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Research and analysis of the results of particulate matter emissions from the slitting machine

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ABSTRACT

The aim of this study was to assess particulate emissions generated during the cutting of high-density polyethylene (HDPE) bags using an automatic slitting machine. Measurements were performed using an EEPS 3090 spectrometer, enabling real-time analysis of particle number (PN) and particle mass (PM) concentrations. The results showed that the cutting process generates short-term emission peaks directly associated with individual cutting events. The maximum particle number concentration reached 1.0×10^7 particles/cm³ in the vicinity of the emission source, while particle mass concentration reached up to 2.0×10^4 µg/m³. A decrease in concentration was observed with increasing distance from the source, with values at the operator position reaching approximately 2.1×10^6 particles/cm³. The obtained results indicate that mechanical processing of HDPE materials may constitute a significant source of airborne particulate matter in industrial environments. The study provides baseline data for further analysis and development of emission reduction strategies.

Keywords: cutting process, HDPE, microplastics, particulate emissions, polymer processing, slitting machine.

INTRODUCTION

In light of the growing challenges related to climate protection and the reduction of environmental impacts resulting from industrial activity, the European Union has adopted a comprehensive policy framework aimed at achieving climate neutrality by 2050. The European Green Deal and the European Climate Law establish legally binding targets for greenhouse gas emission reductions and promote systemic transformation of energy systems, industrial processes, and consumption patterns [1,2]. These actions are supported by the 2030 Climate and Energy Framework, which defines intermediate targets for emission reduction, renewable energy deployment, and improvements in energy efficiency [3].

Achieving these objectives requires not only decarbonization of the energy sector but also modernization of industrial production systems, especially in sectors characterized by high material throughput and significant environmental footprint. The plastics manufacturing and processing industry remains one of the key areas requiring intensified sustainable development measures due to the continuously increasing global production of polymeric materials and associated waste streams [4]. It is estimated that cumulative global plastic production has exceeded several billion tonnes, creating substantial environmental pressure related to resource consumption, emissions, and end-of-life management [4].

Among commonly used thermoplastic polymers, high-density polyethylene (HDPE) is widely applied in packaging, agriculture, and technical products due to its favorable mechanical strength, chemical resistance, and low production cost [5]. Despite these advantages, HDPE production and processing generate environmental burdens associated with energy use, emissions of volatile compounds, and generation of solid and airborne particulate waste [5,6]. In the context of circular economy strategies promoted by the European Union, improving the environmental performance of polymer processing operations becomes a crucial element of sustainable industrial transformation.

Mechanical processing operations such as cutting, trimming, and slitting of polymer films constitute an integral part of HDPE bag manufacturing. During these operations, mechanical stresses acting on the material may lead to fragmentation of the polymer matrix and generation of fine particles. Experimental studies have demonstrated that industrial polymer processing can result in the emission of fine and ultrafine particles (PM and UFP), which may become airborne within production facilities.

Monitoring and reduction of dust emissions from industrial installations are considered essential elements of environmentally responsible manufacturing and sustainable production systems. Various technical solutions, including local exhaust ventilation and filtration systems, are applied to minimize particulate release; however, effective implementation requires prior identification and quantification of emission sources.

Furthermore, mechanical abrasion and fragmentation processes have been identified as important mechanisms of microplastic generation. Research indicates that mechanical stress significantly contributes to the formation of secondary microplastics, even in the absence of thermal degradation processes [7]. Similar mechanisms are observed in abrasion-driven polymer wear processes, which have been recognized as a substantial source of microplastic particles released into the environment [8]. Although many studies focus on environmental fragmentation of plastics, the underlying physical mechanisms are directly applicable to industrial cutting and slitting operations, where localized stress concentrations may promote particle detachment.

Airborne microplastics and polymer-derived fine particles are increasingly recognized as emerging environmental contaminants with potential implications for both environmental quality and human health [6]. Therefore, assessment of emissions associated with individual stages of HDPE bag processing – particularly mechanical cutting operations – is essential for identifying opportunities to reduce particulate release. Such analyses support the implementation of cleaner production strategies, improve occupational safety conditions, and contribute to broader climate neutrality and environmental protection objectives defined by European policy frameworks.

Recent studies have increasingly focused on particulate emissions generated during polymer processing operations, including extrusion, thermal treatment, and mechanical handling. It has been shown that such processes may release both fine and ultrafine particles, which can remain airborne and contribute to occupational exposure in industrial environments. Additionally, mechanical processes such as abrasion, cutting, and shredding have been identified as important sources of secondary microplastics, generated without the need for high-temperature degradation. Table 1 summarizes selected studies related to particulate emissions and microplastic generation during polymer processing and mechanical operations.

The reviewed studies indicate that mechanical processing of polymers, including shredding,

Table 1. Summary of selected studies on particulate emissions and microplastic generation during polymer processing and mechanical operations

Reference	Aim of the study	Key findings
Swinnerton et al., 2024 [9]	Investigation of airborne microplastics generated during mechanical shredding of plastics (including HDPE)	Particle concentrations increased up to 2910× compared to background; emissions in the range of 10–420 nm reached up to 1.3 × 10^6 particles/ cm^3
Turk et al., 2025 [10]	Analysis of microplastic generation during mechanical processes in construction (cutting, grinding)	Mechanical operations such as cutting and grinding significantly contribute to airborne microplastic emissions in industrial environments
Mompó-Curell et al., 2024 [11]	Characterization of HDPE microplastics and their behavior in environmental systems	HDPE particles persist and interact with environmental systems, confirming their relevance as a pollutant
Ali et al., 2026 [12]	Review of microplastic release from polymer-based materials	Limited studies exist on emissions from specific industrial processes, indicating a research gap
Gazal et al., 2020 [13]	Review of plastic pollution and microplastics in the environment	Microplastics are widespread contaminants with significant environmental and health impacts

cutting, and abrasion, can generate significant amounts of airborne particulate matter and microplastics. Reported particle concentrations are often several orders of magnitude higher than background levels, highlighting the potential occupational and environmental risks associated with such processes. At the same time, the available literature shows that there is still a lack of detailed experimental data for specific industrial operations, particularly for slitting processes in HDPE bag production. This confirms the existence of a research gap addressed in the present study.

Although previous studies have investigated particulate emissions and microplastic generation during general polymer processing and mechanical operations, there is still a lack of detailed experimental data regarding emissions associated with industrial slitting processes of HDPE bags under real operating conditions. Therefore, this study provides new experimental insights into the intensity and spatial distribution of particulate emissions associated with such processes. This study evaluates particulate emissions generated during the cutting process of HDPE bags using an automatic slitting system, with the aim of identifying emission sources and quantifying particulate generation. By identifying emission sources and quantifying particulate generation, it becomes possible to propose technical modifications and mitigation measures aligned with sustainable development principles and industrial environmental management strategies. The aim of this study is to quantify particulate emissions generated during the cutting process of HDPE bags using an automatic slitting machine and to analyze their spatial distribution. It is hypothesized that the cutting process results in measurable emission peaks directly associated with individual cutting events and that emission intensity decreases with increasing distance from the source.

RESEARCH METHODOLOGY

The study focused on a machine (slitter) designed for fully automatic packaging of vegetables into mesh bags (Figure 1). Its functionality allows for handling bags of various sizes and enables the user to set a specific frequency for both packing and simultaneous bag cutting. In this research, bags sized 34 × 46 cm (cut side) were used, and two cutting cycle frequencies of 2 seconds and 3 seconds were analyzed.

For preliminary testing, Portable Emissions Measurement Systems (PEMS) equipment was used, which, due to its design, allows for precise measurements in various environmental conditions [13–19]. Given the planned schedule, the preliminary research focused on particle analysis in terms of both count and mass. For this purpose, the TSI Engine Exhaust Particulate Sizer 3090 was used, operating with a time resolution of 10 Hz (Figure 2, Table 2). The recorded data are continuously converted, including both linear and logarithmic scaling. Concentration units are normalized (dN/dlogDp) to facilitate easy comparison with data obtained using different instruments. The device measures in 32 channels with

Figure 1. View of the slitter (cutting module) with measurement equipment in operation

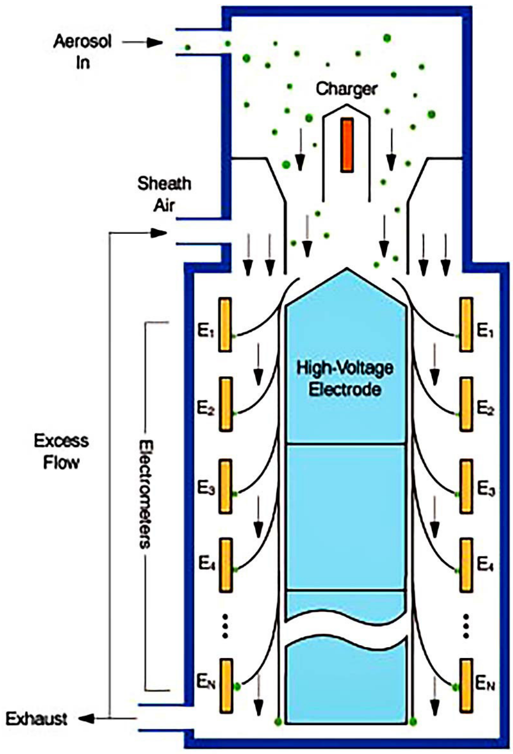

Figure 2. TSI EEPS 3090 measuring equipment operation diagram

varying particle size and concentration, leveraging sensitive electrodes. The spectrometer's sensitivity enables measurement from 200 particles/cm³, equivalent to about <1 µg/m³.

Before measurement, the exhaust sample undergoes conditioning—either through the additional equipment of the device or in a CVS tunnel at the sampling point. The tested gas volume then passes through a filter, capturing particles larger than 1 µm, i.e., those with diameters outside the measurement range. The sample is subsequently directed to a chamber with an electrode, where particles acquire an electric charge, resulting in ion generation. Due to this charging, particle size classification can be conducted. The charging electrode is positioned at the top of the device. From this point, the tested particles move to the annular gap, located between two coaxial cylinders. Ambient air is directed to the gap surrounding the particles. The cylinder comprises a stack of highly sensitive, isolated, ring-shaped electrodes. One end is grounded, while the other connects to sensitive amplifiers, creating an electric field between the cylinders. Ambient air, containing positively charged particles, is directed into the gap between the rings, where the sensitive electrodes register signals from the charged particles—the charge/signal is directly proportional to particle size.

Table 2. Technical specifications of the EEPS 3090 analyzer

Parameter	Value
Size of measured particles	5.6 ÷ 560 nm
Number of measurement channels	16 channels per decade (32 in total)
Number of electrode channels	22
Resolution	10 size channels/second
Sample exhaust flow	10 dm³/min
Compressed air flow	40 dm³/min
Inlet sample temperature	10–52 °C
Device operating temperature	0–40 °C
Total device weight	32 kg

During measurements, the sampling probe collected samples from specific locations to obtain the concentration distribution and the flow rate of particulate emissions:

- directly in the exhaust system of the main cutting module (1);
- directly in the exhaust system of the supplementary cutting module (2);
- at selected points within the gas cloud above the cutting module (3);
- at the operator's workstation (4);
- along the communication path beside the machine (5) (Figure 3).

Each measurement was repeated five times under the same operating conditions to ensure repeatability of the results. The number of repetitions was sufficient to identify consistent emission trends and characteristic peak values.

An additional evaluation of pre-measurement conditions, referred to as the background level, was conducted. The measurements were performed in a room used as an assembly workshop; however, no operations were carried out during the tests. The particle concentration in the test environment was 4.6 × 10^1 µg/m³, and the particle number (PN) size distribution as a function of particle diameter (D) is presented in Figure 4. The measured values were influenced by ambient contaminants entering from the production hall and by air supplied through the ventilation system. Moreover, since the measurements were conducted during the heating season, the background air quality was affected by emissions from residential heating sources. Background concentrations were measured prior to the cutting process and used as a correction level for the process measurements to isolate emissions generated by the investigated operation. Characteristic peaks associated with

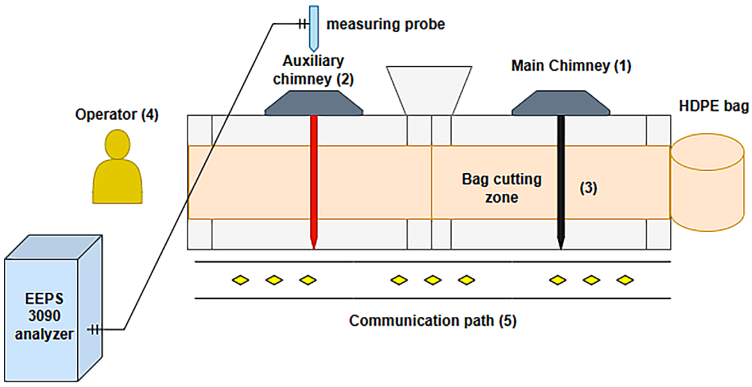

Figure 3. Schematic representation of the measurement setup, including the cutting section of the HDPE bag slitting machine, main chimney (1), auxiliary chimney (2), gas cloud above the cutting zone (3), operator position (4), communication path (5), sampling probe, and EEPS 3090 analyzer

individual cutting events were then identified and analyzed based on the corrected data.

The recorded data were processed using time-resolved averaging to identify characteristic emission peaks associated with individual cutting events. Background concentrations were taken into account to distinguish process-related emissions from ambient pollution. Due to the exploratory nature of the study, the analysis focused on identifying trends and peak values rather than applying advanced statistical methods. Measurements were conducted under repeatable operating conditions of the slitting machine to ensure consistency of the obtained results. Measurement uncertainty is primarily associated with the characteristics of the EEPS 3090 analyzer and environmental variability; however, the applied methodology enables reliable identification of emission trends and relative differences between measurement locations. Due to the exploratory nature of the study and the limited dataset, advanced statistical analysis (e.g., variance or hypothesis testing) was not applied. Instead, the analysis focused on identifying consistent trends and peak emission values.

THERMAL EFFECTS ON MESH BAGS: RESEARCH AND ANALYSIS

High-density polyethylene (HDPE), as a polyolefin composed of long-chain saturated hydrocarbons, undergoes thermal degradation primarily via random chain scission and β-scission mechanisms at elevated temperatures. Under oxygen-deficient conditions, pyrolysis leads to the formation of low-molecular-weight hydrocarbons such as methane, ethylene, propylene, and other C_2–C_4 aliphatic species. At higher temperatures, secondary reactions promote aromatization processes, resulting in the formation of benzene,

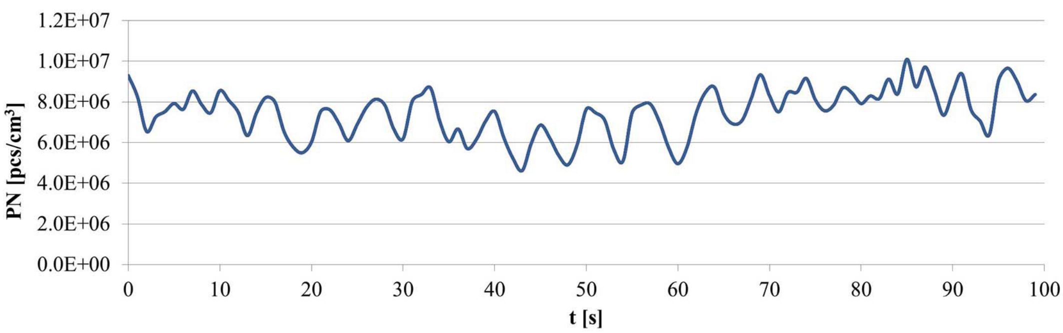

Figure 4. Particle number as a function of size distribution

toluene, xylene (BTX), and other volatile organic compounds (VOCs) [20,21].

In oxidative environments, complete combustion predominantly produces carbon dioxide (CO_2) and water vapor (H_2O). However, incomplete combustion conditions favor the formation of carbon monoxide (CO), partially oxidized intermediates (e.g., aldehydes and ketones), and particulate matter (PM) [21,22]. The composition and quantity of emitted products depend strongly on temperature, oxygen availability, heating rate, and the presence of polymer additives. Recent studies have demonstrated that plastic combustion and thermal degradation processes can generate significant amounts of soot and fine particles with complex chemical composition, including adsorbed organic compounds and trace inorganic constituents [22,23].

Fine particulate matter formed during polymer degradation is of particular concern due to its ability to penetrate deep into the respiratory system and contribute to adverse health effects [24]. Although industrial polymer processing typically does not involve open combustion, localized thermal and mechanical stresses may induce partial thermal degradation and fragmentation, potentially leading to the emission of ultrafine particles. Therefore, characterization of particle number (PN) and particle mass (PM) concentrations during polymer processing operations is essential for evaluating environmental and occupational exposure.

PN and PM) concentrations were measured at multiple locations during operation of the mesh bag cutting system (Figures 5–17). The cutting cycle duration was 3 s per bag. The spatial distribution of measured concentrations enabled identification of pollutant dispersion patterns and assessment of the influence of machine operation on the surrounding environment.The analysis revealed that, irrespective of measurement location, characteristic concentration peaks occurred immediately after each cutting event, indicating a direct relationship between mechanical processing and particle emission.

Inside the chimney (Figures 5–10), the maximum instantaneous particle number concentration reached 1.0×10^7 particles/cm³, while the corresponding maximum particle mass concentration was 2.0×10^4 µg/m³. These values represent the highest emission levels observed in the system and confirm that the cutting zone is the primary source of particulate generation.

The high concentrations recorded in this location indicate that mechanical fragmentation of the HDPE material during the cutting process is the dominant mechanism responsible for particle formation. The results also highlight the importance of effective exhaust and filtration systems in limiting the release of particles into the surrounding environment.

In the measurement cloud above the chimney (at a height of 70 cm), averaged from points located along the chimney axis at radii of 25 cm and 50 cm (Figures 11–14), the highest instantaneous particle number concentration reached 2.2×10^6 particles/cm³, while the maximum particle mass concentration was 2.5×10^3 µg/m³. The observed reduction in concentration compared to the emission source indicates a rapid dispersion of particles in the surrounding air, although elevated levels are still present at this distance. This suggests that the cutting process generates particles that can spread beyond the immediate emission zone and contribute to local air contamination.

At the operator position (Figures 15–18), the maximum instantaneous particle number concentration reached 2.1×10^6 particles/cm³, while the corresponding maximum particle mass concentration was 1.6×10^3 µg/m³. These values indicate

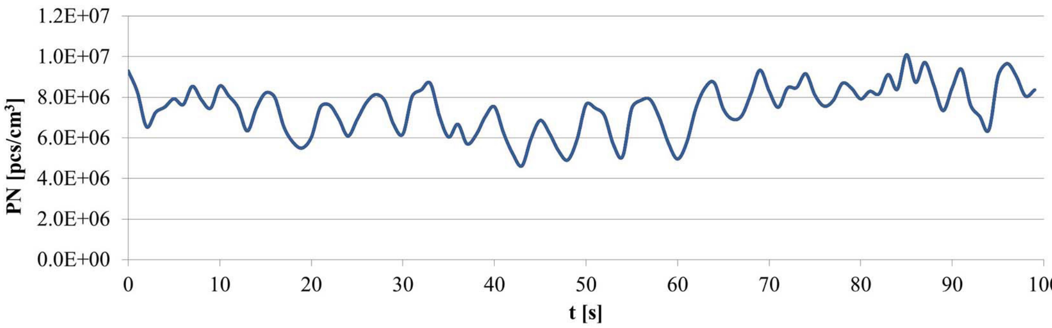

Figure 5. Total particle concentration during the bag-cutting process at a frequency of every 3 seconds – chimney center

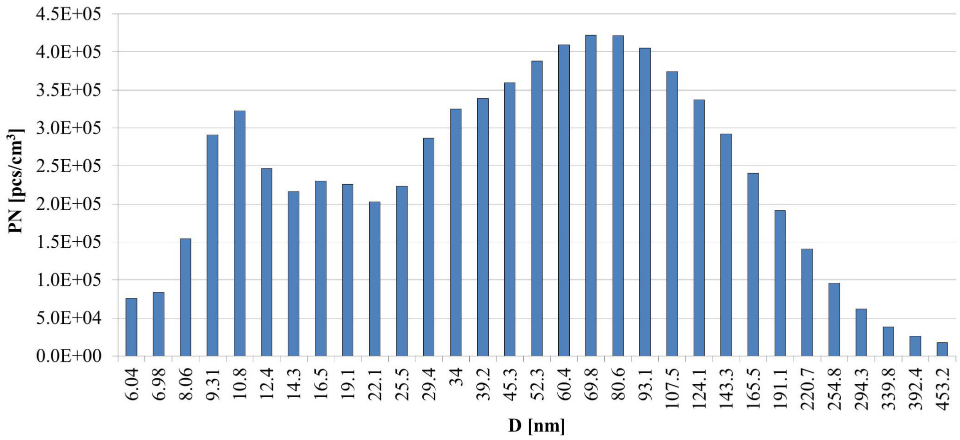

Figure 6. Average size distribution of particle number as a function of particle diameter during the bag-cutting process at a frequency of every 3 seconds – chimney center

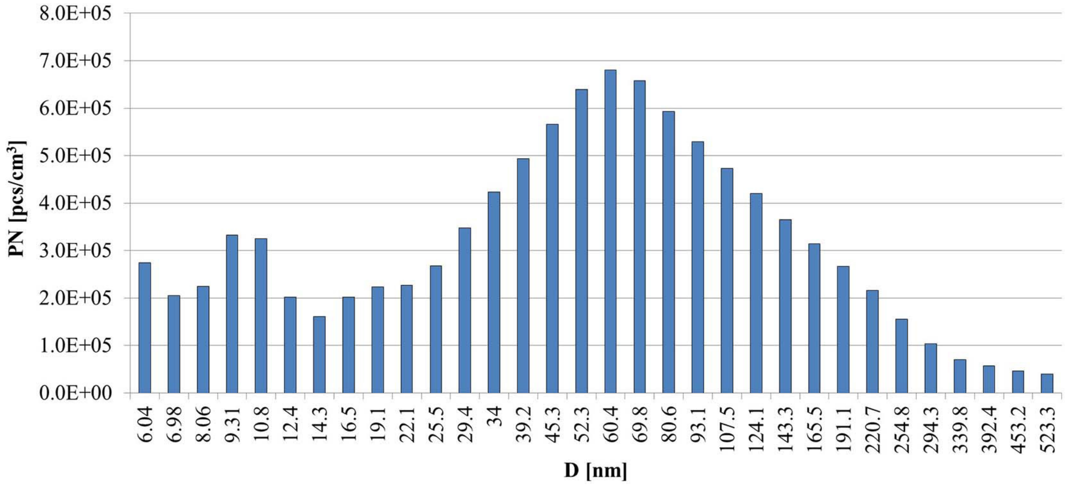

Figure 7. Maximum particle number concentration during the bag-cutting process at a frequency of every 3 seconds – chimney center

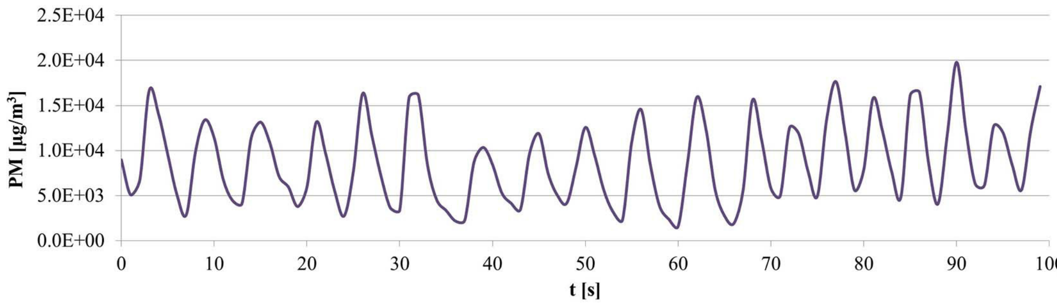

Figure 8. Particle mass concentration over time during the bag-cutting process at a frequency of every 3 seconds – chimney center

that elevated particle concentrations are present not only near the emission source but also at locations directly associated with worker exposure.

The results confirm that the cutting process generates short-term, high-intensity emission events, characterized by decreasing concentration gradients with increasing distance from the emission source. This behavior is consistent with typical dispersion patterns of particulate matter in indoor industrial environments.

The measurement equipment and the configuration of the machine's exhaust system enabled the determination of the emission intensity for the number and mass of particulate matter during the

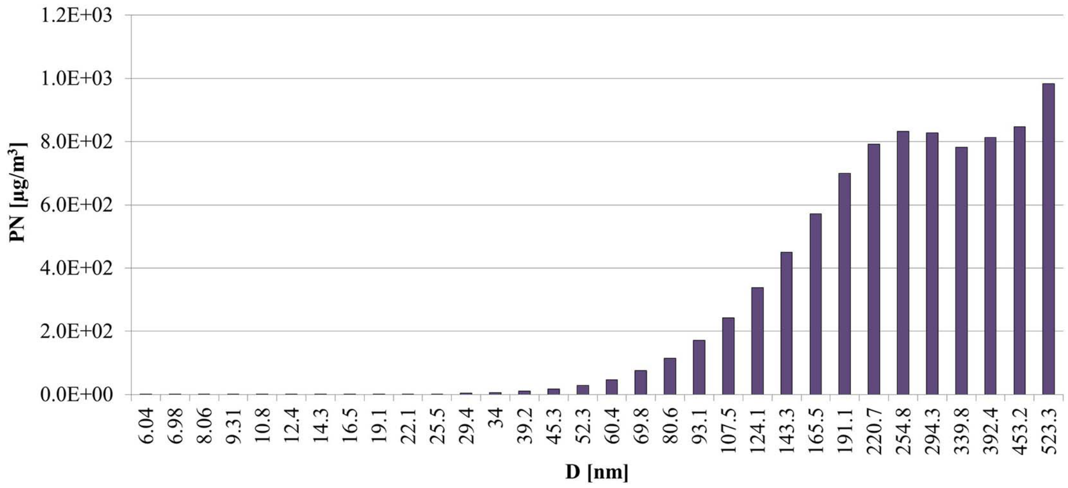

Figure 9. Average mass distribution of particles as a function of particle diameter during the bag-cutting process at a frequency of every 3 seconds – chimney center

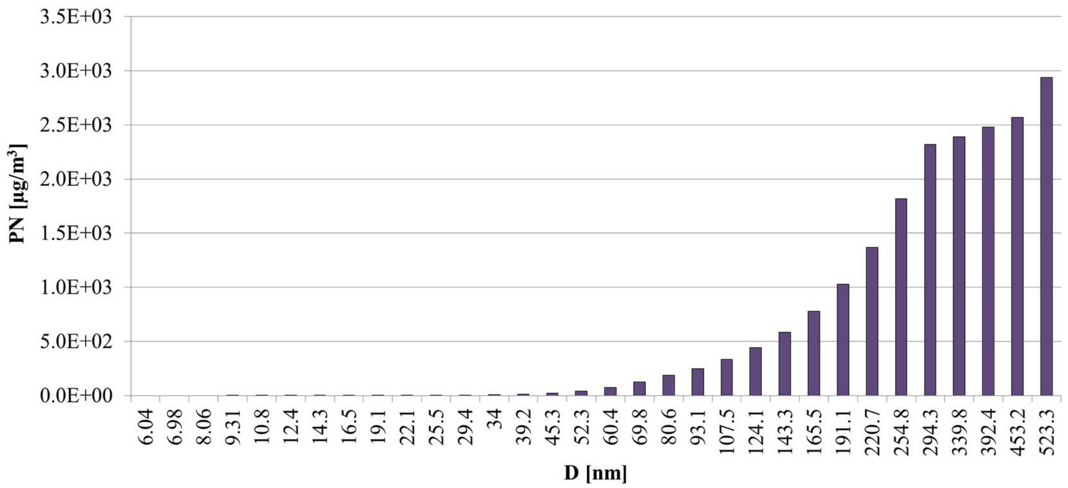

Figure 10. Maximum particle concentration during the bag-cutting process at a frequency of every 3 seconds – chimney center

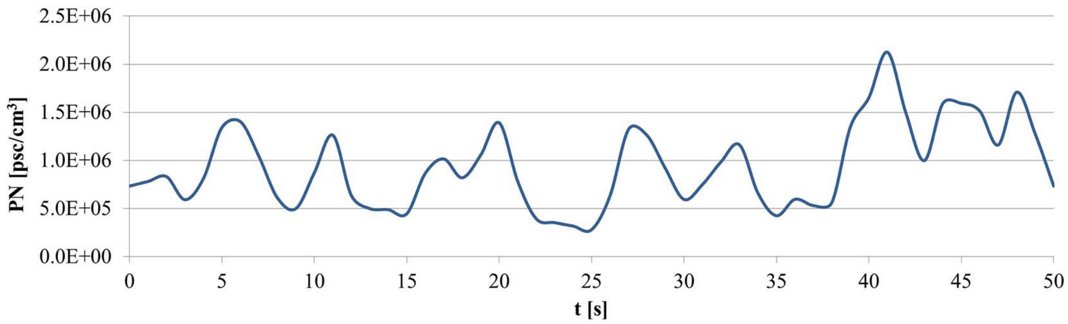

Figure 11. Total particle number concentration during the bag-cutting process at a frequency of every 3 seconds – cloud above the chimney (70 cm)

bag-cutting process. Pollutant emissions were measured at the outlet of the main exhaust chimney and the additional exhaust, known as "auxiliary chimney," which removes harmful substances generated during the trimming of bags. The obtained emission values can be summarized as follows:

- main chimney:
- PN emission: 7.7E+11 particles/bag

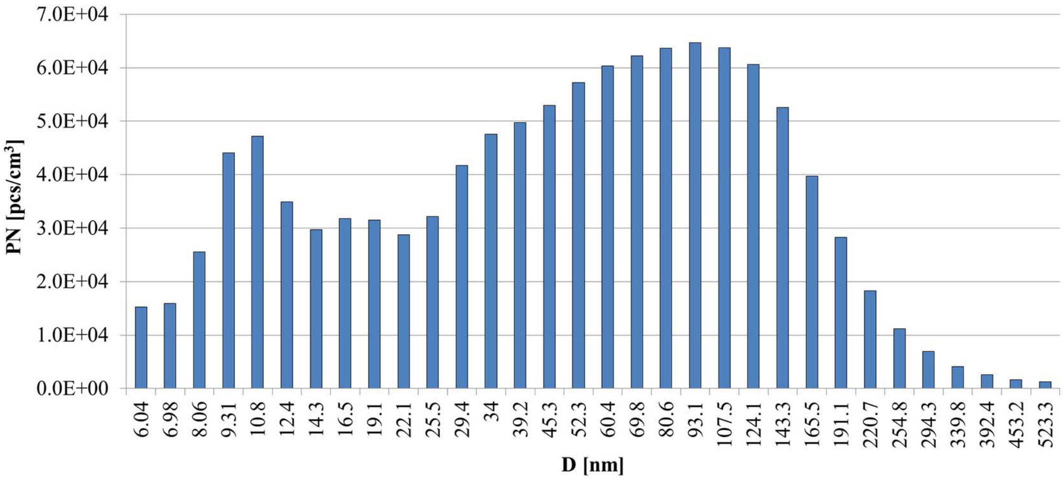

Figure 12. Average size distribution of particle number as a function of particle diameter during the bag-cutting process at a frequency of every 3 seconds – cloud above the chimney (70 cm)

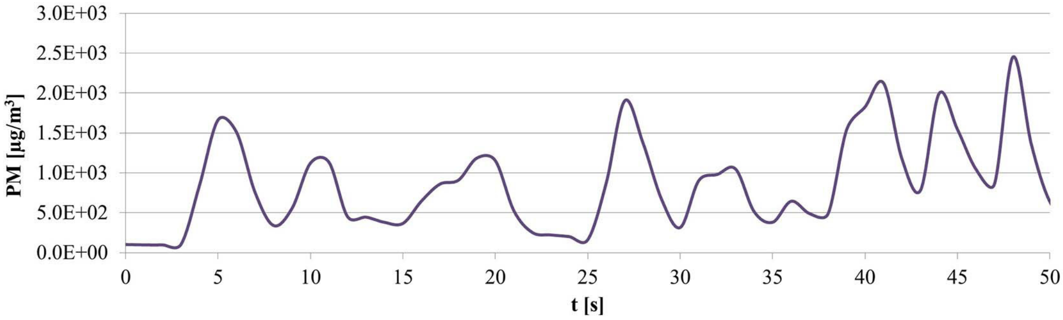

Figure 13. Particle mass concentration over time during the bag-cutting process at a frequency of every 3 seconds – cloud above the chimney (70 cm)

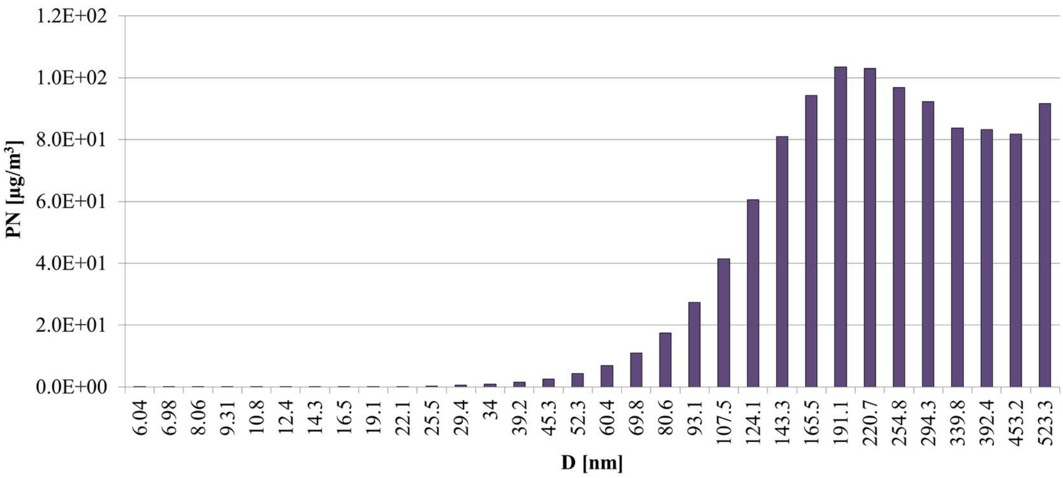

Figure 14. Average mass distribution of particles as a function of particle diameter during the bag-cutting process at a frequency of every 3 seconds – cloud above the chimney (70 cm)

- PM emission: 8.7E+02 µg/bag
- PN emission: 1.3E+11 particles/s
- PM emission rate: 1.4E+02 µg/s
- auxiliary chimney:
- PN emission: 1.4E+12 particles/bag
- PM emission: 1.2E+03 µg/bag
- PN emission: 2.5E+11 particles/s
- PM emission: 2.2E+02 µg/s.

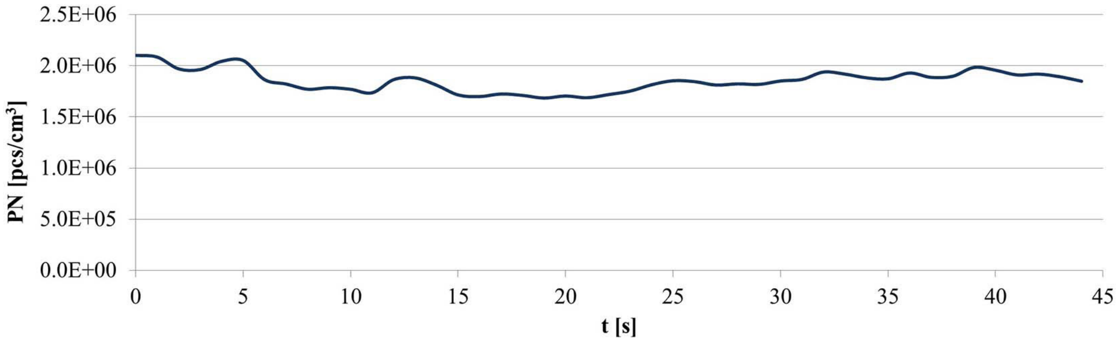

Figure 15. Total particle number concentration during the bag-cutting process at a frequency of every 3 seconds – operator's position (70 cm)

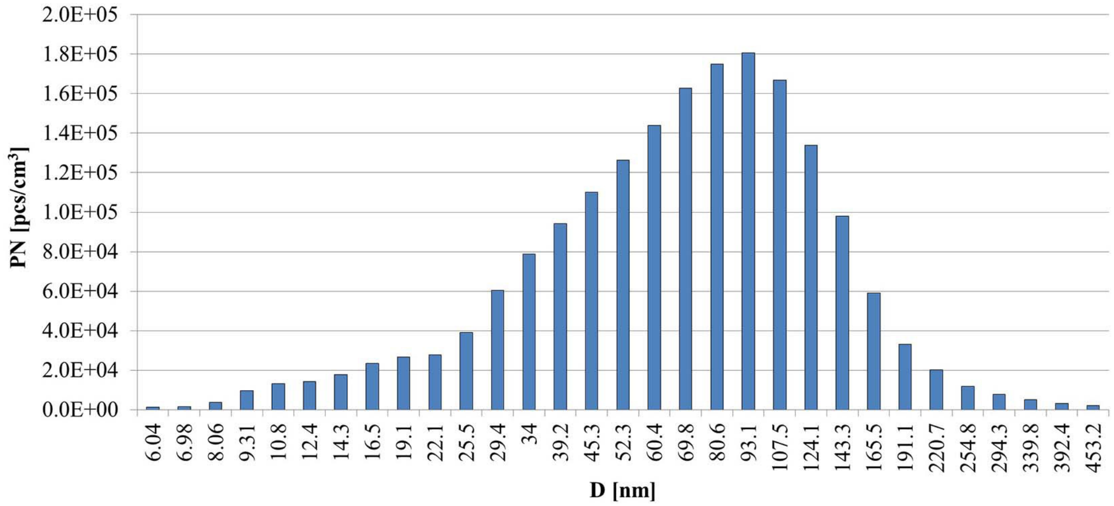

Figure 16. Average size distribution of particle number as a function of particle diameter during the bag-cutting process at a frequency of every 3 seconds – operator's position (70 cm)

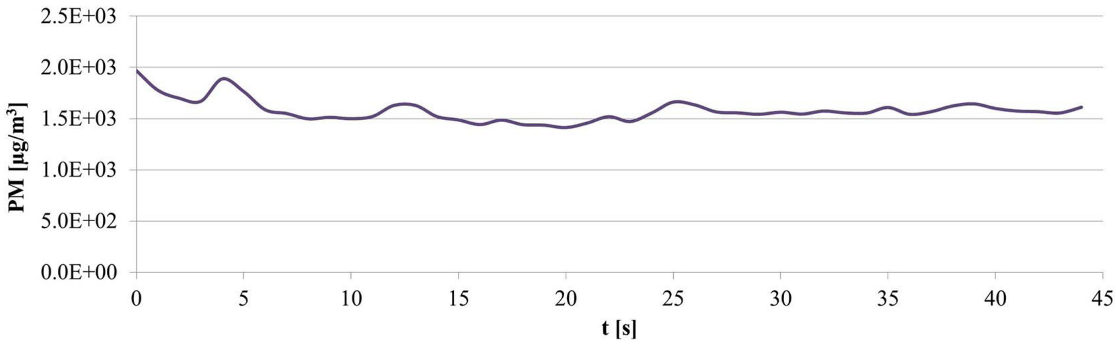

Figure 17. Particle mass concentration over time during the bag-cutting process at a frequency of every 3 seconds – operator's position (70 cm)

The presented results reflect the per-second pollutant emissions based on a bag-cutting rate of one cut every 3 seconds. Based on the calculations, it is estimated that emissions increase by 25% if the cutting frequency is increased to one cut every 2 seconds.

DISCUSSION

The obtained results confirm that the cutting process of HDPE bags is a significant source of particulate emissions, characterized by short-term peaks of high PN and PM concentrations. These

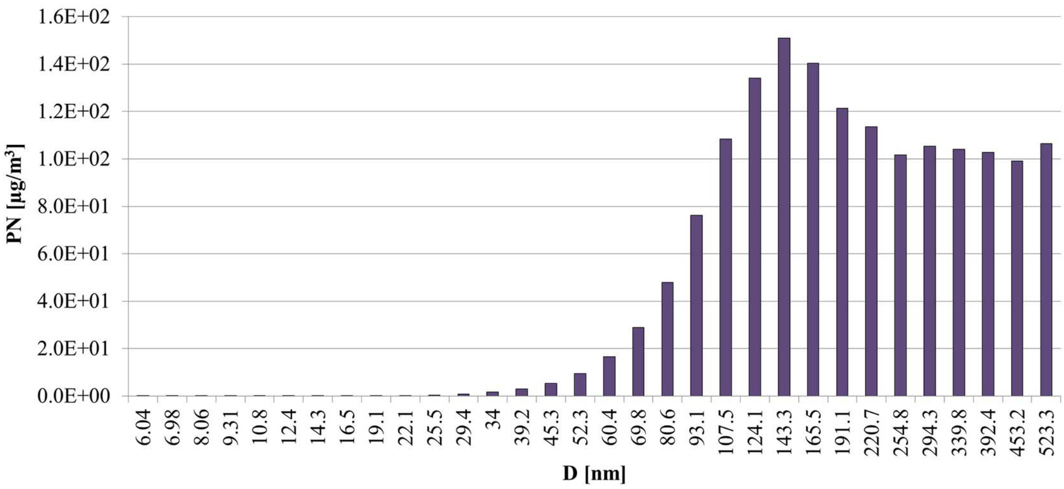

Figure 18. Particle mass concentration over time during the bag-cutting process at a frequency of every 3 seconds – operator's position (70 cm)

peaks occur immediately after individual cutting events, indicating that mechanical fragmentation of the polymer material is the dominant mechanism responsible for particle generation.

Particle number concentrations observed in this study (up to 1.0×10^7 particles/cm³) are within the range reported in previous studies on mechanical processing of polymers, where –values on the order of 10^6–10^7 particles/cm³ have been observed [9,10]. Similarly, the particle mass concentrations measured in this study are comparable to values reported for industrial microplastic generation processes [11,12], confirming that the emission intensity observed in the present work is consistent with existing literature.

The observed emission characteristics are consistent with findings reported in previous studies on mechanical processing of polymers, where cutting, abrasion, and shredding processes were identified as important sources of airborne particulate matter and microplastics. In particular, the presence of high particle concentrations in the ultrafine size range confirms that mechanical stress alone, without the need for thermal degradation, may lead to the formation of fine particles. A clear spatial dependence of particle concentration was observed, with the highest values recorded in the immediate vicinity of the emission source (chimney), followed by lower concentrations in the surrounding measurement points, including the operator's workstation. This trend is consistent with typical dispersion behavior of particulate matter in indoor industrial environments and highlights the importance of distance and ventilation conditions in reducing exposure levels. The comparison of emission intensity between measurement locations indicates that local exhaust systems play a key role in controlling pollutant dispersion. However, the presence of elevated particle concentrations outside the direct emission zone suggests that current ventilation solutions may not be fully effective in capturing all generated particles.

From an environmental and occupational safety perspective, the obtained results indicate that even relatively simple mechanical operations, such as cutting of HDPE bags, may contribute to airborne particulate pollution. The comparison with background levels further confirms that the cutting process significantly increases particle concentration beyond ambient conditions.

These findings emphasize the need for improved emission control strategies, including

Table 3. Summary of characteristic particulate emission values at selected measurement locations

Measurement location	PN (particles/cm³)	PM (µg/m³)	Interpretation
Chimney (source)	~1.0×10^7	~2.0×10^4	Highest emission peaks
Above chimney (70 cm)	~2.2×10^6	~2.5×10^3	Rapid decrease due to dispersion
Operator position	~2.1×10^6	~1.6×10^3	Exposure risk for workers
Background	Significantly lower	Significantly lower	Ambient conditions

optimization of local exhaust ventilation, enhancement of filtration efficiency, and potential modification of process parameters, such as cutting frequency, to reduce emission intensity. A summary of characteristic emission values at selected measurement locations is presented in Table 3.

The presented data clearly illustrate the spatial variation of particulate emissions and confirm the highest exposure levels in the immediate vicinity of the emission source.

CONCLUSIONS

The conducted study confirmed that the cutting process of HDPE bags using an automatic slitting machine generates measurable emissions of particulate matter, including both PN and PM. The results indicate that the emission process is strongly correlated with individual cutting events, leading to short-term peaks of high particle concentrations.

The highest concentrations were observed in the immediate vicinity of the emission source, with a gradual decrease in concentration as the distance from the cutting module increased. This confirms that the main source of particulate emissions is directly associated with the mechanical fragmentation of the polymer material during the cutting process.

From a practical perspective, the obtained results highlight the need to implement effective emission control strategies in industrial environments where such processes are performed. Potential mitigation measures may include the application of local exhaust ventilation systems, improvement of filtration efficiency, and optimization of process parameters such as cutting frequency.

It should be noted that the present study has an exploratory character and is based on a limited number of measurements. Therefore, further research should include a larger dataset, extended measurement campaigns, and the application of statistical analysis methods to improve the reliability of the results.

Despite these limitations, the study provides valuable baseline data on particulate emissions from polymer cutting processes and contributes to a better understanding of their environmental and occupational impact.

Particulate emissions generated during the HDPE bag cutting process are of particular concern due to potential exposure of machine operators and other workers present in the production hall. The elevated particle concentrations observed at the operator's position indicate that such processes may contribute to increased occupational exposure and should be considered in the design of effective workplace air quality control strategies.

The present study has several limitations. The number of measurement repetitions was limited due to the industrial conditions of the study, and the analysis was focused on a specific production setup. Additionally, advanced statistical analysis was not applied due to the exploratory nature of the study. Future research should focus on increasing the number of measurement repetitions, applying statistical analysis methods (e.g., variance analysis), and improving the experimental design by including additional measurement points and extended observation periods.

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REFERENCES

1. European Commission. The European Green Deal. COM(2019) 640 final; European Commission: Brussels, Belgium, 2019.
2. European Parliament; Council of the European Union. Regulation (EU) 2021/1119 establishing the framework for achieving climate neutrality (European Climate Law). Off. J. Eur. Union 2021, L243, 1–17.
3. European Commission. 2030 Climate and Energy Policy Framework. COM(2014) 15 final; European Commission: Brussels, Belgium, 2014.
4. Geyer R., Jambeck J.R., Law K.L. Production, use, and fate of all plastics ever made. Sci. Adv. 2017, 3, e1700782. https://doi.org/10.1126/sciadv.1700782
5. Al-Salem S.M., Lettieri P., Baeyens J. Recycling and recovery routes of plastic solid waste (PSW): A review. Waste Manag. 2009, 29, 2625–2643. https://doi.org/10.1016/j.wasman.2009.06.004
6. Hahladakis J.N., Velis C.A., Weber R., Iacovidou E., Purnell P. An overview of chemical additives present in plastics: Migration, release, fate and environmental impact during their use, disposal and recycling. J. Hazard. Mater. 2018, 344, 179–199. https://doi.org/10.1016/j.jhazmat.2017.10.014
7. Song Y.K., Hong S.H., Jang M., Han G.M., Jung S.W.,

Shim W.J. Combined effects of UV exposure duration and mechanical abrasion on microplastic fragmentation by polymer type. Environ. Sci. Technol. 2017, 51, 4368–4376. https://doi.org/10.1021/acs.est.6b06155

8. Kole P.J., Löhr A.J., Van Belleghem F.G.A.J., Ragas A.M.J. Wear and tear of tyres: A stealthy source of microplastics in the environment. Int. J. Environ. Res. Public Health 2017, 14, 1265. https://doi.org/10.3390/ijerph14101265
9. Swinnerton S., Su J., Tsai C.S.J. The emission and physicochemical properties of airborne microplastics and nanoplastics generated during the mechanical recycling of plastic via shredding. Sci. Rep. 2024, 14, 24755. https://doi.org/10.1038/s41598-024-73775-0
10. Turk J., et al. Microplastic generation during mechanical operations in construction materials. Environ. Sci. Eur. 2025, https://doi.org/10.1186/s12302-025-01228-0
11. Mompó-Curell R., Alonso-Molina J.L., Amorós-Muñoz I., Mendoza-Roca J.A., Bes-Piá M.A. Characterization of HDPE microparticles in sludge aerobic digestion and their influence on the process. J. Environ. Manag. 2024, 365, 121704. https://doi.org/10.1016/j.jenvman.2024.121704N
12. Ali A., Khan M.Z. Textile microplastics in wastewater: a critical review of removal and carbonization technologies. C 2026, 12(1), 24. https://doi.org/10.3390/c12010024
13. Gazal A.A., Gheewala S.H. Plastics, microplastics and other polymer materials – a threat to the environment. J. Sustain. Energy Environ. 2020, 11, 113–122.
14. Fuć P., Lijewski P., Szymlet N., Sokolnicka B., Siedlecki M., Dębowski T. Analysis of particle mass and number emission from an SI engine with direct fuel injection and a particulate filter. Proc. International Scientific Automotive Conference on Automotive Vehicles and Combustion Engines (KONMOT) 2018, 421.
15. Pielecha J., Skobiej K., Gis M., Gis W. Particle number emission from vehicles of various drives in the RDE tests. Energies 2022, 15(17), 6471. https://doi.org/10.3390/en15176471
16. Pielecha J., Skobiej K., Kubiak P., Woźniak M., Siczek K. Exhaust emissions from plug-in and HEV vehicles in type-approval tests and real driving cycles. Energies 2022, 15, 2423. https://doi.org/10.3390/en15072423
17. Pielecha I., Wierzbicki S., Sidorowicz M., Pietras D. Combustion thermodynamics of ethanol, n-heptane, and n-butanol in a rapid compression machine with a dual direct injection (DDI) supply system. Energies 2021, 14(9), 2729. https://doi.org/10.3390/en14092729
18. Jasiński R., Markowski J., Pielecha J. Probe positioning for the exhaust emissions measurements. Procedia Eng. 2017, 192, 381–386. https://doi.org/10.1016/j.proeng.2017.06.066
19. Rymaniak Ł., Merkisz J., Szymlet N., Kamińska M., Weymann S. Use of emission indicators related to CO_2 emissions in the ecological assessment of an agricultural tractor. Eksploat. Niezawodn. 2021, 23(4), 605–611. https://doi.org/10.17531/ein.2021.4.2
20. Bajerlein M., Rymaniak Ł. The reduction of fuel consumption on the example of ecological hybrid buses. Appl. Mech. Mater. 2014, 518, 96–101. https://doi.org/10.4028/www.scientific.net/AMM.518.96
21. Al-Salem S.M., Antelava A., Constantinou A., Manos G., Dutta A. A review on thermal and catalytic pyrolysis of plastic solid waste (PSW). J. Environ. Manag. 2017, 197, 177–198. https://doi.org/10.1016/j.jenvman.2017.03.084
22. Huang Y., Chen H., Wang X., Chen H. Emission characteristics of volatile organic compounds from pyrolysis of typical plastic wastes. J. Hazard. Mater. 2019, 369, 586–594. https://doi.org/10.1016/j.jhazmat.2019.02.045
23. Yang H., Chen H., Wang X., Zhang S., Chen H. Formation of particulate matter and soot during plastic waste combustion. Fuel 2020, 262, 116535. https://doi.org/10.1016/j.fuel.2019.116535
24. Wiedinmyer C., Yokelson R.J., Gullett B.K. Global emissions of trace gases, particulate matter, and hazardous air pollutants from open burning of domestic waste. Environ. Sci. Technol. 2014, 48, 9523–9530. https://doi.org/10.1021/es502250z
25. World Health Organization. WHO global air quality guidelines. WHO: Geneva, 2021.