life cycle of a plastic bottle: nurdles manufactured into bottles, bottles processed into bottled drinking water, and finally consumed and discarded.

The first stage of the cycle is production, including the water source and the production of PET bottles. At the very beginning, nurdles, also known as plastic pellets, are unintentionally spilled into marine environments, polluting the water at its source. Once exposed to seawater, the salty and oxidative environment accelerates surface weathering, breaking nurdles down into smaller particles. Additionally, during PET bottle production, injection molding subjects the bottles to high temperature, pressure, and shear forces, shedding some PET particles.

The next stage is packaging. In this process, capping is a major contributor to MP release, according to previous studies. This is due to the abrasion between the bottle neck and the cap, since both are threaded in appearance. The abrasion enables MPs to shed as well. Other subprocesses such as filling and shrink-wrapping are potential contributors, but their effects on MPs inside bottled drinking water are relatively minor compared to capping.

The following stage is the storage and handling of bottled drinking water. Studies have found that compared to unused ones, many more MPs are generated in containers that are first stored and then reused. In fact, all thermal storage conditions (room temperature, refrigerator cooling, and freezer freezing) release MP particles, and concentrations rise dramatically after the sixth reuse. In real-life scenarios, MP generation is moderate in PET bottles stored in a hot car. However, when bottles are

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exposed to heat, such as in microwaves or when boiling water is poured in, much higher contamination is detected.

Finally, there are typically three methods of handling PET bottles: melting, mechanical fragmentation, and landfill disposal. Each process is a potential contributor to microplastic release into the environment. As mentioned earlier, high temperature exposure and shear forces result in the shedding of MP particles. As such, melting and mechanical fragmentation, especially shredding, produce MPs that later enter the environment. In addition, landfill seems to combine several mechanisms: photodegradation, thermal oxidation, and wastewater discharge occurring simultaneously.

In conclusion, capping during the packaging of bottled drinking water produces the strongest MP contamination inside bottles, while recycling and landfill disposal during handling pose the greatest negative impact on the environment. In the future, we can try to identify possible leverage points at any stage of the life cycle of bottled drinking water that can reduce heat exposure, shredding, abrasion, and chemical reactions that shed MPs.

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