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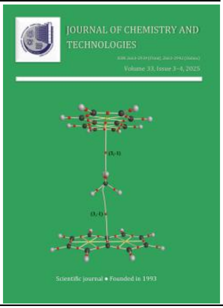

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COMPARATIVE ASSESSMENT OF MICRO- AND NANOPLASTIC RELEASE FROM POLYPROPYLENE AND POLYCARBONATE BOTTLES UNDER SIMULATED USE CONDITIONS

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Abstract

This study provides a comprehensive comparison of polypropylene (PP) and polycarbonate (PC) bottles with respect to their chemical and mechanical stability under simulated conditions of routine consumer use, including thermal and chemical stress. The release of micro- and nanoplastics was systematically evaluated using dynamic light scattering (DLS) and scanning electron microscopy (SEM). SEM analysis revealed noticeable surface degradation, microcrack formation, and material fatigue, particularly in PP samples, indicating progressive structural deterioration. DLS measurements confirmed the presence of a broad particle size distribution ranging from 3.6 to 3777 nm, with high polydispersity indices (PDI > 0.7), reflecting heterogeneous particle release. Overall, PP exhibited a higher tendency to release micro- and nanoplastics, which is attributed to its lower thermal resistance and reduced chemical stability compared to PC. However, an environmental impact assessment using the AGREEMIP framework showed that PP has a comparatively lower overall environmental footprint. In contrast, PC presents higher potential health and environmental risks, primarily due to the possible release of toxic monomers and the hazardous reagents involved in its synthesis.

Keywords: Microplastic; Distribution; Degradation; Polypropylene; Polycarbonate.

ПОРІВНЯЛЬНА ОЦІНКА МІГРАЦІЇ МІКРО- І НАНОПЛАСТИКОВИХ ЧАСТИНОК З ПОЛІМЕРНИХ ПЛЯШОК У ЗМОДЕЛЬОВАНИХ ЕКСПЛУАТАЦІЙНИХ УМОВАХ

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Анотація

У дослідженні порівнювали поліпропіленові (PP) та полікарбонатні (PC) пляшки щодо їх механічної та хімічної стійкості під час імітації умов використання. Вивільнення мікро- та нанопластикових частинок виявляли за допомогою динамічного розсіювання світла (DLS) та сканувальної електронної мікроскопії (SEM). SEM показала відмінності у морфології та ознаки деградації обох типів пластику. PP виявився менш стабільним і вивільняв більше частинок, ніж PC, особливо через нижчу хімічну та термічну стійкість. Аналіз DLS показав високий полідисперсний індекс (PDI > 0.7), що свідчить про широкий розподіл частинок за розміром (від 3.6 до 3777 нм). Застосування інструменту AGREEMIP дозволило оцінити екологічність складу матеріалів. PP має нижчий вплив на довкілля завдяки відсутності токсичних розчинників та високій стабільності при повторному використанні. Натомість PC, хоч і більш довговічний, має вищу екологічну загрозу.

Ключові слова: мікропластик; розподіл; деградація; поліпропілен; полікарбонат.

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Introduction

Various types of chemical additives are used in polymer materials to improve their properties, enhance performance, and meet regulatory requirements. These additives are designed to accomplish certain performance objectives, such as strengthening stability, increasing mechanical qualities, or making sure that materials satisfy safety standards for interaction with food and other delicate applications [1–5]. Children's bottles for food and water storage are a crucial category of goods with diverse applications and high safety standards. These bottles are essential for infants and young children, serving as reliable tools for feeding, hydration, and nutritional needs. Made from a variety of materials such as plastic, glass, or silicone, these bottles must meet strict safety regulations to ensure they are free from harmful substances, durable, and easy to clean. The materials used in children's bottles are chosen for their chemical stability and resistance to high temperatures, as they are frequently subjected to heating, sterilization, and even mechanical wear from brushing. However, because they are often made from polymers, careful attention is required to prevent the migration of potentially hazardous substances or the release of microplastics, especially when subjected to repeated use and washing [6–7]. The list of chemical additives used in the chemical technology of obtaining polymers for their further use in the production of children's polymer products is given in the table 1 [8–10].

Beyond safety, children's bottles are designed with practical features, like leak-proof lids, ergonomic shapes, and age-appropriate sizes. Their widespread use spans from infant formula bottles to water bottles for school-aged children, making them an essential product for caregivers and parents worldwide. Ensuring the safety and quality of these bottles remains a priority, as they are directly linked to the health and well-being of children. Children's bottles for food and water storage are typically made from a range of polymers chosen for their durability, safety, and ease of processing.

The polypropylene (PP), polyethylene (PE), polycarbonate (PC), Tritan™ copolyester, silicone, polyamide (PA, Nylon), polylactic acid (PLA) are the main types of polymers commonly used (Fig. 1) [11–12].

Table 1

A list of the main classes of chemical additives used in manufacturing of children's bottles for food and water storage

Class of Additives	Purpose	Examples	Applications
Plasticizers	Increase flexibility, reduce brittleness, and improve processability	Phthalates (e.g., DEHP), adipates, citrates	Soft polymers like PVC, packaging, baby products
Stabilizers	Prevent degradation due to heat, UV light, and oxidation, extending material lifespan	Benzotriazoles, HALS (light stabilizers), calcium-zinc stabilizers	Polymers for outdoor use, automotive parts, containers exposed to heat
Antioxidants	Protect polymers from oxidation during processing and in-service life	Phenolic antioxidants, phosphites, thioethers	Food packaging, preventing material breakdown and contamination

Polypropylene is used most often because it is light, highly resistant to heat and chemicals, and strong. This polymer is used especially often for baby bottles and food storage containers because it does not contain harmful chemicals such as Bisphenol A (BPA). It is also microwave safe and can withstand frequent sterilization. The polyethylene (PE) products, namely based on high-density polyethylene (HDPE) are often used in caps and other bottle components. Low-density polyethylene (LDPE) is occasionally used for softer bottle parts or squeezable bottle designs. Polycarbonate was widely used in baby bottles and food containers due to its clarity and strength. However, concerns about BPA leaching from polycarbonate have led to its decline in use, with many manufacturers now opting for BPA-free alternatives. However, data on the chemical and mechanical stability of such products are few and limited. Studying the composition of chemicals and particles that migrate from polymer baby food, PC baby bottles, non-PC baby bottles is of critical importance, especially as these containers are exposed to a variety of conditions during everyday use [13–15].

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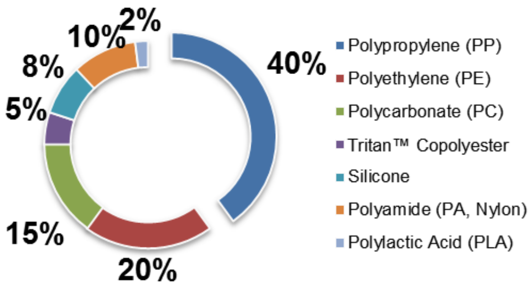

Fig. 1. The main types of polymers commonly used on the production children's bottles for food and water storage

Beyond simple exposure to food or liquid contents, bottles frequently undergo mechanical wear due to cleaning practices such as brushing. This physical abrasion introduces additional pathways for contamination: not only can chemicals embedded within the polymer migrate into the contents, but nanoparticles and microplastics from the bottle material itself may also disperse into the liquid. Repeated cleaning of polymer containers (milk bottles, water bottles) can increase the emission of these particles, raising concerns about accidental ingestion by infants [20–22].

The authors [23] in a paper used targeted screening techniques to examine 79 multilayer plastic baby food pouches for the migration of bisphenols and phthalic acid esters (PAEs), as well as other chemicals, including non-intentionally added substances (NIAS). On the other hand, the mechanical and chemical stability of children's bottles for food and water storage after pouring water/milk mixture into them or solutions imitating the liquids, exposure to these solutions during the time, and next mechanical cleaning of the inner surface when using a brush have never been reported. Many industries in Ukraine produce children's bottles for food and water storage with different colours, shapes, sizes, and formats with different polymeric materials. Ukraine's manufacturers are increasingly adhering to stringent testing for chemical migration, particularly in baby bottles and food storage containers. This shift ensures that products meet health and safety guidelines, crucial for parents who are looking for safer, certified products for their children. Ukraine has a modest local polymer manufacturing industry, which covers only part of the demand for high-quality food-grade polymers. For advanced polymer materials like Tritan™, silicone, and BPA-free alternatives, many businesses rely on imports from the EU, Turkey, and other regions. However, import logistics have become more challenging due to economic and geopolitical issues. Very few studies have been done yet to determine the contamination of microplastic in children's bottles for food and water storage investigated brands of Ukraine and imported goods from Europe. In Ukraine, the Technical Regulation of Materials and Items in Contact with Food (CMU Resolution No. 105 of January 13, 2016) establishes requirements for materials that come into contact with food, including plastic from which baby bottles, food containers, and water bottles are made). The regulation defines the permissible standards for the migration of chemicals from materials into food and controls their safety. Ukraine also adopted the law "On materials and objects intended for contact with food products". This complex legislative act contains elements from several legislative acts of the European Union (EU) regarding materials and objects that come into contact with food products. In connection with the war, polymer containers, such as water bottles and special bottles for baby feeding, are increasingly used in Ukraine, since during periods of prolonged air raids people are forced to stock up for several hours. After relatively long storage, namely longer than it would be in peacetime, more thorough washing with brushes is often carried out.

The problem of micro- and nanoplastics entering the environment and living organisms is becoming increasingly important due to the widespread use of polymer packaging, in particular reusable plastic bottles. Under the influence of mechanical friction, ultraviolet radiation and temperature fluctuations, polymeric materials degrade, releasing microparticles into the environment. The greatest concern is invisible nanoplastics, which easily penetrate biological systems.

Until now, most research has focused on the study of disposable polyethylene terephthalate

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(PET) bottles, while reusable polypropylene (PP) and polycarbonate (PC) bottles have remained less studied. At the same time, they are widely used in everyday life, sports and for baby food.

Such particle release, coupled with the migration of potentially hazardous chemicals, creates a dual exposure scenario. While EU and other regulatory guidelines address chemical migration under standard conditions, there is less clarity on the impact of mechanical stress on plastic containers used repeatedly over long periods. Given the vulnerability of infants to contaminants and the critical developmental stages they undergo, understanding these migration patterns and the effects of mechanical wear is essential. This research thus seeks to uncover the extent and nature of migration and dispersion under both passive and active use conditions, ultimately contributing to safer material design and improved regulatory standards for baby food bottles and other contact materials.

This study is one of the first to combine structural analysis (SEM), particle release assessment (DLS), and eco-assessment of the material composition using AGREEMP, which allows not only to determine the level of degradation, but also to assess the environmental safety of the material from the perspective of green chemical design.

Materials and methods

Studying the release of microplastics from bottles requires a comprehensive approach that encompasses both experimental and predictive (theoretical) methods

Preparation of test sample

Representative samples of bottles made from polymers such as polypropylene (PP), polycarbonate (PC) are selected. To ensure a consistent test environment, the bottles were washed and sterilized prior to testing to remove any potential contaminants (Fig. 2.).

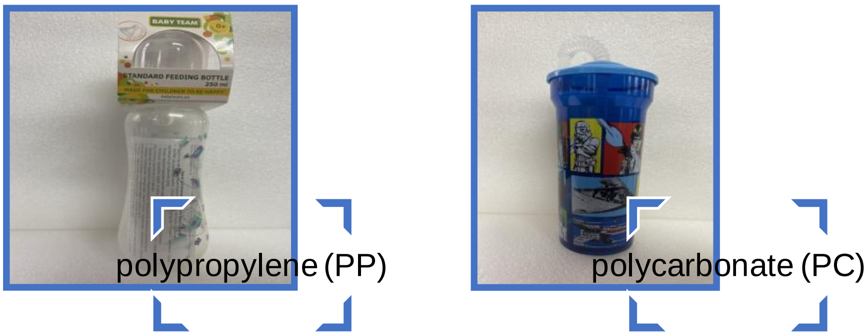

Fig. 2. Images of the polypropylene (PP) (Trademark BABY TEAM) and polycarbonate (PC) (TM "Polissya" (PP Polissya, Kobrin metro station)) bottles that were studied

Simulated Mechanical Impact

Standards include migration testing after mechanical wear, like brushing [25]. This is particularly important since repeated washing can alter the surface properties of the bottle, potentially increasing the migration of chemicals or releasing microplastics. Mechanical impacts such as scrubbing or brushing can erode the polymer surface, resulting in microplastic particles, which are small fragments of plastic typically less than 5 millimetres in size (Fig. 3). To determine the release of microplastic particles from the inner surface of baby bottles after simulated mechanical wear was carried out SEM analyses. The bottle's interior was subjected to a brushing procedure to simulate the mechanical impact of washing. A hard brush typically used for bottle cleaning was selected to mimic everyday was used. The test water with temperatures (45 °C) to replicate real washing conditions was used. After cleaning, water was filled into the bottles and left for 24 hours until the next wash. The 25 washing cycles were carried out, after which surface studies were carried out.

After each cleaning process and soaking in a container of water, this liquid was drained into a container and, after 25 washing cycles, was analyzed by DLS.

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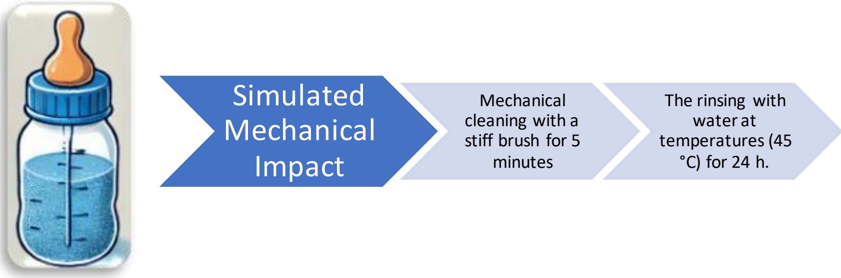


Fig. 3. Graphical representation of the experimental approach

Scanning electronic microscopy analysis

The SEM analysis to compare the surface morphologies and micro-structures change surface after mechanical cleaning of the inner surface when using a brush and water has been used. A Tescan Vegall XMU SEM instrument was used to obtain SEM images. In the second variant, the water solution evaporated to dryness, which remained at the bottom of the container after intensive cleaning with a brush, was analysed [26–27; 35].

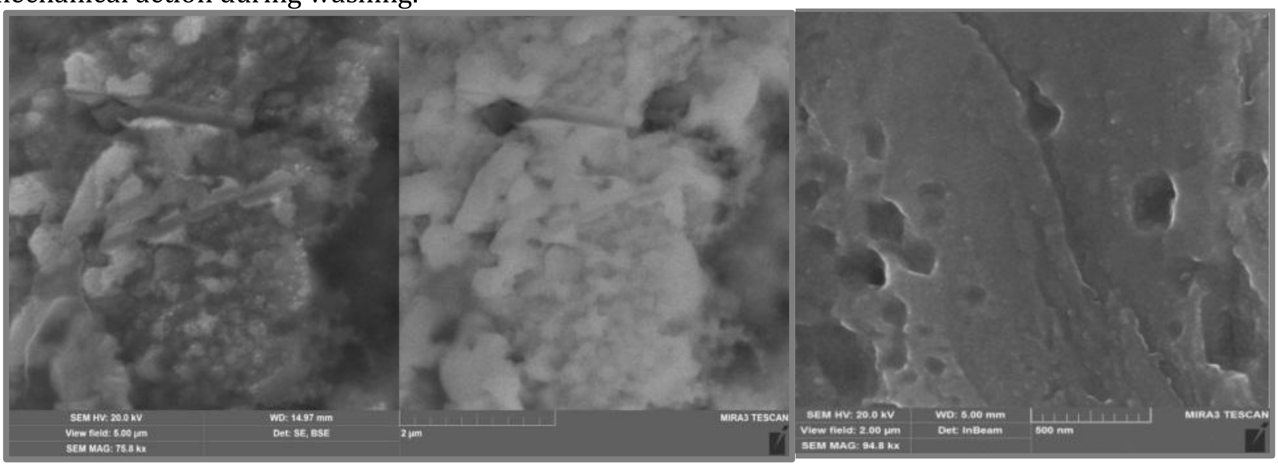
Microplastic extraction and analysis

After the test procedure (as described in section 2.2), were analyzed using a Malvern Nano ZS Zetasizer laser diffractometer. The diffractometer measurements are based on the principle of dynamic light scattering (DLS) and make it possible to accurately determine the particle size in the range from nanometers to hundreds of micrometers. The particle size distribution and the number of particles were recorded. This quantitative assessment helped to determine the degree of microplastic migration. The second part of the experiment involved obtaining the particle size distribution and measuring the average particle size in water that was poured into the containers after simulated mechanical action during washing.

Results

Scanning electron microscopy (SEM) of the polymeric materials polypropylene (PP) and polycarbonate (PC) bottles after simulated tests simulating mechanical wear

To observe the surface morphology and the change in the material microstructure and the surface morphology of the bottles after mechanical brushing of the inner surface, a Tescan Vega 3 scanning electron microscope (SEM) was used to obtain SEM images (Figure 4). This SEM image shows the surface morphology of the polymer bottle after mechanical brushing. The surface appears uneven and damaged, with visible pores, cracks and roughness. On the surface of the Polypropylene (PP) materials being examined, uneven pores, porosity, as well as large and small holes can be seen. The presence of pits and voids suggests that the brushing process abraded the surface, potentially removing polymer layers. The image resolution highlights the microstructural features with a magnification of 37.9 kX, indicating significant surface changes due to the combined effects of migration and mechanical cleaning [25–27].



Polycarbonate (PC)

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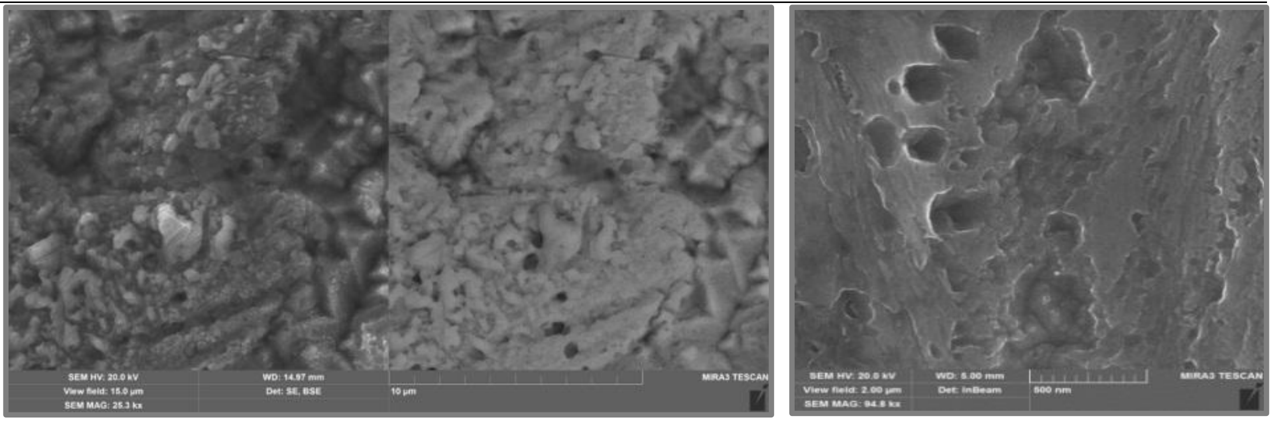


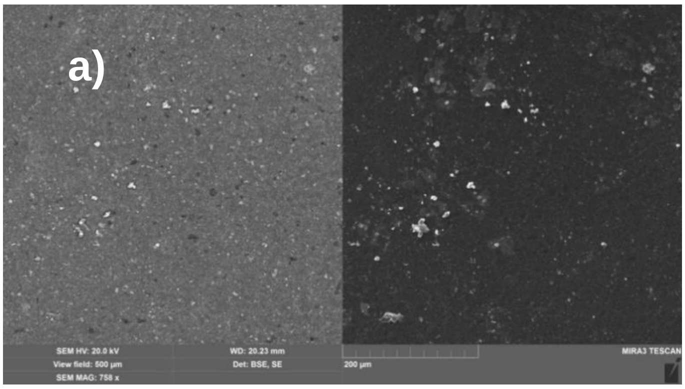
Polypropylene (PP)

Fig. 4. SEM micrographs showing the erosion of the polypropylene (PP) (a) and polycarbonate (PC) bottles (b) after simulated tests simulating mechanical wear

Morphological analysis of the surface of MPs

Fig. 5 shows the analysis and investigation of the surface morphology of MPs using SEM [35]. The analysis of the evaporated residue of the aqueous solution collected from the bottom of the tank after mechanical brushing and adding water indicates the presence of microplastics of various morphologies, including irregular fragments, spherical particles, and fibrous structures. The SEM images demonstrate that the mechanical treatment of plastic containers results in the formation of particles with heterogeneous surface textures and irregular shapes. Polypropylene (PP) particles exhibit a predominantly fragmented and lamellar morphology (Fig. 5). Polycarbonate (PC) microplastics appear smoother, more compact, and have rounded edges. The surface of PC fragments has fewer deformation marks and appears denser compared to PP. This morphology is consistent with the amorphous structure and higher hardness of PC, which provides better scratch resistance and results in the delamination of smaller, more uniform fragments. At higher magnification, random jagged edges resulting from localized brittle fracture can be observed.

Dynamic light scattering (DLS) was used to establish the size distribution of micro- and nanoplastics. The size distribution of polymer microparticles in water obtained from different types of plastic containers, polypropylene (PP) and polycarbonate (PC), shows a noticeable difference (Fig. 6). It was found that the particles of micro- and nanoplastics differ and are in the micrometer range [17–18; 29]. This size differentiation provides crucial information about the heterogeneity of plastic particles present in the sample, contributing to a better understanding of their potential environmental and biological impacts. For polypropylene, the typical particle size is in the range of 1–100 µm, and particles with sizes characteristic of nanoplastics (<1 µm) are also found. The broad size distribution indicates that PP is more susceptible to the formation of both large microparticles and smaller fragments during mechanical processing, whereas PC tends to generate more angular microstructures due to its higher brittleness and rigidity.



Polycarbonate (PC)

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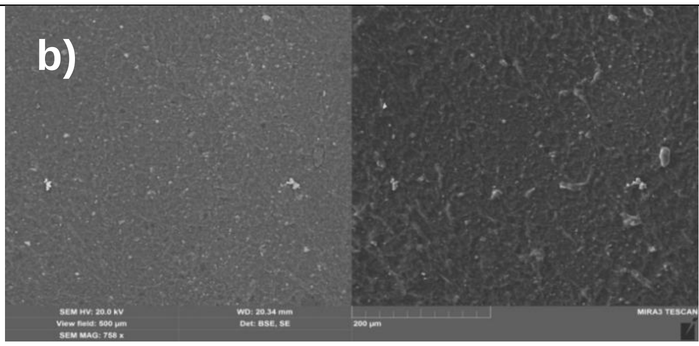
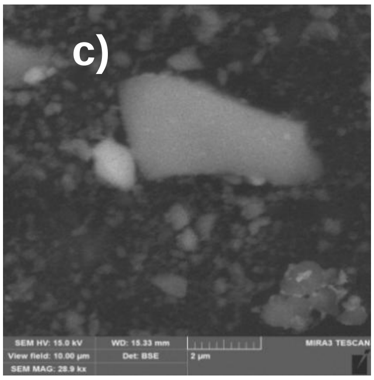
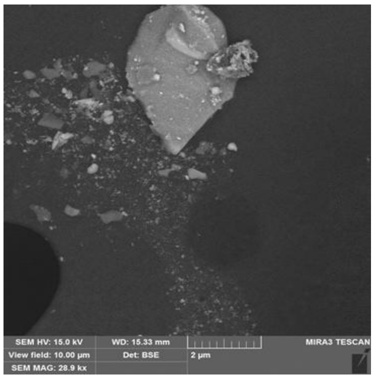


Polypropylene (PP)



Polycarbonate (PC)



Polypropylene (PP)

Fig. 5. SEM analysis of micro plastics that was identified in the evaporated-to-dry aqueous solution remaining at the bottom of the container after intensive cleaning of two types of bottles: a-b 200 µm and c 2µm

Particle size analysis using Dynamic Light Scattering (DLS) of micro- and nanoplast in solvent

The polycarbonate (PC) microplastics that migrated into water exhibited a more regular and smoother surface morphology compared to polypropylene (PP) particles. This can be attributed to the higher hardness and brittleness of PC, which results in the formation of fragments with cleaner edges and less surface deformation under mechanical action. The main fraction of PC-derived particles was found to be in the range of 0.1–10 µm. Analysis of the particle size distribution revealed a narrower range for PC, indicating its higher resistance to abrasive wear and the generation of fewer fine fragments compared to PP (Fig. 6–7). Dynamic light scattering (DLS) analysis of the aqueous solution obtained after mechanical cleaning of a polycarbonate (PC) bottle with a brush and subsequent storage of water in it for 72 hours confirmed the predominance of microplastic particles within the submicron range.

The polydispersity value is 0.734, indicating a fairly high polydispersity, which indicates a significant spread in particle sizes. It is generally accepted that if PDI < 0.1, this indicates a narrow distribution (mono-disperse system), and here it is more than 0.7, which means that both large and small particles are present in the solution simultaneously. Analysis of the volume distribution peaks shows that there are three peaks, namely Peak 1: 999.4 nm (20.4 % of the volume), indicating a main particle size of almost 1 µm. Peak 2: 108.0 nm (17.57 %) and Peak 3: 3.6 nm (almost negligible), which are inherent to traces of small particles or impurities. The hydrodynamic diameter Z-Average value is 1753 nm and this is a rather large average particle size, indicating the presence of large clusters. The polydispersity index is 0.537, indicating a high polydispersity of the system (broad particle size distribution) (Fig. 7). The bulk of the particles are concentrated in the range of 1000–5000 nm. There is a pronounced large peak near 3777 nm, indicating particle clusters. Peak 1 at 391.8 nm (9.5 % vol) is characteristic of smaller particles, possibly single. Peak 2 at 3777 nm (9.5 %) is characteristic of larger particles.

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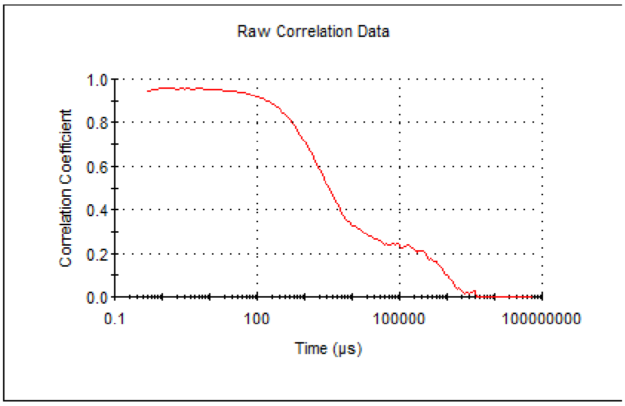
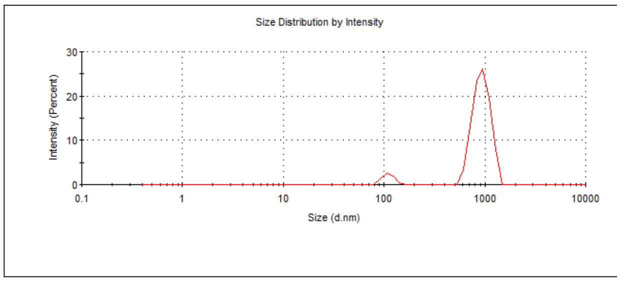
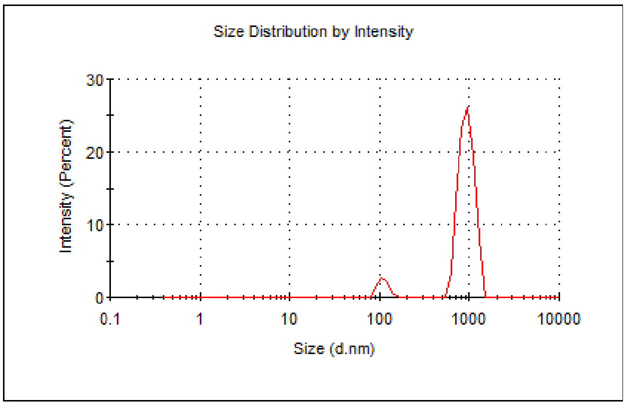


Temperature (°C):	25,0	Duration Used (s):	70
Count Rate (kcps):	131,2	Measurement Position (mm):	4,65
Cell Description:	Disposable sizing cuvette	Attenuator:	4

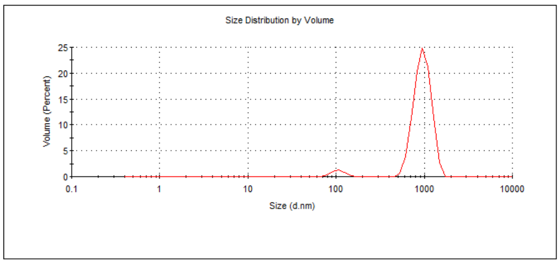
			Size (d.nm):	% Intensity:	St Dev (d.nm):
Z-Average (d.nm):	1619	Peak 1:	935,4	93,6	174,1
PdI:	0,734	Peak 2:	110,1	6,4	13,86
Intercept:	0,852	Peak 3:	0,000	0,0	0,000





Temperature (°C):	25,0	Duration Used (s):	70
Count Rate (kcps):	131,2	Measurement Position (mm):	4,65
Cell Description:	Disposable sizing cuvette	Attenuator:	4

			Size (d.nm):	% Volume:	St Dev (d.nm):
Z-Average (d.nm):	1619	Peak 1:	969,4	96,4	204,4
PdI:	0,734	Peak 2:	108,0	3,6	17,67
Intercept:	0,852	Peak 3:	0,000	0,0	0,000



Polycarbonate (PC) bottle

Fig. 6. DLS analysis of the aqueous solution was obtained after mechanical cleaning of the Polycarbonate (PC) bottle with a brush and subsequent storage of the water in it for 300 hours

The evaluation the greenness of Polycarbonate (PC) and Polypropylene (PP) bottles by uses analytical tool AGREEMIP

The assessment can be performed using user-friendly open-source software, freely downloadable from mostwiedzy.pl/agreemip (Fig. 8, Table 2-5) [30].

Criterion 1: Removal of Polymerization Inhibitors

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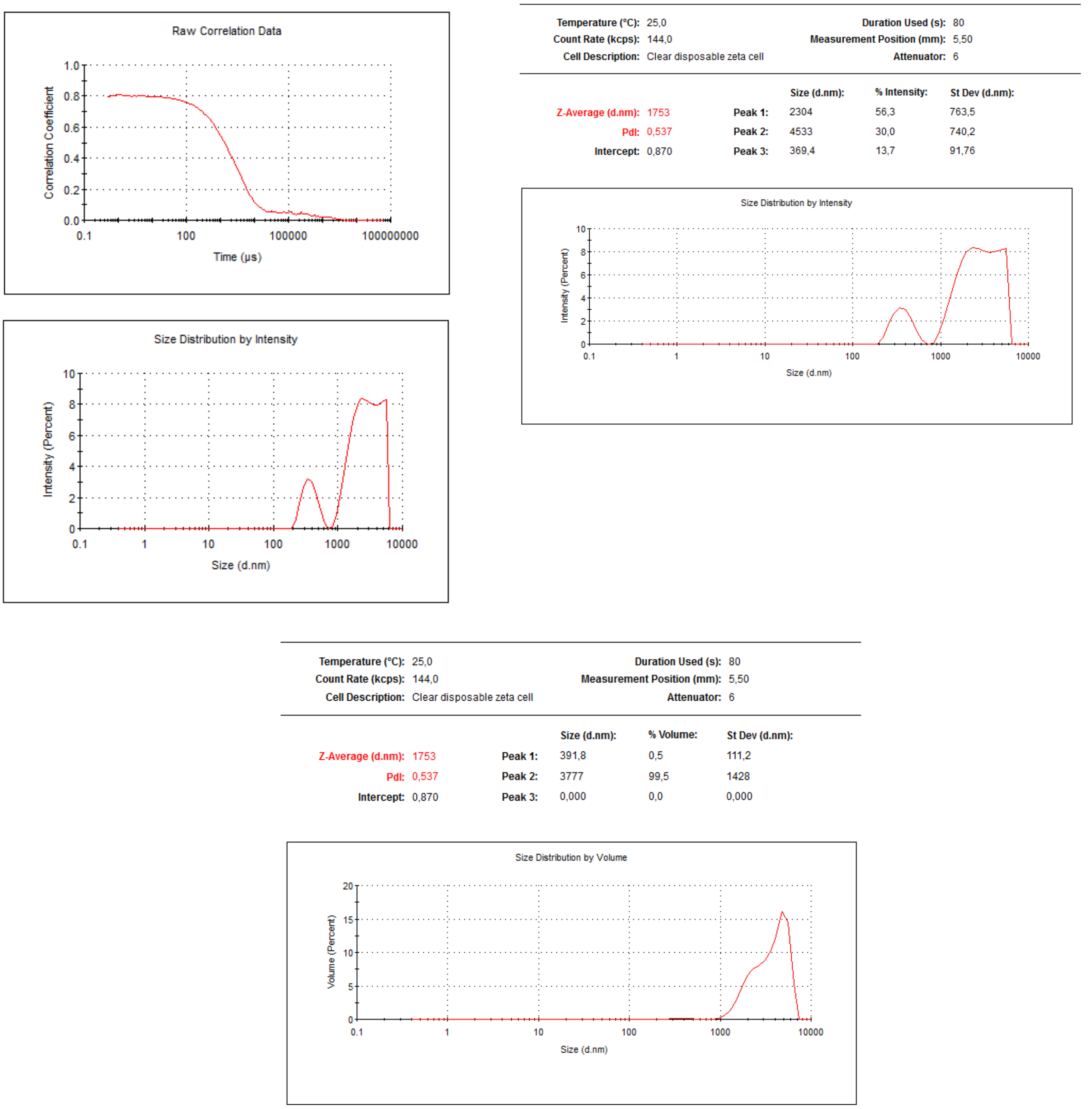

Polypropylene (PP) bottle

Fig. 7. DLS analysis of the aqueous solution was obtained after mechanical cleaning of the Polypropylene (PP) bottle with a brush and subsequent storage of the water in it for 300 hours

Polycarbonate (PC) synthesis is typically carried out by phosgene or transesterification with bisphenol A (BPA) (Table 2). Inhibitors (e.g. hydroquinone derivatives) are commonly used to prevent premature polymerization. Removal is typically achieved by solvent extraction, distillation, or washing, which may involve toxic solvents (e.g. chlorinated solvents).

Polypropylene (PP) is synthesized by Ziegler-Natta or metallocene catalysis. Polymerization inhibitors are typically not required due to the controlled catalytic process. The system is designed to minimize inhibitor-free side reactions, and cleanup is typically limited to catalyst removal.

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Polycarbonate (PC) Bottle **Polypropylene (PP) Bottle**

Fig. 8. The evaluation the greenness of Polycarbonate (PC) and Polypropylene (PP) bottles by uses analytical tool AGREEMIP

Table 2

Comparative Criterion 1

Polymer	Use of Inhibitors	Need for Removal	Removal Method
Polycarbonate (PC)	Yes (e.g., hydroquinone)	Yes	Solvent extraction, distillation
Polypropylene (PP)	No	No	Not required

Criteria 2–7: Functional Monomer, Template, Cross-Linking Agent, Porogen/Solvent, Other Reagents/Adjuvants/Carriers, Core/Particle Preparation, and Surface Modification

To assess the environmental friendliness of polycarbonate (PC) and polypropylene (PP) bottles using the AGREEMIP criteria (in particular, criteria 2–7), each stage of their synthesis and functional use was analyzed based on the principles of environmental chemistry, focusing on the main criteria (Table 3, Fig. 10).

Table 3

Criteria 2–7

Criterion	Polycarbonate (PC)	Hazard statement (H)	Polypropylene (PP)	Hazard statement (H)
2. Functional Monomer	BPA (toxic)	Functional Monomer — BPA (Bisphenol A) Hazard statements: H361, H319, H315, H302 H361 – Suspected of damaging fertility or the unborn child H319 – Causes serious eye irritation H315 – Causes skin irritation H302 – Harmful if swallowed	Propylene (fossil-based)	Propylene Hazard: H220 – Extremely flammable gas
3. Template	Not used	-	Not used	-
4. Cross-Linking Agent	None used	-	None used	-
5. Porogen/Solvent	Chlorinated solvents	Dichloromethane (DCM): H351 – Suspected of causing cancer H319, H315	Solventless/ bulk	-
6. Other Reagents/Carriers	Phosgene (or alt.)	Phosgene (in conventional synthesis): H330 H331, H314 Very hazardous Diphenyl carbonate — a safer alternative with fewer penalties.	Ziegler–Natta catalysts	Ziegler–Natta Catalysts ($TiCl_4$ + AlR_3) TiCl4: H314 – Causes severe skin burns and eye damage H331 – Toxic if inhaled.
7. Core / Surface Modification	Not used		Not used	

The criteria considered were functional monomers, Template, Crosslinking agent, Porogen/solvent, other reagents/adjuvants/ carriers, Core/particle preparation, Surface modification. Polypropylene (PP) demonstrates greater environmental friendliness across most of AGREEMIP Criteria 2–7 due to solvent-free synthesis, simpler catalytic systems, and the absence of toxic monomers or crosslinkers (Fig. 10). Polycarbonate (PC) has lower environmental friendliness due to the use of toxic monomers (BPA), hazardous reagents (phosgene), and the use of solvents. The figure 6 shows a radar chart that visually compares Polycarbonate (PC) and

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Polypropylene (PP) according to AGREEMIP criteria 2–7. The red zone (PC) shows high risks, especially for criteria 2 (BPA) and 6 (Phosgene/Diphenyl carbonate). The green zone (PP) is much smaller, indicating lower toxicity and better environmental performance (Fig. 9).

Criterion 9: Polymer particle size assesses the environmental and health impacts of the final size of polymer particles, with smaller sizes (especially nano- and microplastics) being of greater concern due to their persistence, mobility and potential toxicity (Table 5). Typical particle size after degradation or wear: often in the microplastic range (1–1000 μm), especially under environmental stress (UV, heat, friction). There is currently a wealth of literature demonstrating the presence of PC microplastics in water and soil. PC fragments have been shown to leach bisphenol A (BPA), a known endocrine disruptor. Polypropylene (PP) also forms microplastics, but to a lesser extent than PC due to its better stability and slower degradation. However, PP particles are hydrophobic and can adsorb pollutants, but do not usually leach harmful monomers [31–34].

Table 4

AGREEMIP Criteria 9 Evaluation

Polymer	Particle Size Risk	Notes
PC	Microplastics + BPA leaching	Higher risk due to degradation & leachables
PP	Microplastics only	Lower risk, chemically inert

Criterion 12: Final Product Reusability

This criterion evaluates how many times a polymer product can be reused before disposal, degradation, or loss of functionality. It considers mechanical durability, chemical stability, and retention of safety/performance over repeated use. PC bottles are often reusable and durable (used in reusable water bottles, labware, baby bottles). Mechanically strong and resistant to impact and heat. However, repeated use (especially at high temperature) can lead to leaching of BPA, especially when exposed to hot liquids or microwave heating [19–20]. Reusability is compromised by chemical safety issues. Degradation over time can pose health risks. PP bottles and containers are highly reusable, with excellent chemical resistance and thermal stability. Safe under repeated dishwashing, microwave heating, and mechanical stress. No harmful monomer leaching, making it suitable for food contact applications.

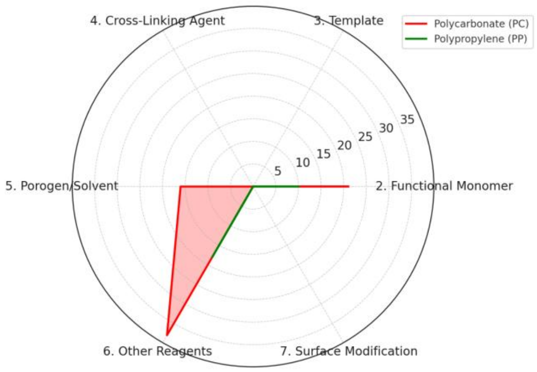

Fig. 9. Radar chart that visually compares Polycarbonate (PC) and Polypropylene (PP) according to AGREEMIP criteria 2–7

Criterion 10: Template Elution Solvent

This criterion assesses the greenness and hazard profile of any solvent used to remove a template or clean the polymer surface (Table 5). Even if no template is used, any solvent used in post-treatment or purification is considered here. In PC production (especially lab or fine-grade processes), organic solvents like acetone, methanol, or dichloromethane (DCM) may be used for purification or surface treatment. PP synthesis does not involve template elution. Post-treatment (if any) is usually mechanical or involves water washing.

Criterion 11: Template Elution Technique

This criterion assesses the environmental impact and safety of the technique used to remove the template or clean the polymer surface, focusing on energy consumption, operational safety, and waste generation. In PC-related polymer work or MIP (Molecularly Imprinted Polymer) applications, thermal treatment, solvent extraction, or ultrasound-assisted elution may be used. These often involve high-temperature treatment or hazardous solvents, contributing to the environmental load. Thus, solvent-intensive methods generate toxic waste. Also, energy-

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demanding processes (e.g., Soxhlet extraction, reflux) are common. PP manufacturing generally does not require any template elution technique. The process is template-free and relies on thermal polymerization or extrusion, with no post-synthesis cleaning.

Table 5

AGREEMIP Criteria 10 Evaluation

Polymer	Template Elution Solvent	Hazard statement (H)	Hazard Example
PC	Acetone, Methanol, DCM	Acetone: H225 (Highly flammable, 5 pts), H319 (Eye irritation, 3 pts) Methanol: H225, H301 (Toxic if swallowed, 8 pts), H370 (Causes damage to organs, 10 pts) DCM: H351 (Carcinogenic, 10 pts), H319 (Eye irritation, 3 pts).	Flammable, toxic, carcinogenic
PP	None or water	-	-

Conclusions

Polypropylene (PP) has been found to release micro- and nanoplastics faster and in larger quantities than polycarbonate (PC) and polypropylene has lower chemical and thermal stability, making it more susceptible to degradation under conditions of use, such as mechanical stress in the process of exposure. In contrast, PC is more resistant to degradation due to its higher molecular weight and stronger chemical structure. However, the exact rate of release of micro- and nanoplastics depends on the specific environmental conditions and influencing factors.

Microplastics from PP bottles were found to have a larger range of particle sizes and a higher total concentration of micro- and nanoplastics due to the higher susceptibility of polypropylene to abrasion. Microplastics from PC bottles, on the other hand, showed a smaller average particle size and a narrower distribution because polycarbonate is less brittle. The PP bottle shows a significantly higher proportion of large nanoparticles (~3777 nm), while the PC bottle has a dominant peak at ~970 nm. The polydispersity index (PDI) of the PC sample is higher (0.734), indicating a broader particle distribution, compared to the PP sample (0.537). The PP sample has a much larger second peak (~3777 nm), which may indicate aggregation or the presence of large particles.

SEM analysis showed that the shape of polycarbonate particles is smoother and rounder, while that of polypropylene is fragmented and lamellar. This difference in morphology is related to the mechanical properties of the materials.

Polypropylene (PP) has a significantly lower environmental and health hazard score than Polycarbonate (PC). The absence of highly toxic reagents such as phosgene and BPA in PP synthesis makes it the greener option, especially when evaluated using AGREEMIP. Polypropylene (PP) bottles demonstrate significantly better greenness performance compared to Polycarbonate (PC) when evaluated under the AGREEMIP criteria.

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