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DO WE KNOW PM_1 IN POLAND INSIDE OUT?

The paper provides a concise review of key publications on particulate matter of aerodynamic diameter below 1 μm (PM_1) having been published in Poland in the years 2007–2022. Data and conclusions related to the study of concentrations, chemical composition, and content of selected toxic and carcinogenic compounds in PM_1 as well as methods and conclusions on the assessment of the origin of PM_1 in various regions of Poland have been tabulated. The conclusions of this review attempt to outline the directions of further research that could prove crucial in obtaining information and filling the identified gaps in knowledge about PM_1 in Poland. While this work may be theoretical, it can serve as a valuable and compact source material for research groups, organizations supervising and financing research, as well as those responsible for assessing air quality and mitigating negative health effects related to air quality.

1. INTRODUCTION

Most straightforward, atmospheric particulate matter (PM) called atmospheric aerosol, suspended particulates or shortening (with loss of precision) particulates or dust are particles suspended in the atmosphere [30]. Aerosol is a mixture (solution) of solids and/or liquid droplets (dispersed phase) suspended in a gas mixture (dispersion medium) [3]. In atmospheric aerosol, the dispersion medium is atmospheric air [4]. For consistency in the following paragraphs, both atmospheric suspended particulates and atmospheric aerosol will be denoted as PM. It is an international standard approved by organisations such as the World Health Organization (WHO), the European Environmental Agency (EEA), or the United States Environmental Protection Agency (US EPA), as well as a kind of standard in scientific publications and textbooks.

The size of PM particles is usually expressed by a conventional aerodynamic diameter, which is the diameter of a material sphere with a density of 1 g/cm^3 that has the same terminal velocity as a given particle [4, 30]. It is assumed that the dispersed phase of atmospheric aerosol constitute particles with an aerodynamic diameter between 10^{-3} and

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10^2 μm [4, 30]. The physicochemical properties of PM are closely related to the size of these particles. However, due to various processes governing PM in the atmosphere and the related changing physicochemical properties of PM, it is impossible to classify the size of individual particles. Therefore, the impact of PM on the natural environment, as well as human health and life, is examined and determined concerning specific particle size fractions. The $PM_{x–y}$ fraction of the dispersed phase of the atmospheric aerosol consists of all particles having aerodynamic diameters between x and y μm, with $PM_{0.001–x}$ being denoted as PM_x.

Although on a global scale, the coarse PM must constitute the majority of PM mass in the air (due to the great importance of generating PM sources such as deserts, seas and oceans, soil surfaces, natural processes during vegetation, etc.), in urban areas most of the mass of PM is fine PM, especially the PM_1 fraction [18, 20], due to the origin of PM, more precisely speaking, from the fact that particularly in urban areas majority of anthropogenic emitters release gases and particles from the combustion, pyrolysis or processing of various fuels and materials. Hence, PM in these areas consists mainly of carbon, hydrocarbons, oxides of various metals and secondary organic and inorganic matter and, contrary to typical PM particles associated with natural origin, are most often very fine particles and constitute mainly the PM_1 fraction [20, 22, 42]. What is important, is that most compounds with known or hypothetical harmful effects on health or the environment are accumulated in PM_1 due to the origin of this fraction. Probably for these reasons, the stronger statistical relationships or responses of the studied biological materials are observed in the case of submicron PM than in other fractions [1, 6, 44]. It is worth emphasizing, however, that the common colloquial claim that fine PM has a stronger effect than total PM on health is not correct. PM contains $PM_{2.5}$ or PM_1, thus the impact of total PM is not less than the impact of fine PM.

Data about fine PM concentration are generally available for various areas of Europe, especially today, almost 20 years after the introduction of the obligatory monitoring of $PM_{2.5}$ in selected areas. However, research on PM_1 seems to be more interesting considering the observed mass size distribution of PM and PM components (more precisely, the values of median aerodynamic diameter (MMAD) and the geometric standard deviation (GSD)) for various locations [8, 25, 36, 42], as well as due to the aforementioned stronger responses of the organism or cells during the interaction of fine particles. Although the database on the mass concentration of PM_1 and its chemical composition across Europe is still quite poor, especially when it comes to measurements of longer duration, in Poland there is already quite a lot of information on this topic. It is widely known that scientists from Europe dealing with PM as well as employees and members of various institutions, i.a. the European Environment Agency, signal the negative impact of high concentrations of particulate matter in Poland (especially fine particulate matter and its main components) on air quality in other regions of Europe. Therefore, it was necessary to undertake research firstly focused on determining the origin of fine PM, and then reducing emissions from its main emitters.

In this work, information on PM_1 concentrations as well as on the origin was collected based on information on the contribution of certain selected compounds or groups of compounds in the mass of PM_1 (using various approaches or different mathematical models). This work is a summary of the current state of knowledge and a base for institutions that are responsible for air quality management in Poland and which, based on already available data, could coordinate the development of PM monitoring in the missing scope. Moreover, this overview may be useful for other purposes, for example, institutions financing research in Poland and scientists applying for these funds. It seems that on the basis of the information collected here, it will be possible to assess gaps in the state of knowledge about PM_1 in Poland, its origin and its impact. Such an attempt was made by the author of the work in conclusions.

2. METHOD

The papers cited in this review were identified by searching in Google Scholar, Springer, PubMed, Science Direct and Scopus databases using the combination of the following keywords: *PM_1 concentrations in Poland*, *PM_1 in Poland*, *origin of PM_1 in Poland*, *size segregated particulate matter in atmospheric air in Poland*, and *PM mass size distribution in atmospheric air in Poland*. Only peer-reviewed research articles available in Polish and English languages published between 2005 and 2022 were considered. The survey was conducted in August 2022. In all the databases listed above about 120 000 records were found. Subsequently, papers in which the assumed keywords appeared in the title and/or in the abstract were selected. After eliminating duplicates, the extracted articles were read and those that did not match the assumed criteria were eliminated. Finally, 32 studies were selected. The results of the review are presented in the form of tables in the Appendix.

3. RESULTS

3.1. PM_1 CONCENTRATION

Fine PM research in Poland began at the beginning of the twenty-first century at the Institute of Environmental Engineering of the Polish Academy of Sciences. Since 2001, continuous, monitoring of $PM_{2.5}$ concentrations has been carried out in Zabrze, one of the cities of Upper Silesia typical in terms of air pollution and its sources. The first paper on PM_1, studied using the gravimetric method, comes from 2007 and describes the results of the first long measurement campaign in Poland taking into account this fraction (Table A1). It is not excluded that during this period in Poland, the concentration and/or

chemical composition of PM_1 and/or fine PM, in general, was monitored in other scientific centres. However, the results of these studies should not have been published so far. Based on the annual measurement series, it was possible for the first time to recognize and describe the seasonal variability of PM_1 concentrations and to indicate the shares of submicron PM in total PM in Zabrze – a typical industrialized city of Upper Silesia [8]. In the next research, the focus was on qualitative research of PM_1 collected in Zabrze, including, among others, a new technique for PM testing (XPS). It was applied to this fraction of PM, allowing us to examine the elemental composition of the surface layer of PM. The dominant role of carbon in the elemental composition was demonstrated, and further analyses allowed to indicate the carbon compounds that it forms in the surface layer of PM_1 [7].

About 5 years later, the first publication devoted to PM_1 in Lower Silesia was published [33]. Not only PM_1 but also $PM_{2.5}$ and PM_{10} concentrations were examined at several points characteristic of selected types of emissions in the urbanized urban area of Wrocław.

Subsequent work has already allowed the systematic discovery and description of PM_1 properties in other regions, especially in Silesia (quantitatively the largest amount of research). The focus was on the study of the chemical composition of PM_1 as it became clear that the results concerning only the fractional composition of PM and the shares of PM_1 in PM as well as seasonal variability of these parameters will not be sufficient either to indicate the emission sources responsible for the found – very high concentrations of PM_1 or to reliably attempt to estimate the health exposure of inhabitants of Polish cities to PM_1. Therefore, at several institutions in Poland, including Institute of Environmental Engineering of the Polish Academy of Sciences in Zabrze, Silesian University of Technology, Wrocław University of Science and Technology, Warsaw University of Life Sciences, the University of Gdańsk and the AGH University of Science and Technology in Krakow, a study of the content of selected, characteristic, PM_1 components was started or research was carried out allowing a comprehensive assessment of PM_1 macro- and microcomponents. Most studies were carried out in the southern part of Poland: in cities and suburban regions of Upper and Lower Silesia, in Krakow; several works were devoted to coastal regions and one selected location in Warsaw [9–17, 19, 21–24, 26, 27, 29, 31, 35, 37–41, 43] (Table A1).

Most attention was paid to the study of the elemental composition of PM_1. In the beginning, it seemed that the assessment of elemental composition would be a good enough source of information to assess the origin of PM_1 in almost every region. Unfortunately, the first works have already shown that this is not the case. Almost all of them signalled the blurring of the impact of various emission sources in urban areas and the inability to isolate the PM elemental profile appropriate for a specific/sought-after source. The need to collect very large data sets to assess the origin of PM in various areas and the organizational and economic problems associated with it were also pointed out. It became clear that for effective use of elemental composition data for a reliable

assessment of PM_1 origin in urbanized areas, monitoring this composition should be carried out with much higher time resolution, and preferably in semi-automatic or automatic mode [8, 13, 16, 19, 23, 24, 29, 33, 40, 41, 43].

A similar problem was noted in studies devoted to the content of polycyclic aromatic hydrocarbons in PM_1 [9–12, 23, 24]. The multitude of PAH sources in the urban space, but also the transformations of PAHs both in the atmosphere and even after collecting the sample for the filter indicated that knowledge of the content of this group of compounds in PM_1 is also not enough to assess the origin of PM_1. Nevertheless, knowledge of this parameter turned out to be crucial for the possibility of organizing different areas and regions due to the strength of the possible inhalation impact of PM_1 (short and long term) on health. In many papers, there have been attempts to estimate the impact of PM_1 on health associated with the content of PAHs and/or selected heavy metals along with attempts to assess the increase in the risk of cancer (carcinogenic risk). It has been clearly shown that the greater the impact of municipal and industrial emissions on air quality in a given area, the greater this risk is. The need to expand research on toxic and carcinogenic components in PM, especially PM_1, was also pointed out. It was also concluded that a full exposure assessment should take into account the results of tests from a long series of measurements and a full view of the chemical composition of PM_1, including knowledge of speciation forms of some metals. Regarding it, one of the world's first studies was started based on the speciation analysis of chromium and arsenic in PM, in principle in 13 PM fractions, which allowed their quantitative estimation of PM_1 mass [13]. PM_1 chemical composition research was also done based on water. It was indicated that it is an important component of PM_1. The knowledge of water content in PM_1, with properly conducted chemical analysis (temperature fractions), allows a fairly accurate determination of compounds formed by specific elements [27].

Quite an interesting approach and idea for assessing the origin of PM_1 was presented in research devoted to selected receptors in Zabrze and Katowice. It was based on examining the mass distribution relative to the aerodynamic diameter of both PM and selected compounds and elements in PM. This gave a picture of the modality of the distribution of PM and compounds in PM and the variability of this statistic depending on the place, and thus the strength of the impact of these dominant and minor sources of emissions, but also the season and thermodynamic conditions of the atmosphere. It was shown for the first time in Poland that most components, especially toxic and carcinogenic, have a peak (local maximum, the first or the only) in the range of aerodynamic diameters up to 1 μm [19, 23, 24].

Already the first studies of the content of organic carbon and selected ions extractable in water showed that secondary organic and inorganic aerosol in the case of PM_1 mass is of great importance [21, 24], especially organic secondary compounds and ammonium sulfate. Therefore, attention in further studies was directed to the assessment of the content of these components in PM_1 and attempts to use information from these

studies to assess the origin of PM_1 or at least to indicate the amount of PM_1 mass that comes from the transformation of PM precursors in the atmosphere. Most of these studies were carried out for the region of Upper Silesia and Gdynia [14, 21, 24, 26, 31, 34, 35, 38, 39].

3.2. PM_1 ORIGIN

Table A2 compiles data from studies to determine the origin of PM_1 in different areas of Poland. One of the simplest ways in which these conclusions began was to recognize the seasonal variability of concentrations of both PM_1 itself and its selected components [7, 43]. It was most often assumed that traffic emissions should have a more or less constant share in PM_1 concentrations in the summer and winter seasons, while any excess in concentration over the level read in the summer season will be caused by emissions related to energy production. This can be, depending on the receptor, either emissions associated with the combustion of fuels in heating boilers in power plants or combined heat and power plants, or emissions from the combustion of coal and other fuels in domestic boilers or both. Of course, it is clear, that this is a significant simplification and it only allows us to indicate certain trends and dependencies characteristic of places or areas in Poland. It seems that it would be a very good idea to link the data on the mass size and number size distribution of PM (or PM_1 itself) in the receptor with data about distributions of PM particles from specific sources. So far no such methodology or mathematical apparatus has been developed. Up to now, the only idea to use mass and number size distribution in the assessment of the origin of PM (including PM_1) was to analyze the variability of local maxima (their position and their number) and median value of these distributions depending on the place and season, and thus rather it was an attempt to relate the existing state to these data (if the point is close to the intersection, we assume the dominant impact of traffic emission) [18–20, 23, 42].

In the next research, simple indicators were used to assess the origin of PM_1. These were both enrichment factors (EFs) of PM_1 in selected elements and specific diagnostic ratios (based on concentrations of PAHs in PM_1). The EFs allowed us to assess, more or less, the strength of the influence of anthropogenic emission on the concentrations of a specific element in PM. Unfortunately, a huge disadvantage of this approach is in general imprecise referencing to the elemental composition of, most commonly for the soil, the upper continental crust composition, which represents the averaged composition. It is clear that it is a matter with completely different grain sizes and properties than the one that creates mineral matter of natural origin in the area of research (each of the analyzed). Therefore, it would be ideal to select such matter in the receptor each time and relate the obtained results regarding the content of elements in PM_1 to its elemental composition. However, even these simple calculations also allowed to divide the elements studied in PM_1 in some way [19, 22, 24, 41]. This did not give any knowledge about their sources, but allowed, for example, their inclusion in specific types of matter

quite precisely, and further the use of quite precise stoichiometric calculations aimed at determining the total mass of compounds that were present in PM_1 [18–20, 22]. It should be emphasized that this approach is unique in the literature and has the potential to further develop and undertake wider applications in combination with knowledge about the elemental composition of mineral matter in a given receptor.

In the case of diagnostic ratio, many reports and data from the world literature were used to interpret them: about the values in specific sources or groups of sources assumed by the relations of specific PAHs in the PM sample. These values were related each time to the values obtained for PM_1 in any receptor [10, 23, 24]. Again, the weakness of this methodology was a non-strict approach to data on PAHs' relations in PM from specific sources, i.e., to data constituting a kind of reference. It was never (in the case of any of the sources) PM with such a grain size distribution as PM_1, and it had a completely different chemical composition. The chemical composition of PM emitted from a specific source as well as different (than in the tested receptors) thermodynamic conditions cause, among others, a completely different distribution of PAH into those in the volatiles and solids. What is more, the PAHs collected in PM_1 studies in Poland should usually be suspected of being partially altered in relation not only to PAHs in various sources but also to PAHs in the receptor (artifacts resulting from the time of collection, method of collection, time in transport and many other factors). However, some clues have been found regarding the variability of diagnostic ratio values in different areas and conditions through this simple method.

In some of the papers collected in Table A2, statistical methods were used to assess the origin of PM_1, including in particular: principal component analysis PCA and positive matrix factorization PMF [13, 14, 27, 29, 40]. It is assumed that these are some of the best methods used to assign specific concentrations to specific sources in a specific receptor [5]. In this way, i.a. was shown that the origin of PM_1 differs qualitatively and quantitatively between Zabrze and Warsaw. It was possible to capture the impact of industrial emissions in the cities of Upper Silesia on PM_1 concentrations or typical municipal emissions in almost every of the studied areas, including for example Krakow. Nevertheless, the correctness of the results obtained was dependent quite strongly on two main factors: 1. If the statistical methods were applied to all components of PM_1 or only to the elemental composition of PM_1, 2. How large were the analyzed data sets. The first factor is crucial because only knowledge of the mutual relations of some water-soluble ions in PM_1 or the relationship between concentrations of organic and elemental carbon allows to estimate, more or less accurately, the amount of secondary matter in PM_1. Without knowledge of the share of this matter and linking it with specific sources, it is not possible, on the basis of knowledge only about the dependencies of the elements themselves, to assign specific emission sources to PM_1. As for the second factor – the number of data samples used in statistical analyses – it should be said that this is the biggest drawback of research so far. Generally, whether PCA or PMF is used, in a general sense, a matrix is built, which is transformed (rotated) so as to reduce the number

of variables (e.g., data on element concentrations). Of course, it is practically impossible to obtain pure components (sources), so such a rotation is chosen to make it as good as possible. The mathematical parameter limiting the applicability of these techniques is the rank of this matrix. The rank of the matrix is not greater than both the number of samples and the number of analyzed components. Due to the fact that elements of this matrix are results of measurements and elements with zero concentration or empty samples were priorly removed, the rank equals the minimum of number of samples and number of analyzed parameters of PM. If the decomposition in both PCA and PMF have to give interpretable results, the number of components has to be significantly lower than the rank, since it is obvious, for example, that having 12 samples of PM analyzed for 20 components, the decomposition into 12 components will give ideal, useless result, that every source is responsible for a single sample. Similarly, the decomposition of 365 samples of 4 parameters into 4 or even 3 components will not give good results. Hence, it is important to understand that both the number of non-zero analyzed parameters as well as the number of samples have to be significantly larger than the assumed number of sources in the PCA or the PMF procedure.

However, in general, undertaking this research was reasonable. It pointed out some problems and limitations but also pointed to the methods and skills that should be developed in the future and on which it is necessary to work. The authors' experiences described in the discussions (Tables A1 and A2) and the conclusions from these works show also other problems besides the typically economic and technical ones were faced in experiments, namely the resolution of sampling, the availability of measurement sites, the cost of chemical analyses, etc. Problems related to the research itself and the possibility of ensuring the appropriate quality and reliability of the obtained results were also shown. Some papers refer to typical artefacts, but also to problems related to contamination of blanks (among others, filters) or difficulties in obtaining adequate weighing accuracy (hygroscopicity and electrostatic of filters).

So far, it seems that exhaustive PM_1 studies have been carried out using a simple methodology of chemical mass closure [18–20, 22, 26]. Although they do not give the possibility of accurately assigning part of the PM_1 mass to a specific source, they give an almost complete picture of the division of PM_1 into specific groups of matter. PM_1 sources can be quite accurately divided combining these studies with a thorough analysis of meteorological conditions (including the analysis of air mass inflows per receptor) and analysis of gaseous air pollutants. What is also important, this methodology does not require a huge amount of data, but only the selection of representative measurement periods and the use of a well-thought-out strategy of collecting PM_1 and directing samples for specific analyses. It is almost certain that such a step (chemical mass closure analysis) should start each subsequent experiment in which the final result would be a quantitative assignment of PM_1 mass to sources.

4. CONCLUSIONS

In Poland, in many areas, PM_1 research has not been conducted so far. While in Upper and Lower Silesia or Krakow and Gdynia PM_1 have been quite intensively studied, there are regions of Poland where such research is missing. Therefore, there are reasons to focus on research in at least a few large cities where air quality problems periodically appear, e.g., Opole, Rzeszów, Łódź or Lublin. Research in other regions, including non-urban, is also important. They will identify the influx of polluted air from urban areas and assess its contribution to PM_1 concentrations. To properly assess the origin of PM_1, systematic studies are needed not only of PM precursors such as SO_2, NO_x, O_3 or VOCs but also of other parameters such as variability of ammonia concentrations in selected regions.

The research conducted so far lacks a certain regularity and consistency. It seems that, for example, when examining the composition of PM_1 to assess the exposure of residents, it will be good to focus on comprehensive research in the future. In large cities, there are no studies devoted to the simultaneous study of several groups of toxic and/or carcinogenic components in PM_1 along with additional parameters determining overall exposure (e.g., concentration of PAHs in the gas phase or VOCs concentration) and linking future analyses with the actual state (data on average age, etc., from a given place and not from the literature).

There is a shortage of large collections of data on the chemical composition of PM_1 which would give the possibility of effective use of popular statistical methods to assess the origin of PM_1. This proposal concerns many regions in Poland. In addition, it seems necessary to apply a case-by-case approach to data from each area, taking into account its specificities. So far, the results have not given clear answers in any receptor as to the percentage share of individual emitters in PM_1 concentration. Perhaps the lack of inclusion in the analysis of certain data, such as data on PM precursors or their initial analysis using chemical mass closure, will allow us to achieve clear answers in the next steps.

Previous studies also indicate that some specific sources of emissions depending on the region should not be overlooked, such as industrial emissions. Therefore, it seems appropriate to determine the exact profiles of PM_1 emissions and their precursors for typical and unusual (incidental) Polish emitters. It is also impossible to ignore the contribution of periodic incidents such as grass burning, landfill fires, forest fires or mass events using flares, smoke candles or fireworks.

So far, data on the mass distribution of PM_1 have been published only for the region of Upper Silesia (several receptors). It seems that such data could be used to assess the origin in almost every region after the development of a certain mathematical apparatus. Given that these distributions are characteristic of each source, size distribution in the receptor is the same (if not better) parameter of PM for assessing the origin of PM as the chemical composition of PM. For future studies, one should consider whether mon-

itoring the distributions themselves, both the mass, number and volume of PM_1 particles, would not be more efficient in assessing the origin of PM_1. It is worth noting that there are already many automatic devices that give results equivalent to reference methodologies in the field of PM mass concentrations, whose principle of operation forces the measurement of PM concentration in many particle size ranges. This data can be successfully used with proper processing.

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APPENDIX

Table A1

Results of the research on PM_1 concentrations in Poland over the period 2006–2022

No.	Details of measurement	Results/Insights
1	Zabrze, urban background 17 January–30 December 2006 Concentration of PM_1, $PM_{2.5}$, PM_{10} and total PM Klejnowski et al. 2007 [7]	In summer, PM_1 concentrations ranged from 3.7 to 94.58 µg/m³; the mean concentration was 25.13 µg/m³. The average share of PM_1 in total PM was about 54%. In winter, PM_1 concentrations ranged from 11.23 to 204.28 µg/m³; the mean PM_1 concentration was 57.43 µg/m³. The average share of PM_1 in total PM was ca. 65%. Submicron particles accounted for about 70% of fine PM.
2	Zabrze, urban background June–August 2007; October 2007–January 2008 Concentration and chemical composition of a surface layer of PM_1, $PM_{2.5}$, PM_{10} Klejnowski et al. 2012 [8]	The average PM_1 concentration in summer was 10.39 µg/m³ and in winter 40.73 µg/m³.
3	Wrocław, urban background May–July 2011 Concentration of PM_1, $PM_{2.5}$, PM_{10} Sówka et al. 2012 [33]	PM_1 concentrations ranged from 6.26 to 18.36 µg/m³. Research showed the dependence of PM_1 concentrations on the degree of urbanization and land transformation. The highest PM concentrations were recorded in sites characterized by high car traffic.
4	Zabrze, urban background 7 May–2 August 2007; 26 October–27 December 2007 Concentration of 13 fractions of PM and PM-bound PAHs and heavy metals Rogula-Kozłowska et al. 2012 [23]	The average PM_1 concentration in summer was 9.65 µg/m³ and in winter 33.65 µg/m³. In summer, PM_1 accounted for 51% and in winter 72% of PM_{10}. In summer, PM_1 was dominated by particles with aerodynamic diameters of 0.4–0.65 µm, while in winter 0.26–0.4 µm.
5	Zabrze, urban background Racibórz, rural background 1 August–31 December 2009; 1 August–31 December 2010 Concentration and chemical composition of PM_1 EC and OC, ions Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, NO_3^-, SO_4^{2-}, 21 elements), Rogula-Kozłowska et al. 2013 [22]	In Zabrze, the monthly average PM_1 concentrations were in the range of 16.66 –60.17 µg/m³. The highest average concentration of PM_1 was recorded in November and the lowest in August. In Racibórz, the average monthly PM_1 concentrations ranged from 13.32 to 57.27 µg/m³ and the highest one was recorded in December. 50% of PM_1 in Zabrze and 40% in Racibórz was a secondary aerosol derived from the transformation of gaseous PM precursors.

Table A1

Results of the research on PM_1 concentrations in Poland over the period 2006–2022

No.	Details of measurement	Results/Insights
6	Zabrze, urban background 26 October–7 December 2007; 11 January–22 March 2008 Concentration of PAHs and metals (Cr, Mn, Co, Ni, As, Se, Cd, Pb) in 13 PM fractions Rogula-Kozłowska et al. 2013 [24]	The average PM_1 concentration in the period 26 October–27 December 2007 was 33.65 μg/m³ and in the period 11 January–22 March 2008 25.55 μg/m³. In the first period, PM_1 accounted for 73%, and in the second period 66% of PM_{10}.
7	Wrocław, city centre December 2009–October 2010 Elemental composition and concentrations of PM_1, $PM_{2.5}$ and PM_{10} Zwoździak et al. 2013 [43]	In summer, PM_1 concentrations ranged from 3.7 to 25.5 μg/m³, and the average concentration was 8.9 μg/m³ while in winter, PM_1 concentrations ranged from 16.4 to 40.7 μg/m³, and the average concentration was 25.5 μg/m³.
8	Racibórz, quasi-rural background 1 January–30 June 2011 Concentration and chemical composition of PM_1 (EC and OC, water-soluble ions, 21 metals) Rogula-Kozłowska et al. 2014 [21]	Average monthly PM_1 concentrations ranged from 11.1 to 40.1 μg/m³. The average PM_1 concentration for the entire measurement period was 26.2 μg/m³. Average monthly PM_1 concentrations were at least twice as high in the cold season (January–March) as in the warm season (April–June). The maximum 24-hour concentration of PM_1 was recorded in January and reached 124.1 μg/m³.
9	Warsaw, allotments February, June, September, November in the years 2011–2014 Concentration of PM_1, $PM_{2.5}$, PM_{10} Dmochowski et al. 2015 [2]	In the allotment gardens, 11 measurement sites were designated depending on the distance from the Łazienkowska Thoroughfare and Waszyngtona Avenue – two main streets in the Praga Południe district. A decrease in PM_1 concentrations occurred along with the increasing distance from the streets. The lowest average concentrations of PM_1 were recorded in 2012 and, depending on the distance from these streets in the range of 20–40 μg/m³, and the highest in 2013 – 55–110 μg/m³.
10	Katowice, urban background Złoty Potok, regional background Katowice, urban traffic site 2 August 2009–27 December 2010 The concentration of PM_1-bound PAHs Kozielska et al. 2014 [10]	During the heating season, the average PM_1 concentration for the regional background point (village Złoty Potok) was 16.37 μg/m³ (3.49–71.41 μg/m³), for the urban background 40.70 μg/m³ (17.33–73.59 μg/m³), and urban traffic site 41.55 μg/m³ (20.50–88.34 μg/m³). In the non-heating season, the average concentrations of PM_1 were respectively: 10.32 μg/m³, 4.82–16.06 μg/m³), 20.83 μg/m³ (7.99–34.86 μg/m³), 18.40 μg/m³ (11.83–27.72 μg/m³).

Table A1

Results of the research on PM_1 concentrations in Poland over the period 2006–2022

No.	Details of measurement	Results/Insights
11	Katowice, traffic site (A4 motorway and intersection) Motorway – 13 March–19 June 2012; Intersection – 20 June–3 September 2012 Concentration and elemental composition of PM_1 and mass-size distribution of PM Rogula-Kozłowska 2015 [19]	The average PM_1 concentration at the measuring point located at the A4 motorway was 18.75 µg/m³, while at the intersection it was 12.14 µg/m³. The average mass share of submicron particles in total PM was slightly higher on the highway (62%) than at the intersection (55%).
12	Katowice, urban background, Złoty Potok, rural background, A4 motorway in Katowice, traffic site 2 August 2009–27 December 2010 Optical properties and concentration of PM_1 and $PM_{2.5}$ Pastuszka et al. 2015 [17]	In summer, PM_1 concentrations in all locations were 20.83, 10.32, and 18.40, while in winter 40.70, 16.37, 41.55 µg/m³, respectively, fluctuating more in winter than in summer. PM_1 was characterized by a higher light reflectance and mass light absorption coefficient than $PM_{2.5}$. Higher light absorption coefficients were recorded for PM_1 during the heating season, which was associated with a higher content of organic and inorganic matter in submicron particles.
13	Upper Silesia, vicinity of four coal-fired power plants 28 May–23 September 2014 Concentration of metals (As, Cd, Co, Cr, Hg, Mn, Ni, Pb, Sb, Se) in PM_1 Zajusz-Zubek et al. 2015 [40]	The average concentrations of PM_1 in the vicinity of the power plants located in Golejów, Świerkle, Czyżówka and Jaworzno were 12.78 µg/m³ (8.80–17.56), 8.68 (4.24–13.96), 8.74 (6.03–10.29) and 8.13 (4.31–11.62) µg/m³, respectively.
14	Wrocław, urban background July–August 2015 Concentration of PM_1, $PM_{2.5}$, PM_{10} Sówka et al. 2016 [34]	PM_1 concentrations ranged from 0.73 to 11.96 µg/m³. The average PM_1 concentration in the analyzed period was 7 µg/m³.
15	Zabrze, Warsaw, urban background 24 June 2014–22; August 2014 8 January 2015–8 March 2015 Concentration and chemical composition of PM_1 Widziewicz et al. 2017 [37]	In summer, PM_1 concentrations in Warsaw (11.01 µg/m³) and Zabrze (10.77 µg/m³) were similar. In winter, in Zabrze, the PM_1 concentration was more than three times higher than in summer (44.52 µg/m³) and more than twice as high as in Warsaw (16.35 µg/m³). High concentrations in winter were caused by the existing heating period, temperature inversion, and low wind speed. The paper also presents PM_1 concentrations depending on rainy seasons. In general, the rain had a cleansing effect, causing in most cases (except Zabrze in summer) a decrease in PM_1 concentrations, especially in winter.

Table A1

Results of the research on PM_1 concentrations in Poland over the period 2006–2022

No.	Details of measurement	Results/Insights
16	Gdynia, urban background 27 February–27 March 2013; 19 June–9 July 2013; 24 October–12 November 2013; 8 April–11 May 2014 Concentration of water-soluble organic carbon in aerosol (PM_1, $PM_{2.5}$, PM_{10}) Witkowska et al. 2016 [39]	The average PM_1 concentration in winter, spring, summer and autumn was 3.5 (1.5–8.7), 3.3 (2.2–4.5), 1.3 (0.9–2.1) and 1.7 (0.7–2.8) µg/m³, respectively. Average PM_1 concentrations for the heating and non-heating seasons were 2.8 (0.6–8.7) and 2.5 (0.9–4.5) µg/m³.
17	Wrocław, urban background with equal distribution of blocks of flats and individual housing 9 January–26 I 2016; 9 May–23 May 2016 Concentration of PM_1 and metals (As, Cd, Ni) Pachurka et al. 2017 [16]	The average concentration of PM_1 in the spring season was 8.05 (3.2–11.53) µg/m³, while in winter it was 18.16 (2.84–38.20) µg/m³.
18	Kraków, urban background 2 March–14 May 2015; 8 March–22 May 2016 Concentration and chemical composition of PM_1 and $PM_{2.5}$ Samek et al. 2017 [28]	In 2015, the average concentration of PM_1 was 19 (3.6–74) µg/m³, and in 2016 it was 11.7 µg/m³ (4.2–24.6 µg/m³). In both 2015 and 2016, the highest concentrations of PM_1 were recorded in March. In 2015, submicron particles accounted for about 70% of the mass of $PM_{2.5}$, and in 2016 about 60%.
19	Upper Silesia, close neighbourhood of coke plant 4 May–28 August 2015 Concentration and elemental composition of PM_1 Zajusz-Zubek et al. 2017 [41]	The research was conducted near four coking plants located in different towns in Upper Silesia. The mean PM_1 concentration was 12.17 (3.08–26.37) µg/m³. Among all the examined locations, the lowest average concentration of PM_1 was recorded at point K3 (rural area, Łęka – district of Dąbrowa Górnicza) – 3.85 µg/m³, while the highest concentration was recorded at point K4 – 17.35 µg/m³ (urban area, Bytom).
20	Gliwice, urban background April–June (year not specified in the publication) The concentration of PM_1-bound PAHs Kozielska 2018 [9]	PM_1 concentration in spring was in the range of 9.9–73.7 µg/m³, and the average concentration was 23.9 µg/m³.

Table A1

Results of the research on PM_1 concentrations in Poland over the period 2006–2022

No.	Details of measurement	Results/Insights
21	Gdynia, sea shore 1 January–31 December 2012 Concentration of Hg, OC, EC in PM_1 Lewandowska et al. 2018 [11]	The average annual concentration of PM_1 was 27.4 μg/m³. Monthly average PM_1 concentrations ranged from 16.8 to 37.5 μg/m³. The highest monthly average PM_1 concentration was recorded in February and the lowest in August. Dividing the measurement periods into the non-heating season (May–September) and the heating season (January–April, October–December), the average PM_1 concentrations were 24.4 and 28.6 μg/m³, respectively. The maximum 24-hour concentration of PM_1 was recorded in February – 106.7 μg/m³.
22	Gdynia, urbanized coastal zone 1 January–31 December 2012 Concentration of B(a)P, OC, EC in PM_1 and $PM_{2.5}$ Lewandowska et al. 2018 [12]	The mean annual concentration of PM_1 was 27.5 μg/m³. In summer, the average PM_1 concentration was 25.2 (5.8–61.2) μg/m³, and in winter 31.5 (4.5–106.7) μg/m³.
23	Warsaw, urban background 24 June–22 August 2014; 8 January–8 March 2015 Concentration and chemical composition of PM_1 (primary and secondary organic matter and inorganic matter, EC, Na^+, Cl^-), concentration of PM_{10} Majewski et al. 2018 [14]	The average PM_1 concentration in summer and winter was 11 and 17 μg/m³, respectively. In summer, PM_1 particles accounted for about 60% of the mass of PM_{10}, and in winter 40%. The effect of air temperature and precipitation on PM_1 concentrations was demonstrated. The main component of PM_1 was secondary aerosol which accounted for about 57% of the PM_1 mass in winter and 56% in summer. This means that most of the mass of PM_1 in the air came from the transformation of volatile organic compounds, sulfur and nitrogen oxides and ammonia.
24	Zabrze, urban background Warsaw, urban background 24 June–22 August 2014; 8 January–9 March 2015 Concentration and chemical composition of PM_1 (water content, water-soluble ions, OC and EC) Rogula-Kozłowska et al. 2018 [27]	In summer in Zabrze, the average PM_1 concentration was 12.14 (6.47–19.14) μg/m³, while in Warsaw 11.07 (5.67–22.62) μg/m³. In winter, the average PM_1 concentration in Zabrze was 47.14 (8.30–198.50) μg/m³, while in Warsaw 17.41 (4.70–39.00) μg/m³. In Zabrze, the highest concentrations of PM_1 were recorded on 13 February 2015, and in Warsaw on 5 February 2015.
25	Kraków, urban background 2 July 2016–27 February 2017 Concentration and elemental composition of PM_1 and $PM_{2.5}$ Samek et al. 2018 [29]	The average PM_1 concentration in summer was 6.9 μg/m³ and in winter 17.3 μg/m³. In summer, PM_1 accounted for 58% of fine particulate matter, while in winter 29% because the concentration of PM_1 increased slightly during winter compared to a fivefold increase in $PM_{2.5}$ concentration.

Table A1

Results of the research on PM_1 concentrations in Poland over the period 2006–2022

No.	Details of measurement	Results/Insights
26	Poznań, urban background 25 October–22 November 2016; 5 June–20 July 2017 Concentration of PM_1, $PM_{2.5}$, PM_{10}, dependence on atmospheric conditions Sówka et al. 2018 [32]	PM_1 concentration in summer ranged from 2.72 to 10.35 µg/m³, and in winter from 2.47 to 22.87 µg/m³. The average concentration in summer was 5.72 µg/m³ and in winter 8.50 µg/m³.
27	Gliwice, surroundings of school, urban area 24 March–23 May 2014 Upper Silesia, surroundings of 4 power plants, rural area 28 May–20 September 2014; 4 May–28 August 2015 Concentration, elemental composition (metals) of PM_1 Mainka et al. 2019 [13]	The average concentration of PM_1 in rural areas was 9.5 µg/m³ and in urban areas 20.0 µg/m³.
28	Zabrze, urban background 24 June–24 August 2014; 8 January–8 March 2015 Concentration of arsenic species in PM_1 Nocoń et al. 2019 [15]	In summer, the average 24-hour PM_1 concentration was in the range of 4.58–18.92 µg/m³, while the average PM_1 concentration in summer was 10.52 µg/m³. In winter, the average PM_1 concentration was 38.12 µg/m³. The average 24-hour PM_1 concentration in winter ranged between 14.82 and 93.48 µg/m³.
29	Gdynia, urban background 22 December 2016–22 January 2017 Concentration and chemical composition of PM_1 and $PM_{2.5}$ (OC and EC, PAHs) Wiśniewska et al. 2019 [38]	Average daily concentrations of PM_1 were in the range of 6.0–50.0 µg/m³, while the average PM_1 concentration throughout the measurement period was 15.1 µg/m³. The highest concentrations of PM_1 were recorded in southern and south-western advection.
30	Wrocław, Poznań, urban background 26 June–26 July 2014; 7 January–7 February, 31 July–13 August 2015; 9–26January; 9–23 May 25 October–22 November 2016; 5 June–2 July 2017 Concentration and chemical composition of PM_1, $PM_{2.5}$, PM_{10} Sówka et al. 2019 [31]	In Wrocław, in summer, the average daily PM_1 concentrations were in the range of 0.73–11.96, and in winter 2.84–38.20 µg/m³. The average PM_1 concentration in summer was 7.68 and in winter 13.98 µg/m³. Higher concentrations were recorded in 2016 than in 2015. In Poznań, in summer, the average daily PM_1 concentrations were in the range of 2.72–10.35, and in winter 2.47–22.87 µg/m³. The average PM_1 concentration in summer was 5.72 and in winter 8.50 µg/m³.

Table A1

Results of the research on PM_1 concentrations in Poland over the period 2006–2022

No.	Details of measurement	Results/Insights
31	Zabrze, Warsaw, urban background 24 June–22 August 2014; 8 January–8 March 2015 Concentration and chemical composition of PM_1 (EC, OC, water-soluble ions, i.e., Na^+, NH_4^+, Cl^-, SO_4^{2-}, NO_3^-) Rogula-Kozłowska et al. 2019 [26]	In summer, the average PM_1 concentration in Zabrze and Warsaw was comparable and amounted to 12.1 and 11.1 μg/m³, respectively. In winter, the PM_1 concentration in Zabrze (47.1 μg/m³) was ca. 4 times higher than in summer and almost 3 times higher than in Warsaw (17.4 μg/m³). In winter, there were days when in Zabrze the maximum PM_1 concentration reached 200 μg/m³ in Zabrze and 40 μg/m³ in Warsaw.
32	Kraków, urban background 8 January 2018–10 April 2019 Concentration and chemical composition of PM_1 (organic compounds and Cl^-, NH_4^+, SO_4^{2-}, NO_3^-) Tobler et al. 2021 [35]	Average monthly PM_1 concentrations ranged from 15.9 μg/m³ (May 2018) to 61.1 μg/m³ (January 2019). The highest hourly concentration was 251.2 μg/m³ (January 2018).

Table A2

Origin of PM_1

No.	Place\Date\Reference	PM_1 source and apportionment method
1	Zabrze, urban background 17 January–30 December 2006 Klejnowski et al. 2007 [7]	Traffic emission. Analysis of seasonal variation of mass concentration and fractional composition of PM
2	Zabrze, urban background 7 May–2 August 2007, 26 October–27 December 2007 Rogula-Kozłowska et al. 2012 [23]	In winter, the burning of coal, wood and garbage. In summer, traffic emissions, mainly associated with the combustion of petroleum Diagnostic ratios calculated from PAH concentrations
3	Zabrze, urban background 1 August–31 December 2009 Racibórz, rural background 1 August–31 December 2010 Rogula-Kozłowska et al. 2013 [22]	In Zabrze, in both seasons, traffic emissions, municipal emissions and industrial activity. In Racibórz, in winter, the combustion of solid fuels in domestic furnaces, and heating boilers, pollution from the Czech Republic and Germany brought by south-western winds. In summer, the combustion of biomass (leaves, wood) in home furnaces Analysis of PM_1 chemical mass closure and enrichment factors calculated based on the elemental composition of PM_1
4	Zabrze, urban background 26 October–27 December 2007; 11 January–22 March 2008; Rogula-Kozłowska et al. 2013 [24]	Stationary, coal and wood combustion and fuel combustion in car engines Analysis of the chemical composition of PM, enrichment factors calculated based on the concentration of metals in PM_1 and diagnostic ratios calculated based on PAH concentrations
5	Wrocław, city centre December 2009–October 2010 Zwoździak et al. 2013 [43]	Coal combustion and traffic emissions Analysis of the chemical composition of PM, Spearman's rank correlation
6	Racibórz, quasi-rural background 1 January–30 June 2011 Rogula-Kozłowska et al. 2014 [21]	Anthropogenic emissions (combustion of coal, waste and biomass in household furnaces and energy production based on the combustion of hard coal and lignite), the transformation of gaseous PM precursors Analysis of the chemical composition of PM_1, the relationships between its components
7	Katowice, urban background Złoty Potok, regional background Katowice, urban traffic site 2 August 2009–27 December 2010 Kozielska et al. 2014 [10]	In the non-heating season, mainly traffic emissions in all locations. During the heating season, at the urban background point municipal emissions, i.e., coal and biomass combustion in domestic furnaces, and energy production based on the use of hard coal and lignite. At the urban traffic site in winter, also traffic emissions. At the point located in the countryside (regional background), PM_1 concentrations determined by the influx of polluted air Analysis of PAHs concentrations and correlations between individual PAHs compounds

Table A2

Origin of PM_1

No.	Place\Date\Reference	PM_1 source and apportionment method
8	Katowice, traffic site A4 motorway and intersection Motorway 13 March–19 June 2012 Intersection 20 June–3 September 2012 Rogula-Kozłowska 2015 [19]	Exhaust and non-exhaust traffic emissions, condensation of gaseous organic compounds and photochemical transformations of volatile organic compounds and inorganic gaseous precursors. Additionally in winter, the burning of low-quality coal and waste Analysis of PM_1 chemical mass closure and enrichment factors calculated based on concentrations of metals in PM_1
9	Upper Silesia, the neighbourhood of four coal-fired power plants 28 May–23 September 2014 Zajusz-Zubek et al. 2015 [40]	In sites in rural areas, agricultural activities in their vicinity, in sites located closer to urban areas, by urban sources. The identified sources of PM_1 include traffic emissions, combustion of fossil fuels, and crustal matter Principal components analysis (PCA) and enrichment factors based on concentrations of metals in PM_1
10	Zabrze, Warsaw, urban background 24 June 2014–22 August 2014; 8 January 2015–8 March 2015 Widziewicz et al. 2017 [37]	In Warsaw, in both seasons, mainly traffic emissions, as evidenced by the slight difference in PM_1 concentrations between the seasons. In Zabrze, mainly coal combustion and industrial activity Analysis of PM_1 chemical composition and meteorological conditions
11	Upper Silesia, close nationhood of coke plant 4 May–28 August 2015 Zajusz-Zubek et al. 2017 [41]	All analyzed elements present in PM, and the PM itself, mainly from anthropogenic sources: thermochemical processing of coal and resuspension of road dust Analysis of PM_1 chemical composition and enrichment factors based on the concentration of metals in PM_1
12	Gdynia, seashore 1 January–31 December 2012 Lewandowska et al. 2018a [11]	In winter, the consumption of fossil fuels for heating purposes, in summer, maritime transport and activities in the port and shipyard Analysis of the chemical composition of PM_1, the correlation between concentrations of mercury and elemental and organic carbon
13	Gdynia, urbanized coastal zone 1 January–31 December 2012 Lewandowska et al. 2018 [12]	In winter, the burning of coal and wood for heating purposes in individual home furnaces. In summer, traffic emissions. The source with periodic impact on PM_1 concentrations – maritime transport, daily activity at the Port of Gdynia and the use of the access channel to the Port of Gdynia by ships and ferries Analysis of PM_1 and PM_1-bound PAHs, OC and EC concentration; of PAHs/OC, OC/EC coefficients
14	Warsaw, urban background 24 June–22 August 2014 8 January–8 March 2015 Majewski et al. 2018 [14]	15% of PM_1 from traffic emissions, 51% from the combustion of fuels for heating and energy production, PM gaseous precursors (OCs, NO_x, SO_x) Principal component analysis (PCA) and multiple linear regression analysis (MLRA)

Table A2

Origin of PM_1

No.	Place\Date\Reference	PM_1 source and apportionment method
15	Kraków, urban background 2 July 2016–27 February 2017 Samek et al. 2018 [29]	In winter, transformations of PM gaseous precursors (63%), combustion of fuels for heating purposes (27%), resuspension of dust from the soil, industry and traffic emission (10%). In summer, secondary aerosol transformations (49%), traffic emissions, soil dust resuspension and industry (19%) Chemical composition analysis and positive matrix factorization (PMF)
16	Zabrze, urban background Warsaw, urban background 24 June–22 August 2014 8 January–9 March 2015 Rogula-Kozłowska et al. 2019 [27]	In Warsaw, PM_1 in summer, combustion of solid fuels (hard coal, biomass), but not necessarily from local emissions; soil dust resuspension, and traffic emissions. In winter, the combustion of coal and natural gas for heating and the combustion of liquid fuels in car engines. In Zabrze, natural sources, transport emissions and biomass combustion, in winter from coal combustion and transformations of dust gaseous precursors Chemical composition analysis of PM and principal component analysis (PCA)
17	Gliwice, surroundings of school, urban area 24 March–23 May 2014 Upper Silesia, surroundings of four power plants, rural area 28 May–20 September 2014; 4 May–28 August 2015 Mainka et al. 2019 [13]	Resuspension of road dust, including PM from abrasion of vehicle components, and resuspension of soil dust contaminated with stored sewage sludge in agricultural areas, and industrial activities Analysis of elemental composition of PM and principal component analysis (PCA)
18	Gdynia, urban background 22 December 2016–22 January 2017 Wiśniewska et al. 2019 [38]	Transport emissions on the Tri-City ring road, combustion of coal and wood for heating purposes, oil burning Analysis of chemical composition and meteorological conditions, especially the direction of inflow of air masses, diagnostic ratios
19	Zabrze, urban background Warsaw, urban background 24 June–22 August 2014; 8 January–8 March 2015 Rogula-Kozłowska et al. 2019 [26]	In Zabrze, the combustion of coal, biomass and plastic in home furnaces, to some extent traffic emissions and coal combustion in power plants. In Warsaw, traffic emissions and gas combustion, and in winter, additional coal combustion in large municipal power plants. A significant impact of traffic emissions on PM_1 concentrations in Warsaw evidenced by the share of secondary transformation products (45% in summer, 66% in winter), which in winter was higher than in Zabrze (47% in summer, 37% in winter) Analysis of PM_1 chemical composition including chemical mass closure, analysis of Pearson correlation coefficients and selected ratios (e.g., EC/OC, SO_4^{2-}, NH_4^+)