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STUDIA ECOLOGIAE ET BIOETHICAE

20/4 (2022)

STUDIA ECOLOGIAE ET BIOETHICAE

2022, 20, 4: 51-61
p-ISSN 1733-1218; e-ISSN 2719-826X
DOI: http://doi.org/10.21697/seb.2022.29

Microplastic in the Soil Environment – Classification and Sources in Relation to Research Conducted in Poland

Mikroplastik w środowisku glebowym – klasyfikacja oraz źródła w odniesieniu do badań przeprowadzonych w Polsce

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Received: 09 Nov, 2022; Revised: 22 Dec, 2022; Accepted: 28 Dec, 2022

Abstract: In less than a century, plastics have gained enormous popularity and it is now difficult for us to imagine our lives without them. They are very widely used in industry, agriculture, medicine and many others, mainly due to their stability and low production costs – which contribute to a steady increase in demand worldwide. They biodegrade very slowly, and the limited and inappropriate recovery of this raw material from waste has led to a visible accumulation of residual polymers in the environment. As a result of physical, chemical and biological processes, e.g., ultraviolet (UV) radiation, weathering or mechanical abrasion, plastics degrade to fine particles – those less than 5 mm in size are called microplastics. They can be found in the natural environment in various morphological forms, e.g., as fibres, granules, scraps, spheres, particles or fragments, e.g., film, of primary or secondary origin. The presence of microplastics has been found all over the world, in all environments. Only recently has there been a broader focus on microplastics, which includes terrestrial systems where soils are an important part of the environment potentially exposed to contamination. Their main source in soils may be within agriculture (where composts, organic fertilizers, sewage sludge and mulching, as well as irrigation are used) plus transport, landfills and the deposition of atmospheric pollutants.

Keywords: polymers, microplastics, soils, Poland

Streszczenie: W ciągu niespełna wieku tworzywa sztuczne zyskały ogromną popularność i obecnie trudno jest nam wyobrazić sobie nasze życie bez nich. Są one bardzo powszechnie wykorzystywane w przemyśle, rolnictwie, medycynie i wielu innych, głównie ze względu na stabilność i niskie koszty produkcji – co wpływa na systematyczny wzrost zapotrzebowania na całym świecie. Ulegają bardzo powolnej biodegradacji, a ograniczone i niewłaściwe odzyskiwanie tego surowca z odpadów doprowadziło do widocznego nagromadzenia resztek polimerów w środowisku. W wyniku procesów fizycznych, chemicznych i biologicznych np. promieniowania ultrafioletowego (UV), wietrzenia czy ścierania mechanicznego tworzywa sztuczne ulegają degradacji do drobnych cząstek – te, których rozmiar nie przekracza wielkości 5 mm nazywane są mikroplastikami. Występują w środowisku w różnych formach morfologicznych, np. w postaci włókien, granulek, skrawków, kulek, drobin czy fragmentów np. folii, pochodzenia pierwotnego lub wtórnego. Obecność mikroplastiku stwierdzono na całym świecie, we wszystkich elementach środowiska. Dopiero niedawno zaczęto szerzej interesować się mikroplastikiem obejmującym systemy lądowe, w których gleby stanowią ważny element środowiska potencjalnie narażony na zanieczyszczenie. Głównym ich źródłem w glebach może być rolnictwo (gdzie stosowane są komposty, nawozy organiczne, osady ściekowe oraz mulczowanie, nawadnianie) oraz komunikacja, składowiska odpadów i depozycja zanieczyszczeń atmosferycznych.

Słowa kluczowe: tworzywa sztuczne, mikroplastik, gleby, Polska

Introduction

Plastics are very widespread and used on a daily basis in households. They are also very commonly used in industry, agriculture, medicine and many others, mainly due to their stability and low production costs – which contributes to a systematic increase in demand all over the world (Yu et al. 2022, 1; Yang et al. 2021, 2; Geyer, Jambeck and Law 2017, 1). In 2020, total global plastic production was approximately 367 million tonnes. These were mainly thermoplastics, polyurethanes, thermosets, elastomers, adhesives, coatings and sealants, and PP fibres (the data does not include PET, PA and polyacrylic fibres) (PlasticsEurope.org. 2021, 12). The main producer of plastics is China (as much as 32%, which gives 117.44 million tons), while about 55.05 million tons of plastics was produced in Europe – which constitutes 15% (Fig. 1).

Packaging and construction are the two largest segments of plastic applications. Production for the automotive industry is in third place. The remaining are used, among others, in agriculture and in the production of machinery and equipment, in medicine, production of household appliances and many other segments (PlasticsEurope.org. 2021, 20).

In Poland, plastic consumption was estimated at 3.4 million tons in 2020. The main areas of plastic use in Poland are packaging production (34%), construction (19%) and automotive industry (8.8%) (Fig. 2; PlasticsEurope.org 2022, 11).

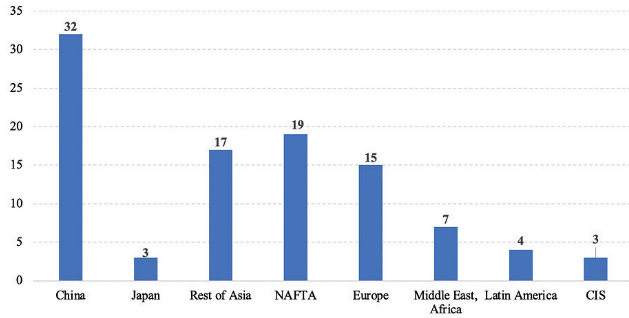
In 2020, 29.5 million tonnes of plastics waste were collected in the EU27+3, which slightly differs from 2018, when 29.1 million tonnes were collected. In 2020, 46% of plastic packaging waste was sent for recycling. The remaining 54% went to energy recovery or landfill, which means there is still a lot of work to be done in this area. However, the trend is positive with more than twice as much plastic waste going for recycling in 2020 as in 2006 (PlasticsEurope.org 2022a, 20).

In contrast, 1.9 million tonnes of plastic waste were collected in Poland in 2018. Between 2006 and 2018, the amount of waste going for recycling increased by 2.7 times, energy recovery increased by 115 times and landfilling decreased by 21%. (PlasticsEurope.org 2020, 48).

Plastics biodegrade very slowly, and the limited and inappropriate recovery of this raw material waste has led to a visible accumulation of polymer residues in the environment.

1. Definition and classification

Plastics that are less than 5 mm in size are called microplastics (Mattsson et al. 2018, 2; Arthur, Baker and Bamford 2009, 9). They can be of primary or secondary origin. This classification is based on the size of plastic particles getting into the environment – primary microplastics are plastic that get into the environment, and secondary ones are larger plastic fragments that degrade in the environment to microplastics. Primary microplastics are produced in the form of microbeads, which are used, for example, in cosmetics (Cole, Lindeque and Halsband 2011, 2589). They include industrial scrubbers, plastic powders, micro-beads in household goods such as toothpaste and face wash, cosmetics etc. Secondary microplastics are derived from larger plastic fragments that have been degraded and decomposed into fine particles as a result of long-term physical, chemical and biological factors, e.g., ultraviolet (UV) radiation, weathering or



NAFTA – North American Free Trade Agreement (United States, Canada, Mexico), CIS – Commonwealth of Independent States (Armenia, Azerbaijan, Belarus, Kazakhstan, Kyrgyzstan, Moldova, Tajikistan, Turkmenistan, Uzbekistan, Russia)

Figure 1. World production of plastics in 2020 [%] (own study based on PlasticsEurope.org. 2021, 13)

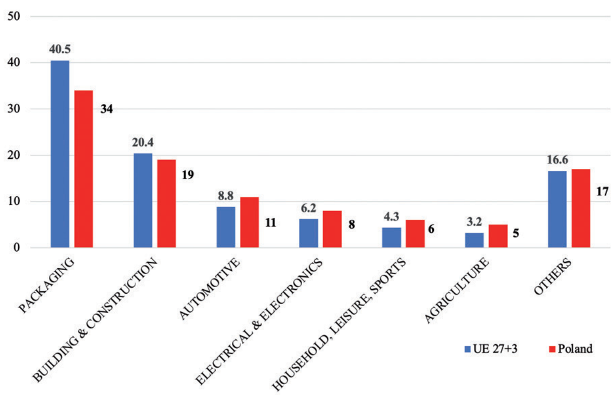


Figure 2. Converters plastics demand by segments in 2020 [%] (own study based on PlasticsEurope.org 2022, 11; PlasticsEurope.org. 2021, 20)

mechanical abrasion (Kim et al. 2020, 301; Dehaut, Hermabessiere and Duflos 2019, 346; Andrady 2017, 17; GESAMP 2016, 8; Arthur, Baker and Bamford 2009, 10; Rilling 2012, 6453). It is worth noticing, that there are bacterial strains capable of degrading plastics. Many studies have been conducted in this direction. They indicated biodegradation of PS by, among others, *Azotobacter bei-jerinckii*, *Xanthomonas sp.*, *Sphingobacterium sp.*, *Rhodococcus rubber Exiguobacterium sp.* strain YT2, *Pseudomonas sp.* and *Acinetobacter* (Nakamiya et al. 1997; Mor and Sivan 2008; Kundungal 2021; Lou 2021). Fungi involved in PS decomposition include *Aspergillus terreus*, *Rhizopus oryzae*, *Phanerochaete chrysosporium*, *Aspergillus niger* (Kundungal et al. 2021). In contrast, *Enterobacter sp.* and *Aspergillus flavus* may be involved in PE degradation (Ren et al. 2019; Zhang et. al. 2020a; Lou et al. 2021).

Microplastics can have a variety of forms and complex chemical compositions. They exist in the environment, e.g., in the form of fibres, granules, trimmings, beads, particles or fragments such as films (Guo et al. 2020, 1). They have high hydrophobicity and relatively stable properties that allow them to exist in the environment for a long time (Yu et al. 2022, 2). The most popular groups in the total production of plastics in the EU27 + 3 in 2020 included, among others, polypropylene (PP), low-density polyethylene and linear low-density polyethylene (LDPE, LLDPE), high-density polyethylene and medium-density polyethylene (HDPE, MDPE), polyvinylchloride (PVC), polyethylene terephthalate (PET), polyurietanes (PUR), polystyrene (PS), expanded polystyrene (EPS) and other plastics (Fig. 3).

It is worth noting that almost all polymers are produced in Poland, e.g., polyvinyl chloride (PVC – Anwil), polyolefins (HDPE, LDPE, PP – Basell Orlen Polyolefins), polystyrenes (PS – Synthos), polyethylene terephthalate (PET – Indorama), as well as some engineering plastics, e.g., polyamides, polyester and epoxy resins (Grupa Azoty, Sarzyna Chemical, Lerg, PCC Rokita). However, the volume of domestic production does not fully meet the needs, so a significant part of the demand is imported (PlasticsEurope 2022, 10).

Plastics are used in the production of, among others:

- PP – food packaging, microwave containers, pipes, car parts, etc.
- LDPE, LLDPE – reusable bags, foil for food packaging, containers, etc.
- HDPE, MDPE – toys, bottles, household items, etc. PVC – floor coverings, wall coverings, cable insulation, garden hoses etc.
- PET – bottles, e.g., for water, juices, cleaning agents, etc.
- PUR – pillows and mattresses, foam insulation for refrigerators, etc.
- PS, EPS – glasses frames, food packaging, e.g., dairy products, etc. Other plastics – other thermosetting plastics, e.g., phenolic resins and others Other thermoplastics – roofing materials (PC), optical fibres (PBT), touch screens (PMMA) and many others (PlasticsEurope.org 2021, 22).

The presence of microplastics (as an emerging pollutant) has been found worldwide, in all elements of the environment (e.g., fresh and saline waters, soils), in food, the human body and even in polar ecosystems (Ivar do Sul and Costa 2014; Free et al. 2014; Curren et al. 2020; Guo et al. 2020; Ragusa et al. 2021; Obbard et al. 2014). Its occurrence has also been confirmed in drinking water (Oßmann 2021, 48). This has been pointed out in legal regulations, e.g., imposing the obligation to monitor the quality of water intended for human consumption (Dyrektywa 2020/2184/UE, art. 13).

Microplastic pollution in the aquatic environment, especially the ocean environment, has attracted the most public and scientific interest. Quite surprisingly, microplastics in soils have been largely overlooked. A German scientist Matthias Rillig (2012) was one of the first in the world to draw attention to microplastics in soils. Only recently has

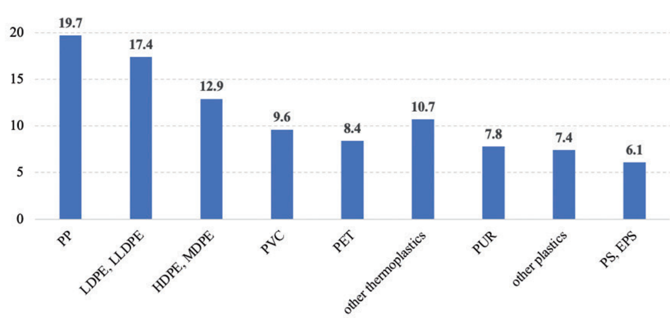


Figure 3. Demand for various plastics in the EU27 + 3 in 2020 [%] (own study based on PlasticsEurope.org 2021, 22)

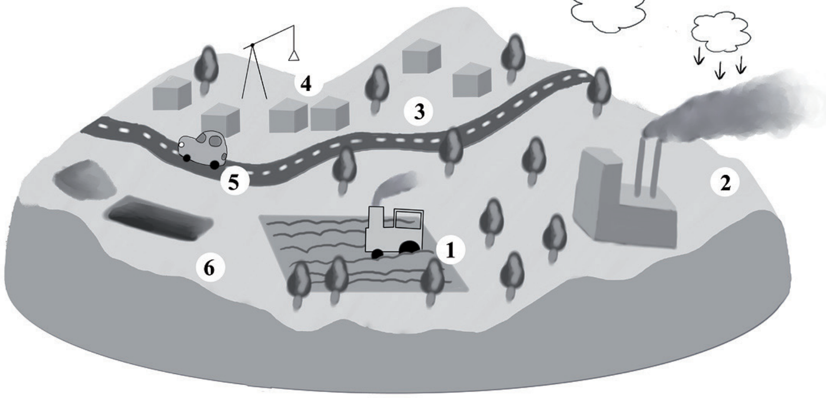
there been a wider interest in microplastics involving terrestrial systems, where soils are an important element potentially exposed to contamination. It is soils that are hugely important in understanding the distribution of plastics in the environment (Piehl et al. 2018, 7).

2. Sources

Microplastics can enter the soil environment from many sources (Fig. 4).

The extensive use of plastic products is associated with the production of a significant amount of waste. Improper handling leads to the accumulation of plastic microbeads in the environment (as previously written about). Landfills, urban and industrial centres can contribute to the introduction of plastic microbeads directly into the environment. Individual plastic bags or bottles left around agricultural fields have been confirmed to be a source of microplastics in soils. Similarly, mulch film (composed of PVC and PE) is widely used in global agricultural production (Yang et al. 2021, 11). Removing it from the surface of agricultural fields is labour-intensive and takes a lot of time, so often (intentionally or unintentionally) significant parts of it remain in the fields. As a result of external factors (e.g., freezing and thawing, UV radiation) and other field works, they are further fragmented (Piehl et al. 2018, 6).

The use of sewage sludge can also lead to microplastic accumulation in soils (Yang et al. 2021, 13; Crossman et al. 2020, 2). The wastewater treatment process itself removes almost 99% of microplastics – which is very beneficial especially for the aquatic environment. However, it should be borne in mind that microplastics accumulate in sewage sludge, which, due to its high organic matter and trace element content, is often used as fertiliser (Corradini et al. 2019, 412). Sewage sludge can also contain toxic and harmful substances such as heavy metals, organic compounds, antibiotics, pathogenic bacteria and parasite eggs (Yu et al. 2021, 4). Another very important source of micropollutants in soils is compost (compost products). Composting is a process that plays an important role in the treatment of biodegradable waste (Slater and Frederickson 2001). Compost products and sludge are a source of nutrients, trace elements and humus and are therefore very often used in agriculture to improve the physical and chemical properties of soils. It is an ecological method of agricultural production, which unfortunately carries the risk of soil contamination with microplastics (Bläsing and Amelung 2018, 427).



1 – sewage sludge, compost, plastic mulching, irrigation; 2 – atmospheric deposition; 3 – littering; 4 – construction site; 5 – tire abrasion; 6 – waste deposal

Figure 4. Main sources of microplastic in soils

One of the most important ways in which microplastics enter soils is through atmospheric transmission. Wind, snowfall and atmospheric conditions play a significant role here (Zhang et al. 2020, 2). Recent studies show that atmospheric transport of microplastics can reach remote areas (up to 95 km) without any local source (Allen et al. 2019, 341). Wind-transported traces of microplastics have even been identified on the Vatnajökull ice sheet in Iceland (Stefánsson et al. 2021, 9).

As a result of climate change, water scarcity is noticed in many parts of the world and it is necessary to irrigate agricultural land with, for example, treated (or partially treated) sewage. This is another way for microplastics to enter the soil environment (Yu et al. 2021, 4). The main sources of microplastics in wastewater are personal care products and detergents. It is estimated that, for example, in China, personal care products can release about 39 tons of microplastics into the environment (Lei et al. 2017, 4). Farmlands can also be flooded by rivers that transport and deposit plastic fragments of various sizes on the soil (de Souza et al. 2018, 1407).

In addition, industrial activities, municipal activities, construction, car tyre abrasion, run-off from asphalt roads and many others are also sources of microplastics (Bläsing and Amelung 2018, 430).

In Poland, preliminary studies are conducted on the sources and occurrence of microplastics in various environments. In the research conducted by Polish scientists, attention was mainly paid to the presence of microplastics in the aquatic environment. Unfortunately, there are not many publications on this issue, especially with regard to the soil environment. Perhaps the main reason is the lack of standardization in measuring methods and further monitoring of microplastics in both soils and other parts of the environment. It can be assumed that the sources of soil contamination with microplastics are comparable to those considered when assessing other environments (e.g., water). Jarosz et al. (2022) points out that microplastics tend to aggregate in soils, waters and sediments, which confirms the assumption (Jarosz et al. 2022, 11).

Analysing the level of microplastic contamination in the Vistula, it was concluded that its sources could include deposition from atmospheric air deposition or runoff from processing plants and wastewater treatment plants. The authors explained that it was difficult (at this stage of the research) to precisely define other sources of these pollutants (Sekudewicz, Dąbrowska and Syczewski 2020). Piskuła and Astel (2022) also identified treated wastewater as a key source of microplastics in the aquatic environment. By examining the content of microplastics in the rivers Słupia and Łupawa in the northern part of Poland, they found the presence of polymers containing mainly polyethylene, polyvinyl chloride, polypropylene, polyester and polystyrene (Piskuła and Astel 2022, 180).

Pollution of lakes with microplastics has also been studied in Poland (lake waters and sediments were analyzed). For example, significant amounts of microplastics were observed in some places around the Ełk Lake, especially on beaches with highly urbanized shoreline and recreational areas. Various sources of these have been identified ranging from surface runoff from urbanized areas to tourism, transportation and agriculture. Potential pollution of agricultural origin is mainly associated with surface runoff from agricultural areas. In the case of beaches and places of tourist interest, the amount and type of pollution are largely determined by anthropogenic factors (e.g., catering facilities, campsites, sports fields, swimming pools, water equipment; Rogowska et al. 2021, 111-115). Atmospheric transmission can also be a source of surface water pollution The possibility of transport of plastic microplastics by wind and precipitation was also pointed out by Kaliszewicz et al. (2020). They found the occurrence of microfibers of typical plastic polymers in inland waters (a river and three lakes) in central and north-eastern Poland, regardless of proximity to urban agglomerations (Kaliszewicz et al. 2000, 1235).

Microplastics have also been found in marine and beach sediments in the southern Baltic Sea. The authors associate their concentration with the degree of urbanization of the nearest regions – the concentration of microplastics in bottom sediments was clearly lower than in beach sediments (their amount decreased from the shore to open deep-sea regions). Graca et al. (2017) indicated that the sources of microplastics may be wastewater treatment plant effluents, marine transportation and tourism. This is also confirmed by Urban-Malinga et al. (2000), who noticed a low concentration of microplastics on beaches in rural localities in the southern part of the Polish coast (e.g., Jarosławiec, Lubiatowo and Rowy) and a much higher concentration in well-known urban resorts (e.g., Międzyzdroje, Mielno, Trójmiasto). The authors pointed to tourism and urbanization as the main factors influencing the concentration of microplastics on beaches. They also noted the uniform distribution of these pollutants, which makes it difficult to identify their sources. However, they suggested that the pollutants may come from the fragmentation of larger plastic waste left on beaches (Urban-Malinga et al. 2020, 8). It should be remembered that approximately 70% to 80% of marine pollutants come from land (GESAMP 2010, 39), so it is very important to recognize the level of microplastic contamination of soils in order to enable monitoring and assessing environmental risks, including risk to human health. In addition, in December 2021, the "FanpLESStic-sea" project was completed. The research conducted within the project focused on removing or decreasing the amount of microplastics in the Baltic Sea. Its purpose was to expand the knowledge on the origin of microplastics and their transportation. It also examined various technologies that can reduce microplastics or their leakage before they reach watercourses (FanpLESStic 2022).

Airborne microplastic is one of the most disturbing pollutants that has been appearing in the environment in recent years. It was found that the main synthetic polymers present in the atmospheric deposition in Krakow were Nylom-66 (47.5–93%), LDPE (7–49.4%), PS (0.8-22.2%), PP (0.2–24.6%) and PET (0.2–1.1%). It was indicated that the source of these pollutants may be the automotive, textile and construction industries, as well as shredded plastic bags, containers, toys, gas and water pipelines (the issue of the use of individual plastics has been referred to earlier; Jarosz et al. 2022, 11, 14). The presence of microplastics in terrestrial environments was also indicated by Deoniziak et al. (2022). The authors proved that high concentrations of microplastics were present in the digestive tract of common blackbirds (*Turdus merula*) and thrushes (*Turdus philomelos*). These are birds with an exceptionally terrestrial lifestyle and a wide range of occurrence. The presence of sand was found in their digestive tract (apart from microplastic particles), which proves that they were feeding on soils (where they took up microplastics along with their food). Deoniziak et al. (2022) believe that these birds can be used as indicators of microplastic pollution in terrestrial ecosystems.

Medyńska-Juraszek and Jadhav (2022) claim that the form, shape and size of microplastic particles are important factors affecting the properties of soils. They found that the presence of microplastic particles in heavy metal-contaminated soils influences metal speciation, particularly an increase in the amount of readily exchangeable and potentially bioavailable forms of Cu^{2+} and Pb^{2+}. They also observed an increase in pH indicative of the effect of microplastics on soil properties related to the sorption/desorption process of metal cations (Medyńska-Juraszek and Jadhav 2022, 5). Huang et al. (2022) found that microplastics affect the ability of plants to root and are also responsible for reducing the rate of photosynthesis (directly disturbing the balance between the content of chlorophyll a / chlorophyll b in plants). They also recognized, that microplastics affect the stability of soil aggregates by interfering with abiotic or biotic factors. According to them, microplastics can affect soil nutrient cycling by altering the dominant types of bacteria in the soil or the genes and enzymes involved in the carbon, nitrogen, phosphorus cycle. This demonstrates the need for further detailed study not only of the sources and content of microplastics in the soil environment, but also to learn more about the interactions occurring between micropollutants and soil.

Conclusion

Regardless of how we classify microplastics and their sources in the environment (and in particular, in soils), their presence is unquestionable. Despite the fact that soils act as a reservoir and source of microplastic to other elements of the environment, there are currently no conclusive results from comprehensive studies relating to the microplastic content of soils. The influence of microplastics on the total biomass production, as well as the bioavailability of xenobiotics on their surface, is also not sufficiently explained. There is also no determination of the thresholds for saturation of individual elements of the environment with microplastics, above which the system will not automatically return to its original state of equilibrium.

The challenge for modern science is to comprehensively analyse the impact of micropollutants on the environment (including human health). It is necessary to develop effective solutions, e.g., for the management of plastic waste to reduce its discharge into the environment, as well as in the water and wastewater industry for the application of effective ways to eliminate microplastics in water and wastewater treatment processes.

Author Contributions: Conceptualization, M.K.; Methodology, M.K.; Validation, M.K., A.P. and A.K.; Formal Analysis, M.K.; Investigation, M.K., A.P. and A.K..; Writing – Original Draft Preparation, M.K.; Writing – Review & Editing, M.K., A.P. and A.K.; Visualization, M.K.; Supervision, M.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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