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BAN ON THE BURNING OF SOLID FUELS IN DOMESTIC FURNACES AND ITS IMPACT ON AIR QUALITY – EXAMPLE OF KRAKOW

The present study assessed the effectiveness of the ban on the burning of solid fuels in domestic furnaces imposed in Krakow, a city of almost one million people, to reduce particulate emissions. The assessment was carried out based on the database of the Inspectorates for Environmental Protection using data on air concentrations of PM2.5, PM10, NO_2, SO_2, O_3 and B[a]P. Our analysis showed that between 2010 and 2021, the annual average concentrations of PM10, PM2.5, NO_2, SO_2 and B[a]P in Krakow decreased by 42%, 40%, 6%, 50% and 60%, respectively, while the annual mean ozone concentration in the city increased by 21.2%. The largest decreases in air concentrations of PM10 (56%), PM2.5 (55%), B[a]P (71%) and SO_2 (75%) were seen in heating seasons. A significant finding from our study was that, as a result of the measures taken, the annual mean concentrations of SO_2 and NO_2 in Krakow did not exceed the legal limit values for the pollutants in any of the years analysed and that the legal limit value for the annual mean concentration of PM10 was not exceeded since 2019. A negative finding was that the limit/target values for PM2.5, B[a]P and the maximum daily 8-hour mean ozone concentration were not met. Although an anti-smog resolution was implemented in Krakow, the air quality during the analysed period remained poor, particularly in heating seasons, and the goals for reducing pollutant emissions were not achieved. However, while the objectives for reduction in PM10, PM2.5 and B[a]P emissions were not met, the reductions in emission levels achieved in Krakow were significantly better than those seen for the entire Małopolska Province. This undoubtedly results from the gradual reduction in the number of solid fuel furnaces and boilers in Krakow, which in turn led to large reductions in particulate and B[a]P emissions from the municipal and residential sectors. Our analyses showed that while the measures taken yielded good results, it is necessary to introduce other solutions to further reduce air pollution in the city.

Keywords: Agglomeration; air pollution; particulate matter; anti-smog resolution; low-height emissions

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1. Introduction

Air pollution is an environmental factor that has the greatest negative impact on human life and health [1-3]. Depending on the substance and duration of exposure, it can lead to several health issues and diseases, mainly those related to the circulatory and respiratory systems, but also those involving the reproductive and nervous systems [4,5]. Air pollution is particularly harmful to children, the elderly and individuals with chronic conditions [6]. It is estimated that every year several million people die worldwide due to poor air quality [7,8].

Polish cities have some of the worst air quality in the EU in terms of PM10, PM2.5 and benzo[a]pyrene. In 2011, as many as 6 out of 10 European cities with the largest number of days when the daily mean limit value for PM10 (50 $\mu g/m^3$) was exceeded were located in Poland. In 2012, the highest annual mean PM2.5 concentrations were recorded at measuring stations in Krakow and Nowy Sącz (both cities are located in southern Poland). In the same year, Poland had the highest annual mean B[a]P concentrations of any European country, followed by Czechia, where the annual mean B[a]P concentration was 3 times lower than that in Poland. As for NO_2 levels, air quality in Poland seems to be significantly better. However, annual mean NO_2 concentrations near the main roads running through large cities such as Krakow or Warsaw exceed the limit value. London is also one of the most NO_2 polluted cities. In turn, the ozone pollution level in Poland is lower than that in southern Europe [9].

Krakow has been dealing with the problem of poor air quality for years. Air quality in Krakow deteriorated due to the city's developing industry and transport sectors and growing population (806,200 people as of now). At the beginning of the 1970s, the annual average concentrations of PM10 in the city exceeded 130 $\mu g/m^3$, which is more than 3 times higher than the current limit value. The highest SO_2 concentrations in Krakow were recorded at the end of the 1980s. They were more than 5 times higher than the limit value for the pollutant. While air pollutant concentrations in Krakow decreased over time, air quality in the city remained very poor.

The important measures taken to reduce low-height emissions in Krakow included the replacement of coal-fired furnaces and boilers, installation of renewable energy sources (i.e. biogas, photovoltaic panels, solar collectors, heat pumps), provision of residential and public buildings with thermal insulation and expansion of district heating and gas networks. Measures were also taken to reduce emissions from transport. They included the purchase of zero- and low-emission public transport buses, the development of new routes for public and cycle transport, the modernisation and repair of tram tracks, the establishment of a paid parking zone and the removal of dust from roads. In order to reduce emissions from industry, inspections were carried out at the highest-emitting plants and a database of pollution emissions from industrial plants was established [10,11].

The one measure that was expected to produce the biggest environmental benefits was the reduction of low-height emissions as a result of the adoption of an anti-smog resolution for Krakow [12]. Under the resolution, the use of solid fuels for heating became prohibited on 1 September 2019. The aim of the resolution was to reduce emissions of pollutants such as PM10, PM2.5 and B[a]P (measured in PM10), which mainly come from the burning of poor-quality fuels in households [13,14].

In the present study, we analysed a range of data describing air quality in Krakow, a city of almost one million people, to answer the question of w*hether the ban on the burning of solid fuels in domestic furnaces was effective in reducing particulate air pollution and to what extent it improved air quality in the city.*

1.1. Air pollution in large cities

Air pollution in large cities comes from multiple sources, which are divided into area, line, point and nonpoint sources. Point sources (which mainly include industrial chimneys emitting NO_x, SO_2, PM10 and PM2.5) seem to be one of the most troublesome sources of pollution emissions. Point source emissions come from fuel combustion and multi-stage production processes in numerous industrial plants. Hundreds, even thousands, of integrated and sector permits, exploitation decisions and notifications of emitting installations are issued or made in large cities [11]. Line sources emit pollutants along a certain path. In large cities, line sources of pollution mainly include main roads and well-developed transport networks. The combustion of fuel in car engines produces emissions of NO_2, PM10 and PM2.5. Another source of particulate emissions is the abrasion of road surfaces, tyres and brakes. The amount and type of pollutants emitted depend on: the type, technical condition and age of vehicles, type of road surface, state of roads, traffic volumes and the type of fuel used, as noted by Karimi et al. [15], Ma et al. [4] and Kicińska [16]. The combustion of diesel creates larger emissions than the combustion of petrol or LPG [17]. The NO_x emissions generated during acceleration are greater than those generated when driving at a constant speed. This aspect is important given the daily traffic jams in large cities [18]. Area sources consist of a number of small emitters located within a given area, with the municipal and residential sector being usually the main contributors to area source emissions. The amount and quality of pollutants emitted from area sources depend on the type and quality of fuel combusted [19]. The largest contributor of air pollutant emissions is the combustion of solid fuels (including among others coal), whereas the smallest contributor is natural gas combustion. An oil-fired boiler emits almost 6 times less particulate matter and 2 times less SO_2 than a coal-fired boiler [20,21]. Emissions from natural gas boilers are even lower. Such boilers generate 30 times less particulate matter than coal-fired boilers, and the SO_2 emissions they generate are negligible. Unlike the combustion of wood or coal, the combustion of natural gas or light fuel oil causes virtually no emissions of B[a]P and other compounds [22,23]. These facts are important in the context of the anti-smog resolutions adopted, which only permit the use of light fuel oil and natural gas for heating [13].

The municipal and residential sectors and transport generate low-height emissions (usually up to a height of 40 m) [23,24].

One other significant source of pollution in a large city is emissions transported into the city from neighbouring areas that form part of a given metropolitan area. Such pollutant emissions are brought into large cities by the wind from the localities that surround them. Most large cities are located near large river valleys, and their dense development and adverse weather conditions (i.e. temperature differences, low wind speed and ground temperature inversion) promote the accumulation of pollutants in the cities [25-27].

1.2. Legal regulations

Two directives are particularly important for air quality and the reduction of low-height emissions in the European Union (EU). The first one is Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe [28], which is also referred to as the CAFE (Clean Air for Europe) Directive. It is the main legal act of the EU that concerns the reduction of air emissions of pollutants such as PM10, PM2.5, O_3,

SO_2, NO_2, NO_x, CO, Pb and C_6H_6. It sets out the reference methods of pollutant measurement, requirements for minimum data capture, limit values for the protection of human health and protection of vegetation, target values and long-term objectives, information and alert thresholds, average exposure indicators, the national PM2.5 exposure reduction target, criteria for determining the number and location of sampling points and the information that must be included in air quality plans. The CAFE Directive amended the following legal acts:

- Council Directive 96/62/EC of 27 September 1996 on ambient air quality assessment and management [29],
- Council Directive 1999/30/EC of 22 April 1999 relating to limit values for sulphur dioxide, nitrogen dioxide and oxides of nitrogen, particulate matter and lead in ambient air [30],
- Directive 2000/69/EC of the European Parliament and of the Council of 16 November 2000 relating to limit values for benzene and carbon monoxide in ambient air [31],
- Directive 2002/3/EC of the European Parliament and of the Council of 12 February 2002 relating to ozone in ambient air [32],
- Council Decision 97/101/EC of 27 January 1997 establishing a reciprocal exchange of information and data from networks and individual stations measuring ambient air pollution within the Member States [33].

The CAFE Directive takes into account the results of the latest research regarding the protection of ambient air and health and its aim is to streamline administrative tasks. In 2012, the Directive was implemented into Polish law through the adoption of the Act of 13 April 2012 amending the Environmental Protection Law and certain other laws [34,28]. The CAFE Directive was amended by the Commission Directive (EU) 2015/1480 [35] of 28 August 2015 amending several annexes to Directives 2004/107/EC [36] and 2008/50/EC [28] of the European Parliament and of the Council laying down the rules concerning reference methods, data validation and location of sampling points for the assessment of ambient air quality. The amendments provided updated standards for measuring PM10, PM2.5, O_3, SO_2 and NO_2 using reference methods and the requirement to update and review the monitoring site selection documentation [35].

The second of the two most important legal acts of the EU regarding air quality is Directive [36] of the European Parliament and of the Council of 15 December 2004 relating to arsenic, cadmium, mercury, nickel and polycyclic aromatic hydrocarbons in ambient air. The Directive concerns the reduction of emissions of polycyclic aromatic hydrocarbons and in particular, the emissions of B[a]P, which are mainly generated by the municipal and residential sectors. It sets out target values for As, Cd, Ni and B[a]P (measured in PM10), the minimum number of sampling points and criteria for selecting their location, data quality requirements and reference methods for assessment of pollutant concentrations. The Directive was amended in 2015 to specify the reference method for measuring ambient air concentrations of B[a]P. A provision was added stating that all measurements must be "*[d]istributed over the year to be representative of various conditions for climate and anthropogenic activities*" [35].

Polish legislation concerning air quality was changed by the Environmental Protection Law of 27 April 2001 [37,38] and several most relevant regulations of the Minister of the Environment. Their aim was to enable the fulfilment of the objectives set out in the two EU Directives. The most important change as regards the reduction of low-height emissions was the adoption of the Environmental Protection Law of 10 September 2015 [39]. Its provisions (art. 96) allowed regional assemblies to adopt the so-called anti-smog resolutions, which are local legal acts that restrict or prohibit the burning of certain fuels (mainly coal) in installations with a capacity of up to 1 MW [39]. The first anti-smog resolution was adopted on 15 January 2016 by the Regional Assembly of the Małopolska Province and concerned the city of Krakow. The resolution only allows the burning of natural gas and light fuel oil in boilers, fires and furnaces, thus prohibiting the burning of solid fuels, such as wood and coal. The resolution has been in force since 1 September 2019 [11]. However, the 2016 resolution was not the first attempt at improving air quality in Krakow. The Resolution of the Regional Assembly of the Małopolska Province of 25 November 2013 [12] was to introduce a total ban on the burning of solid fuels. However, since the resolution was incompatible with the legal regulations applicable at that time, it was annulled [40]. Currently, anti-smog resolutions are in force in 14 out of 16 provinces in Poland (the exceptions are the Warmia-Masuria and Podlasie Provinces) [41].

In 2012, the Regulation of the Minister of the Environment of 3 March 2008 on the levels of certain substances in the air [42] was amended. The amendments established the limit value (phase I – 25 μg/m^3, phase II – 20 μg/m^3), the target value (25 μg/m^3) and the exposure concentration obligation (20 μg/m^3) for PM2.5. The deadlines for compliance with the three values were also specified. Moreover, the margins of tolerance for the PM2.5 limit value for the years 2010-2014 were set out. These were 4, 3, 2, 1 and 1 μg/m^3, respectively. In addition, the alert threshold for PM10 was increased (from 200 to 300 μg/m^3) and the information thresholds for ozone (180 μg/m^3) and PM10 (200 μg/m^3) were specified [43]. In 2019, another regulation was issued, which lowered the alert threshold (from 300 to 150 μg/m^3) and information threshold (from 200 to 100 μg/m^3) for PM10 [44].

The Regulation of the Polish Minister of the Environment of 6 March 2008 on zones for air quality assessment [45] was repealed in 2012. The new regulation changed the zones for air quality assessment from urban agglomerations (>250 thousand residents) and other parts of the province to urban agglomerations (>250 thousand residents), cities (>100 thousand residents) and other parts of the province. The number of zones was reduced from 28 for ozone and 170 for other pollutants to 46 for all pollutants [46,47]. In 2022, the definition of zones for air quality assessment was amended. The new definition set out a division of the territory of Poland into the following air quality assessment zones: urban agglomerations, cities and other parts of the province, which do not change when there is a change in the number of residents. The aim of the regulation was to reinstate 2 zones in cities where the number of residents would decrease below 100 thousand and which would otherwise be excluded from air quality assessment. The status of Krakow as an urban agglomeration (called the Krakow agglomeration) has not changed with the change in the zones for air quality assessment [48,49].

The Regulation of the Minister of the Environment of 13 September 2012 regarding the method for calculating average exposure indicators and the method for assessing the fulfilment of the exposure concentration obligation [50] was amended in 2022. The amended Regulation stated that the average exposure indicators for PM2.5 must be calculated for the zones (urban agglomerations and cities) listed in the relevant annexe to the Act of 7 July 2022 amending the Environmental Protection Law [48]. The amendment resulted from the change in the definition of air quality assessment zones.

The Regulation of the Minister of the Environment of 14 August 2012 regarding the national PM2.5 exposure reduction target [51] set a 2020 target of 18 μg/m^3. The Regulation has not been amended and remains in force [51].

The Regulation of the Minister of the Environment of 8 February 2008 regarding the detailed requirements for air protection programmes [52] was amended in 2012. The new Regulation specified the form and necessary elements of short-term action plans. Moreover, it provided examples of short-term actions to reduce emissions from area, line and point sources [46,53]. In 2019, a requirement was introduced that air protection programmes (APP) must specify the planned emission reductions and reductions in the concentrations of particular pollutants as a result of the remedial actions taken, as specified in a given APP. In addition, indicators for evaluating the implementation of an APP were specified, such as the number of decommissioned solid fuel heating systems, together with an indication of the alternative heat source, length of new cycle paths and the number of air quality awareness campaigns carried out [54]. The APP for the Małopolska Province provides measures to improve air quality in Krakow. The first such program was developed in 2005 and was updated every 4 years. Since 2017, the programme has been updated every 3 years [55].

2. Air quality in Krakow – before and after the introduction of the ban on the burning of solid fuels in domestic furnaces

To determine changes in air quality in Krakow, we used archived data from 2010 to 2021 from the Chief Inspectorate for Environmental Protection [47,49].

2.1. Air concentrations of PM2.5, PM10, NO_2, SO_2, O_3 and B[a]P in Krakow in the years 2010-2021

We calculated the mean concentrations of the pollutants analysed based on the concentrations recorded by 4 measuring stations located in the agglomeration. We analysed air pollutant concentrations by:

i) calendar year,
ii) heating season (1 October of the preceding year to 31 March of a given year), and
iii) non-heating season (1 April to 30 September of a given year).

In order to assess air quality in Krakow, we compared the measured concentrations of pollutants in each of the years and seasons analysed with the limit values, target values and long-term objectives for the pollutants as specified in the Announcement of the Minister of the Environment on the levels of certain substances in the air [14].

The first pollutant we analysed was **PM10**. Air quality in Krakow in terms of PM10 was poor throughout most of the period analysed. The PM10 annual mean limit value (40 $\mu g/m^3$) was exceeded in each of the years analysed. The highest annual mean PM10 concentration (54 $\mu g/m^3$) was recorded in 2011 (Fig. 1a). In the heating seasons 2010/2011 to 2018/2019, PM10 concentrations were high (46-83 $\mu g/m^3$), but decreased continuously (Fig. 1b). Two exceptions were the 2016/2017 and 2020/2021 heating seasons, in which PM10 air concentrations increased slightly compared to the preceding periods. Air quality in Krakow during the heating months improved significantly from 2019 through to the end of the period analysed. The PM10 limit value was met, with the lowest PM10 concentration (37 $\mu g/m^3$) recorded in the 2019/2020 heating season. By comparison, our analysis of PM10 concentrations in non-heating seasons showed that the highest concentration of the pollutant (29 $\mu g/m^3$) was recorded in the non-heating season of 2010. The PM10 annual mean limit value was met in 2016 and from 2019 through to the end of the period analysed. The lowest PM10 concentration (29 $\mu g/m^3$) was recorded in 2020.

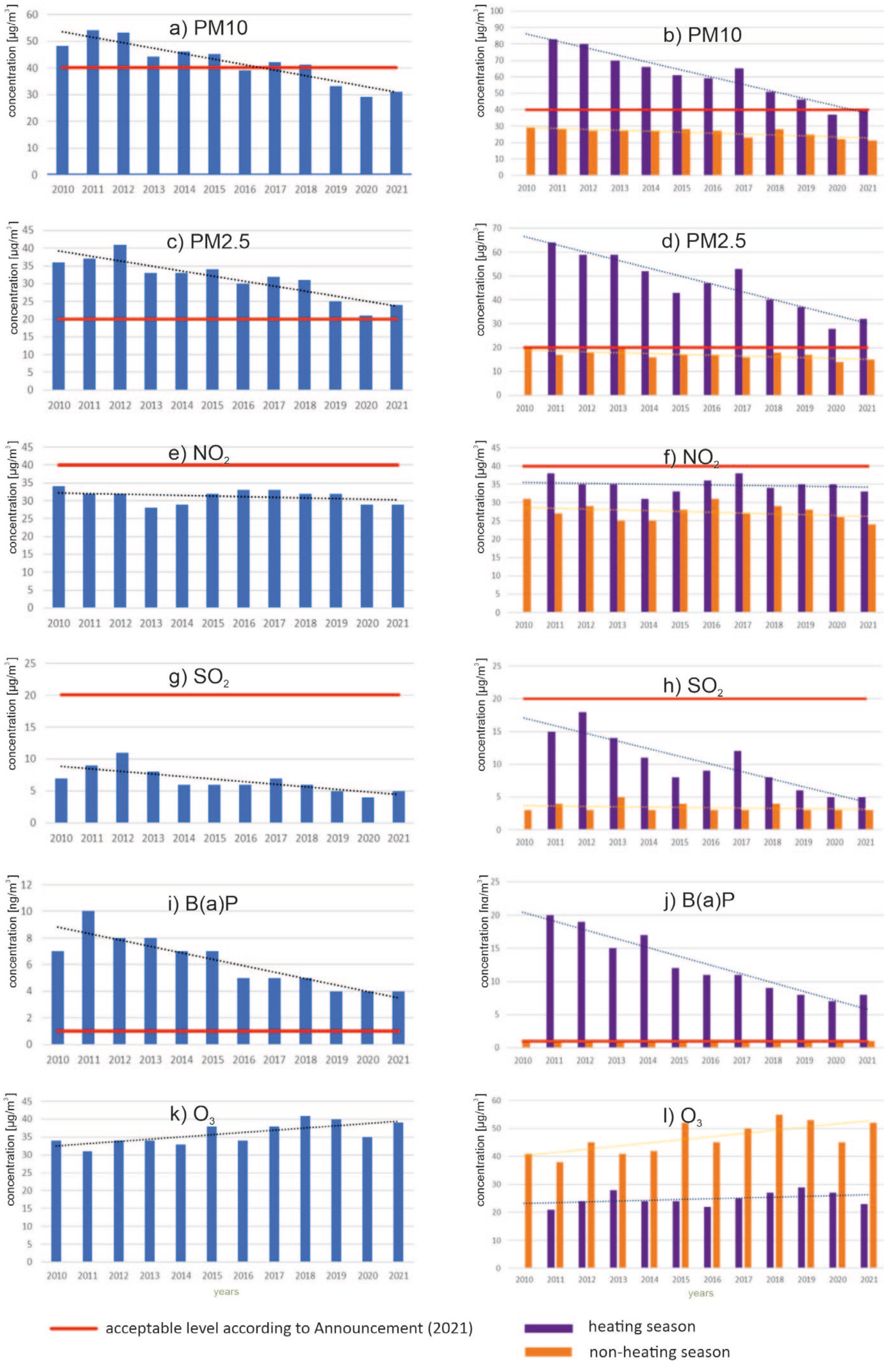

Fig. 1. Average annual concentrations of PM10, PM2.5, NO_2, SO_2, B(a)P and O_3 (a,c,e,g,i,k) and average annual concentrations in the heating and non-heating season (b, d, f, h, j, l) in Krakow air (based on: powietrze.gios.gov.pl; Announcement 2021)

The **PM2.5** annual mean limit value (20 μg/m^3) was exceeded in each of the years analysed (Fig. 1c). The highest PM2.5 concentration was recorded in 2012 and was more than twice higher than the limit value. However, while PM2.5 air quality was poor, there was a downward trend in the PM2.5 concentration. In 2012, 2015, 2017 and 2021, PM2.5 concentrations increased slightly. The annual mean PM2.5 concentration in 2020 (21 μg/m^3) was close to the limit value. As was the case for PM10, PM2.5 concentrations in heating seasons were significantly higher than those in non-heating seasons (Fig. 1d). The highest PM2.5 concentration was recorded in the 2010/2011 heating season and was more than 3 times higher than the limit value. The lowest PM2.5 levels were recorded in the 2019/2020 season. However, they were still almost 2 times higher than the limit value. While the PM2.5 limit value was not exceeded in any of the non-heating seasons analysed, PM2.5 concentrations in the 2010 and 2013 non-heating seasons were equal to the limit value.

The **NO_2** limit value (40 μg/m^3) was met in each of the calendar years analysed (Fig. 1e) and in each of the heating and non-heating seasons analysed (Fig. 1f). The highest NO_2 concentrations were recorded in the 2010/2011 and 2016/2017 heating seasons. In general, air concentrations of NO_2 were higher in heating seasons (31-38 μg/m^3) than in non-heating seasons (24-31 μg/m^3). However, the differences in NO_2 concentrations between the heating and non-heating seasons were not large. The annual mean NO_2 concentrations ranged between 28 and 34 μg/m^3. Changes in NO_2 levels were small and there was no noticeable trend in the concentration of the pollutant.

In the years 2010 to 2021, air quality in Krakow in terms of **SO_2** was good. In none of the years analysed was the SO_2 limit value (20 μg/m^3) exceeded (Fig. 1g). SO_2 concentrations were more than 2 times lower than the limit value in each of the years analysed, except for 2012, when the annual mean concentration of SO_2 was 11 μg/m^3. In the last years of the period analysed, SO_2 concentrations decreased. The only two years when SO_2 concentrations increased were 2012 and 2017. However, there was a large difference in SO_2 concentrations between the heating and non-heating seasons, which decreased over the period analysed (Fig. 1h). SO_2 concentrations in non-heating seasons ranged between 3 and 5 μg/m^3. An analysis of SO_2 concentrations in heating seasons showed that the highest SO_2 concentration (18 μg/m^3) was recorded in the 2011/2012 heating season, while the lowest concentration of the pollutant (5 μg/m^3) was recorded in the last two years analysed.

Air quality in Krakow in terms of **B[a]P** was very poor. The B[a]P target value of 1 ng/m^3 was significantly exceeded over the entire period analysed. Exceedances of the B[a]P target value were recorded both for calendar years (Fig. 1i) and for heating seasons (Fig. 1j). The highest B[a]P concentrations were recorded in heating seasons, particularly in the 2010/2011 heating season, when the B[a]P levels recorded were 20 times higher than the target value. In non-heating seasons, B[a]P concentrations were equal to the target value. B[a]P air concentrations clearly decreased over the years analysed. The only exception was in 2011 when B[a]P levels were 10 times higher than the target value. In the years 2019 to 2021, when B[a]P concentrations were lowest, the B[a]P levels recorded were 4 times higher than the target value.

The last pollutant we analysed was **O_3**. The annual mean ozone concentrations in the years 2010 to 2021 ranged from 31 μg/m^3 in 2010 to 41 μg/m^3 in 2018 (Fig. 1k). Unlike in the case of other pollutants, the highest ozone concentrations (38-55 μg/m^3) were recorded in non-heating seasons and were up to 2 times higher than those in heating seasons (21-29 μg/m^3) (Fig. 1l).

The target value and long-term objective for the protection of human health for the maximum daily 8-hour mean concentration of O_3 were established at 120 μg/m^3. Both the target value and the long-term objective were exceeded in each of the years analysed (Fig. 2a). The maximum daily

8-hour mean concentration of ozone ranged from 122 µg/m^3 (in 2011) to 164 µg/m^3 (in 2015). Since the maximum daily 8-hour mean ozone concentration changed irregularly, no noticeable trend could be observed. Given the significant adverse effects of ozone on plants, a separate parameter – AOT 40 – was established for the period from May to July. The target value and the long-term objective for the parameter were established at 18,000 µm/m^3·h and 6,000 µm/m^3·h, respectively. The target value was only exceeded in 2018 (19,985 µm/m^3·h) (Fig. 2b). In contrast, the long-term objective was exceeded in most of the years analysed. The exceptions were in 2011, 2013 and 2020, when the AOT 40 values recorded (between May and July) were lower than 5000 µm/m^3·h.

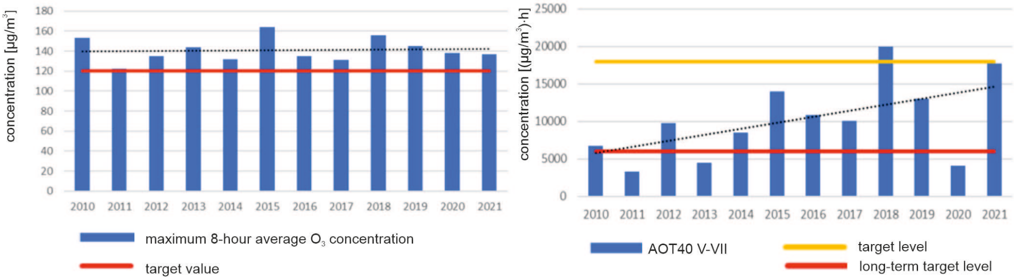

Fig. 2. Maximum 8-hour average O3 and AOT40 concentration in Krakow air
(based on: powietrze.gios.gov.pl; Announcement 2021)

To conclude, during the period 2010-2021 (TABLE 1):
1. the concentrations of PM10, PM2.5, SO_2 and B[a]P decreased gradually,
   – there were decreases in annual concentrations of: B[a]P (more than 60%), SO_2 (more than 50%), PM10 and PM2.5 (approximately 40%) and NO_2 (approximately 6%),
   – in heating seasons, the largest decreases were in the concentrations of SO_2 and B[a]P (more than 70%), followed by the concentrations of PM10 and PM2.5 (more than 50%); the smallest decrease was in the concentration of NO_2 (approximately 4%),

TABLE 1

Changes (%) in average air pollutant concentrations in Krakow in 2010-2021
(based on: powietrze.gios.gov.pl)

Parameter	Change in average concentrations (%) 2010-2021		
	for the entire period	**heating season**	**non-heating season**
PM10	–42.19	–56.22	–21.64
PM2.5	–39.73	–54.67	–20.06
NO_2	–5.85	–3.94	–8.57
SO_2	–50.14	–74.97	–15.56
B[a]P	–60.17	–71.51	0
O_3	+21.20	+13.81	+31.20
O_3 max. 8h average	+1.82		
O_3 – AOT40 (V-VII)	+152.86		

"+" means increase (red); "-" decrease (green); "0" no change

2. ozone was the only pollutant whose concentration increased (by more than 20%),
   - the increase in ozone concentrations was higher for non-heating seasons (31%) than for heating seasons (approximately 14%),
   - the highest increase (153%) was recorded for AOT40 (May-July).

The data above clearly indicate a significant improvement in air quality in Krakow.

2.2. Exceedances of limits for PM10, NO_2, SO_2 and O_3 air concentrations in Krakow in the years 2010-2021

We analysed changes in short-term pollutant concentrations, hourly concentrations of NO_2 and SO_2, as well as the daily concentrations of PM10 and SO_2. The daily maximum 8-hour mean ozone concentration was compared to the limits set by the Minister of the Environment regarding certain air substances. We analysed the number of exceedances of the limits for individual years. One exception was PM10, for which we also determined the number of exceedances of the PM10 limit value, information threshold and alert threshold for non-heating and heating seasons. We did not analyse data for PM2.5 and B[a]P as there are no limits for these pollutants for a period shorter than a calendar year [14].

In each of the years analysed (2010-2021), the number of days when the daily mean concentration of **PM10** exceeded 50 $\mu g/m^3$ was greater than the permitted number of exceedances per year (35). Initially, the number of exceedances of the limit value per year was greater than 100 (except for 2010, when the number of exceedances was 65). In the subsequent years, the number of exceedances decreased to 40. However, in 2018 and 2021, it increased again (Fig. 3a). In non-heating seasons, the number of days when the limit value was exceeded was several times smaller than that in heating seasons (Fig. 3b). In the non-heating seasons analysed, the largest number of exceedances was recorded in April and September. This was most probably due to the prolonged household heating period (www.powietrze.gios.gov.pl). The number of exceedances of the limit value in the heating months decreased constantly over the period analysed (from 121 to 44), with a slight increase (47 days) in the 2020/2021 heating season.

In each of the years (Fig. 3c) and heating seasons (Fig. 3d) analysed, the information threshold for PM10 (100 $\mu g/m^3$) was exceeded. However, the number of days when the information threshold was exceeded decreased (from 56 in the 2011/2012 heating season to 2 in the 2020/2021 heating season). The number of exceedances of the information threshold only increased in the 2016/2017 heating season. While the number of days when the information threshold was exceeded decreased over the period analysed, there were still days when PM10 levels were above 100 $\mu g/m^3$. In 2020, the information threshold was only exceeded once. No exceedances were recorded in non-heating seasons.

The number of days when the daily mean PM10 concentration was above the alert threshold (150 $\mu g/m^3$) decreased over the period analysed, except for the 2011/2012 and 2016/2017 heating seasons. The largest number of days when the alert threshold was exceeded (18) was recorded in the 2011/2012 heating season. From the 2018/2019 heating season to the last heating season analysed, the alert threshold was not exceeded. Our analysis showed that air quality in Krakow in terms of PM10 improved over the years analysed. From 2020 to the end of the period analysed, daily PM10 concentrations were below 150 $\mu g/m^3$ (Fig. 3e). In addition, the alert threshold for PM10 was not exceeded in any of the non-heating seasons analysed (Fig. 3f).

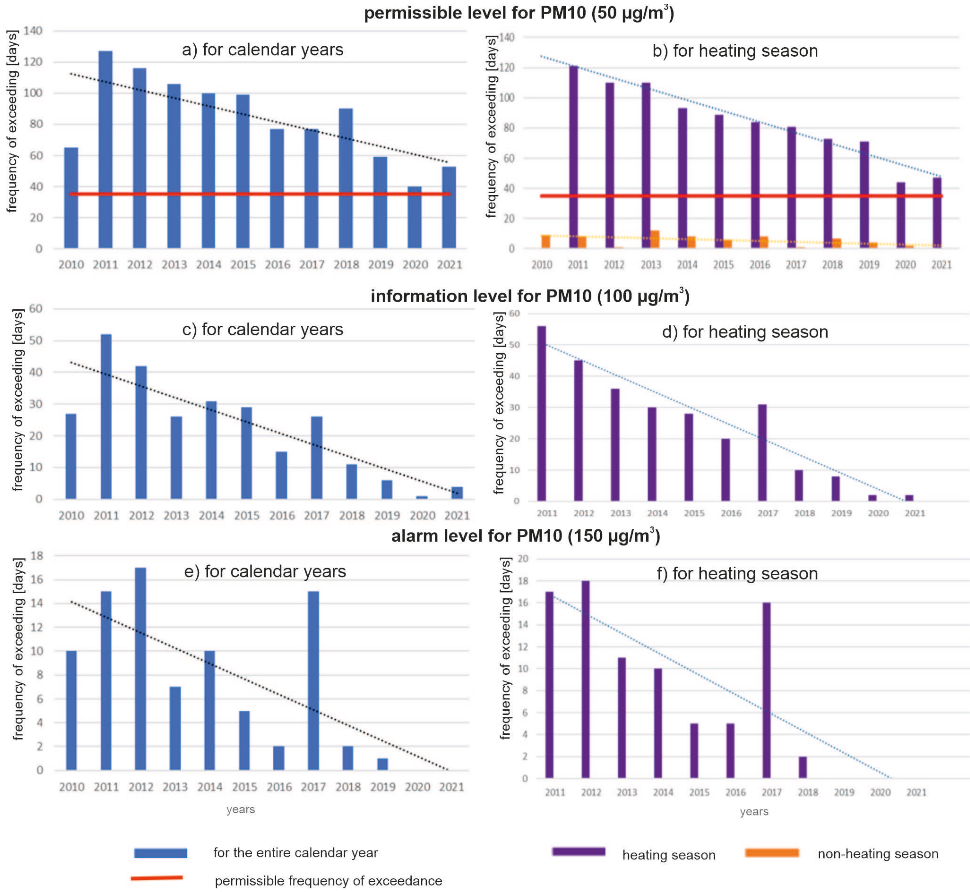

Fig. 3. Number of days exceeding the daily permissible level (a, b), information level (c, d) and alarm level (e, f) for PM10 in atmospheric air in Krakow in 2010-2021 (based on: powietrze.gios.gov.pl; Announcement 2021)

The number of days in which the daily maximum 8-hour mean concentration of O_3 (120 µg/m^3) did not exceed the allowed number of exceedances (25) in any of the years analysed. However, in 2018, the number of exceedances of the target value was equal to the permitted number of exceedances (Fig. 4). Over most of the period analysed, the number of exceedances of the target value ranged between 1 and 9.

In the years 2010-2021, air quality in Krakow in terms of the daily and hourly concentrations of **SO_2** and **NO_2** was good [14,47]. No urban background sampling point showed SO_2 concentrations exceeding the alert threshold for hourly mean SO_2 concentrations (500 µg/m^3), the hourly SO_2 limit value (350 µg/m^3) and the 24-hour SO_2 limit value (125 µg/m^3). In addition, the alert threshold for hourly mean concentrations of NO_2 (400 µg/m^3) and the hourly NO_2 limit value (200 µg/m^3) were not exceeded.

To conclude, the decrease in the number of exceedances of the limit value, information threshold and alert threshold for PM10 indicates an improvement in air quality in Krakow in terms

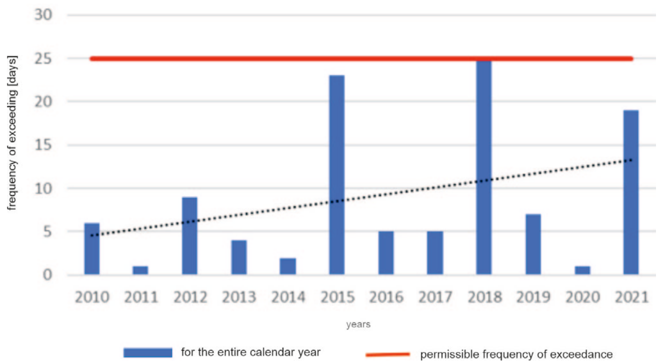

Fig. 4. Number of days in a calendar year exceeding the target level (120 µg/m3) max. 8h average for O_3 in atmospheric air in Krakow in 2010-2021 (based on: powietrze.gios.gov.pl; Announcement 2021)

of PM10 (TABLE 2). The most significant improvement in the period analysed was seen for the alert threshold (approximately 101%) and the information threshold (approximately 95%), while the smallest improvement was seen for the limit value (approximately 51%). Significantly larger decreases (over 110%) were seen for the heating seasons analysed. In the period analysed, the only pollutant for which the number of exceedances per year increased (by almost 200%) was ozone.

TABLE 2

Changes (%) in the number of days exceeding the permissible, information and alarm threshold for PM10 and the target level for O_3 in Krakow in 2010-2021 (based on: powietrze.gios.gov.pl)

Parameter	Change in frequency of exceedance (%) 2010-2021		
	for the entire period	heating season	non-heating season
PM10 – permissible threshold	–50.71	–62.67	–76.19
PM10 – information threshold	–95.44	–94.73	n.e.
PM10 – alarm threshold	–100	–100	n.e.
O_3 – target level	+188.55		

“n.e.” means no exceedance of the specified threshold

2.3. Contribution of particular sectors to pollutant emissions

Changes in air concentrations of PM10, PM2.5, SO_2, NO_2 and B[a]P in Krakow in the years analysed are associated with the different contributions of particular sectors to emissions of these pollutants. One exception is ozone, which is a secondary pollutant and thus was not examined further in the present study.

Based on the data from annual air quality assessments for the Małopolska Province in the years 2018-2021, we also analysed changes in the contribution of the following sectors to pollutant emissions in Krakow:

– industry sector (point source emissions),
– municipal and residential sector (area source emissions),
– road transport (line source emissions).

In addition, for particulate matter, we accounted for emissions from heaps and excavations. Our sectoral analysis was carried out between 2018 and 2021 due to the lack of data for preceding years or different methods for estimating emissions [47].

The contributions of the sources analysed to **PM10** emissions were similar to their contributions to **PM2.5** emissions (Figs. 5a and 5b). The most significant proportions of PM10 and PM2.5 emissions in 2018 were from area sources (54% for PM10 and 65% for PM2.5). In 2020, the share of PM10 and PM2.5 emissions from area sources decreased to approximately 11% and 17%, respectively. Heaps and excavations contributed the smallest proportions of PM10 and PM2.5 emissions in the period analysed. Their contribution decreased from a few percent to less than 1%. However, there was an increase in PM10 and PM2.5 emissions from point and line sources. In 2018, the industrial and transport sectors accounted for approximately 30% of particulate emissions (with point sources accounting for a larger proportion of emissions). In the period from 2020 to 2021, the contribution of these sectors to particulate emissions increased to over 80%, with increasing emissions from transport.

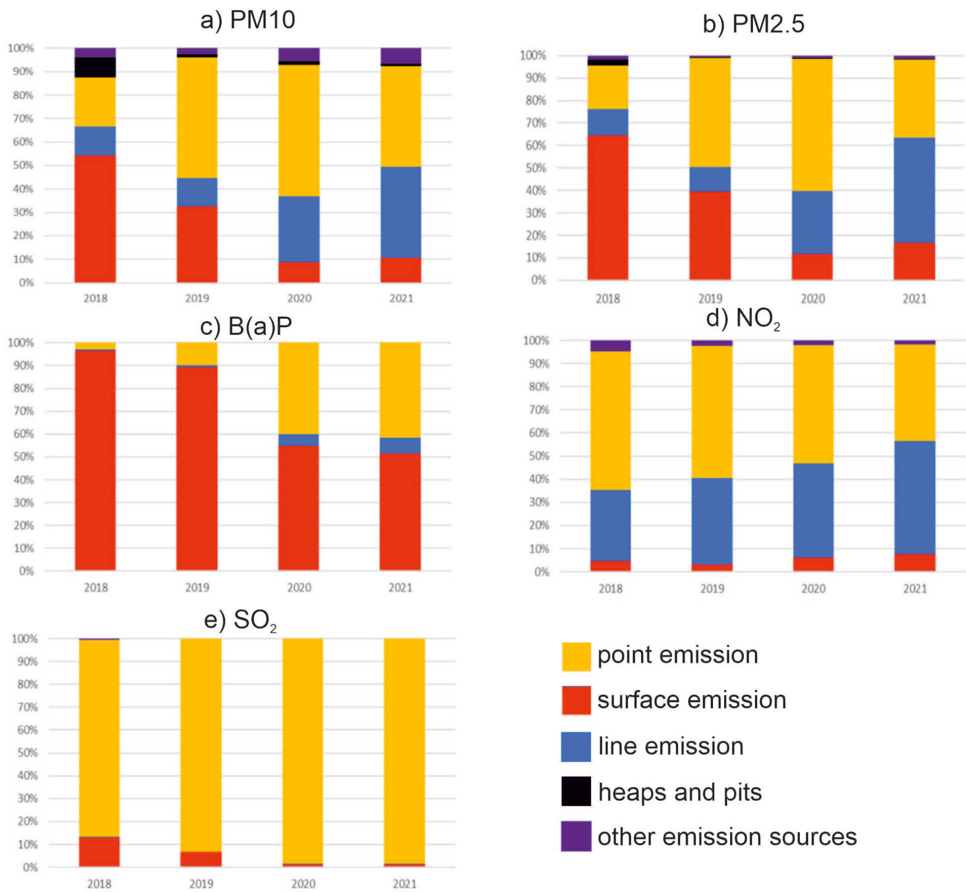

Fig. 5. Share of individual emission sources into atmospheric air in Krakow in 2018-2021 (based on: powietrze.gios.gov.pl)

The municipal and residential sector was and remains the largest contributor of **B[a]P** emissions (Fig. 5c). However, the share of B[a]P emissions from this sector decreased from 96% (2018) to 52% (2021). In contrast, the proportions of B[a]P emissions from other sectors increased. The largest increase (from 3% to 42%) was seen for point source emissions. The smallest proportion of B[a]P emissions was from line sources. The proportion of B[a]P emissions from these sources increased from 1% to 7%, which was the smallest increase compared with other emission sources.

The largest proportion of **NO_2** emissions at the beginning of the period analysed was from point sources (Fig. 5d). In 2018, the proportion of NO_2 emissions from point sources was 60%. The contribution of point sources to the emissions of this pollutant then gradually decreased to 42% (in 2021). At the same time, the share of NO_2 emissions from line sources increased steadily (from 31% to 49%). In 2021, transport was the largest contributor of NO_2 emissions. The proportion of NO_2 emissions from area sources also increased slightly (from 4% to 7%).

The largest contributor of **SO_2** emissions was industry (Fig. 5e). The proportion of SO_2 emissions from transport increased from 86% to 98% over the period analysed. In contrast, the proportion of SO_2 emissions from area sources decreased gradually (from 13% to 1%). The contribution of line sources to SO_2 emissions in the period analysed was marginal (less than 0.5%).

2.4. Comparison of air quality in Krakow with air quality in other Polish cities

We compared air quality in Krakow in the period 2010–2021 with air quality in six selected towns/cities: Tarnów, Katowice, Wrocław, Nowy Sącz, Zakopane and Pszczyna. For each of them, we analysed the levels of PM10, PM2.5 and B[a]P. The only locality where PM2.5 concentrations were not measured was Pszczyna (TABLE S1). The air quality assessment was carried out based on the limits specified in the Announcement of the Minister of the Environment on the levels of certain substances in the air [14].

TABLE S1

Urban background measurement stations in six selected cities in Poland (based on: powietrze.gios.gov.pl)

Station location	Station code	Station type	Measured parameters
Tarnów, ul. Bitwy pod Studziankami	MpTarBitStud	container stationary	PM10, PM2,5, B[a]P
Katowice, ul. Kossutha	SlKatoKossut	container stationary	PM10, PM2,5, B[a]P
Wrocław, ul. Wierzbowa	DsWrocWie	in the building	PM10, B[a]P
Wrocław, ul. Orzechowa	DsWrocOrzech	freestanding dust collector	PM10, B[a]P
Wrocław, wyb. Conrada Korzeniowskiego	DsWrocWybCon	container stationary	PM10, PM2,5, B[a]P
Wrocław, ul. Na Grobli	DsWrocNaGrob	freestanding dust collector	PM2,5
Nowy Sącz, ul. Nadbrzeżna	MpNoSaczNadb	container stationary	PM10, PM2,5, B[a]P
Zakopane, ul. Sienkiewicza	MpZakopaSien	container stationary	PM10, PM2,5, B[a]P
Pszczyna, ul. Bogedaina	SlPszczBoged	container stationary	PM10, B[a]P

In each of the towns/cities analysed, the **PM10** limit value was exceeded, and the highest PM10 air pollution level was recorded in 2010 (Fig. 6a). Over the years 2010-2021, air quality in terms of PM10 improved gradually. The first locality to meet the PM10 limit value was Wroclaw

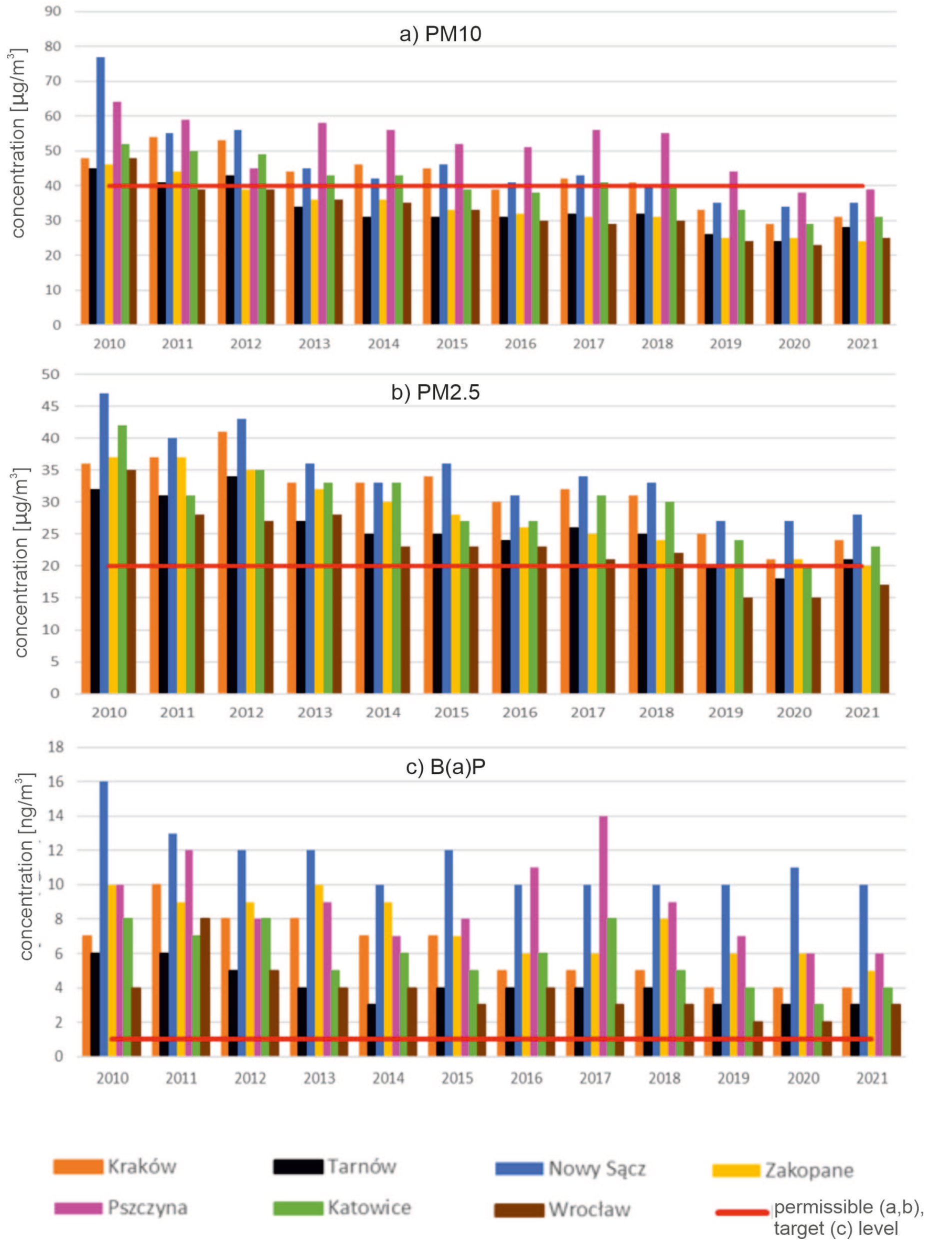

Fig. 6. Average annual concentrations of selected pollutants in atmospheric air in selected cities in Poland in 2010-2021 (based on: powietrze.gios.gov.pl; Announcement 2021)

(in 2011). The last was Pszczyna (in 2020). From 2020 through to the end of the period analysed, PM10 concentrations were below the limit value in each of the towns/cities analysed. Over most of the period analysed, Krakow was the third most PM10 polluted city after Pszczyna and Nowy Sącz. In contrast, Wroclaw had the best air quality in terms of PM10. In most of the towns/cities analysed, the number of days when the limit value for PM10 was exceeded was greater than 35 in almost all of the years analysed. The largest numbers of exceedances of the limit value were recorded in 2010 and 2011. In subsequent years, the number of exceedances decreased. However, in Krakow, Pszczyna and Nowy Sącz, the permitted number of exceedances of the limit value (35) was exceeded in each of the years analysed. In Wroclaw, the number of days with PM10 concentrations greater than 50 μg/m^3 did not exceed 35 from 2019 through 2021. In other towns/cities, the number of exceedances per year fluctuated in the last three years of the period analysed – it fell below 35 and then increased.

In each of the towns/cities analysed, **PM2.5** air concentrations in the years 2010-2018 exceeded the PM2.5 limit value (Fig. 6b). Despite an improvement in air quality in terms of PM2.5 levels in the last years of the period analysed, PM2.5 concentrations were above the limit value (20 μg/m^3) in most of the towns/cities analysed. Nowy Sącz was the most PM2.5 polluted locality, followed by Krakow. In both these cities, the PM2.5 limit value was exceeded in each of the years analysed. The lowest PM2.5 levels were recorded in Wroclaw. From 2019 through to the end of the period analysed, PM2.5 levels in that city were below 20 μg/m^3.

The worst pollutant in the towns/cities analysed was **B[a]P** (Fig. 6c). In each of the towns/cities analysed, B[a]P levels were up to more than ten times higher than the target value for the pollutant in each of the years analysed. However, B[a]P concentrations in the air decreased in the period 2010 to 2021. The highest B[a]P concentrations were recorded in Nowy Sącz, whereas the lowest were recorded in Wroclaw. Krakow ranked in the middle in terms of air pollution by benzo[a]pyrene, which is a carcinogenic pollutant.

We compared changes in air pollutant concentrations in Krakow to those in other towns/cities (TABLE 3). The largest decrease in PM10 concentrations was seen in Nowy Sącz (51.5%), whereas the smallest decrease was seen in Pszczyna (30.8%). Krakow ranked fifth, with a decrease of 42.2%. The largest decrease in the number of exceedances of the PM10 limit value was seen in Wroclaw (75.2%). In Nowy Sącz, the decrease was much smaller (26.1%). Krakow ranked

TABLE 3

Changes (%) in average PM10, PM2.5 and B(a)P concentrations and the number of days with daily PM10 concentration exceeding 50 μg/m^3 in selected cities in Poland (based on: powietrze.gios.gov.pl)

Location	**Change in the number of days with daily PM10 concentration >50 μg/m^3 (%)**	**Change in average concentrations (%)**		
		PM10	**PM2.5**	**B[a]P**
Kraków	–50.71	–42.19	–39.73	–60.17
Tarnów	–66.51	–42.54	–40.98	–50.13
Katowice	–72.72	–41.52	–41.67	–50.49
Wrocław	–75.16	–49.21	–53.20	–64.59
Nowy Sącz	–26.11	–51.50	–40.38	–31,46
Zakopane	–70.13	–48.13	–50.70	–47.55
Pszczyna	–36.32	–30.82	n.m.	–29.74

„n.m.” – not measured

fifth, with a decrease of 50.7% in the number of days with a daily average PM10 concentration greater than 50 µg/m^3. The smallest decrease in PM2.5 concentrations in the years 2010-2021 was seen in Krakow (39.7%). It was probably due to the large road transport volume in the city, whose contribution to PM2.5 emissions increased over the last years of the period analysed. The transport of pollutants from surrounding areas is also not without significance. Nowy Sącz saw the second smallest decrease in PM2.5 concentrations (40.4%).

The improvement in air quality was most significant in Wroclaw (PM10 49%, PM2.5 53.2%, B[a]P 65%). Krakow saw the second largest decrease in B[a]P concentrations (60.2%). The smallest decrease in B[a]P concentrations was seen in Pszczyna (30%).

We also compared the level of improvement in air quality in Krakow with the improvement observed in the entire Małopolska Province based on the data from a report by Krakow Smog Alarm (Pol. Krakowski Alarm Smogowy) [56]. Air quality in Krakow improved significantly, particularly in terms of PM10, PM2.5 and B[a]P concentrations (TABLE 4). The decrease in the levels of these pollutants in heating seasons and calendar years was greater for Krakow than for the entire Małopolska Province (by an average of 10-20%). In the Małopolska Province, there was an unfavourable increase in B[a]P levels in heating seasons (by 14%). The above findings suggest that further measures must be taken to improve air quality in the province. The aforementioned report also indicates that from 2012 to 2020, NO_2 concentrations in Krakow increased by 4%, whereas NO_2 concentrations in the entire Małopolska Province decreased by 25% [56].

TABLE 4

Changes (%) in average concentrations of PM10, PM2.5, B(a)P, NO2 in Kraków and in the Małopolska Province (based on: Kleczkowski, Kotarba, 2020)

Parameter	Time period	Change in average concentrations (%)	
		Kraków	Małopolska Province
PM10	heating seasons	–45.42	–28.73
	calendar years	–40.77	–29.23
PM2.5	heating seasons	–43.76	–32.15
	calendar years	–40.94	–31.03
B[a]P	heating seasons*	–41.50	+14.41
	calendar years**	–53.47	+5.53
NO_2	heating seasons	+9.09	–17.86
	calendar years	+3.92	–25.23

* heating seasons 2014/2015-2019/2020; ** calendar years 2014-2020

3. Assessment of the measures implemented

The ban on the burning of solid fuels introduced in Krakow forced a change in the heating of buildings in the city. The measures taken in this regard included [10]: the replacement of old furnaces and boilers with electric, gas-fired and oil-fired heating systems, the connection of buildings to the district heating network and renewable installations, mainly photovoltaic panels, solar collectors and heat pumps. In addition, to reduce energy consumption, the thermal upgrading of several buildings was carried out.

We analysed the degree of implementation and effects of these measures based on the indicators set out in Air Protection Programmes [10] using:

i) The number of solid fuel furnaces and boilers already decommissioned and remaining to be decommissioned,

ii) the number of checks on compliance with the anti-smog resolution and inspections relating to the burning of waste carried out, together with the number of offences detected,

iii) the annual cuts in pollutant emissions (PM10, PM2.5 and B[a]P) from household heating.

Most solid fuel furnaces and boilers in Krakow were decommissioned between 2012 and 2019 (TABLE 5). The number of old boilers decreased from over 35 thousand in 2010 to approximately 2.5 thousand in 2021. This means that approximately 7.2% of boilers had not been decommissioned in Krakow by 2021 for different reasons. Thus, it can be concluded that the provisions of the anti-smog resolution had not been fully complied with within the time limit set [10].

TABLE 5

Number of liquidated and remaining to be liquidated furnaces and boiler rooms for solid fuels in Krakow in the years 2010-2021

Year	Boilers and furnaces to be liquidated	Liquidated boilers and furnaces
2010*	35,600	364
2011*	35,477	122
2012*	29,327	6,150
2013	27,002	2,325
2014	24,391	2,611
2015	21,473	2,918
2016	17,199	4,274
2017	11,085	6,114
2018	6,829	4,256
2019	2,643	4,186
2020	2,575	68
2021	2,553	22

* number of liquidated furnaces and boiler rooms for solid fuels calculated on the basis of the area of residential premises from which the old heating source was removed, assuming an average area of a residential premises of 76 m^2 (POP 2020)

As not all boilers and furnaces had been decommissioned, inspections were carried out on an annual basis in buildings that still used them. The inspections carried out also covered the burning of waste, including vegetable waste [10]. The number of inspections carried out and offences detected is shown in TABLE 6. The number of infringements of the anti-smog resolution decreased over the period analysed, which is partly due to the gradual reduction in the number of solid fuel furnaces and boilers. There was also a decrease in the number of offences relating to the burning of vegetable waste and vegetable residues.

The replacement of old boilers with other types of heating systems led to cuts in emissions of PM10, PM2.5 and B[a]P (TABLE 7). During the analysed period, the emission reduction objectives outlined in the Air Protection Programmes for the Małopolska Province were not achieved. The degrees to which the emission reduction targets for PM10, PM2.5 and B[a]P were achieved between 2017 and 2023 were respectively: 28%, 21% and 32% [10].

TABLE 6

Number of inspections carried out and detected violations in the field of compliance with the anti-smog resolution and incineration of waste and plant residues in Krakow (based on: POP 2020)

Year	Number of inspections	Number of violations regarding compliance with the anti-smog resolution	Number of offences in in the field of waste and plant residue incineration
2019	13997	294	290
2020	4214	276	122
2021	3189	106	124

TABLE 7

Annual reduction of PM10, PM2.5 and B(a)P emissions in atmospheric air in Krakow (based on: POP 2020)

Year	Emission reduction		
	PM10	PM2.5	B(a)P
	(Mg)		(kg)
2010	10.6	n.d	4.38
2011	4.3	n.d	1.75
2012	41.0	n.d	15.26
2013	82.0	n.d	n.d
2014	93.4	n.d	n.d
2015	102.6	n.d	n.d
2016	110.0	105.00	65.00
2017	137.9	110.80	81.00
2018	78.7	59.70	47.00
2019	91.2	69.36	53.06
2020	8.8	8.44	2.38
2021	21.8	0.26	0.08

“n.d” no data

4. Other proposals under discussion

4.1. Ban on the burning of solid fuels in neighbouring communes

The first widely discussed proposal is the extension of the ban on the burning of solid fuels to communes directly surrounding Krakow. Today, the concentrations of PM10, PM2.5 and B[a]P in the heating months in these communes are significantly higher than those in Krakow. The pollutants are carried by the wind into the lower-lying city, resulting in deterioration of its air quality. The communes which surround Krakow are subject to the anti-smog resolution for the Małopolska Province, which, however, permits the burning of a certain type of coal and biomass [57]. The restrictions proposed would cover the following communes: Krzeszowice, Zabierzów, Liszki, Czernichów, Brzeźnica, Kalwaria Zebrzydowska, Lanckorona, Sułkowice, Skawina, Mogilany, Świątniki Górne, Myślenice, Siepraw, Dobczyce, Raciechowice, Wieliczka, Biskupice, Niepołomice, Igołomia-Wawrzeńczyce, Koniusza, Proszowice, Kocmyrzów-Luborzyca, Słomniki, Michałowice, Iwanowice, Skała, Zielonki, Wielka Wieś, Jerzmanowice-Przeginia. The communes were selected taking into account the main hotspots of pollution and directions from which pollution is transported into Krakow in the heating season. The introduction of the ban would significantly reduce the amount of pollution carried by the wind into Krakow. The effectiveness of such a solution in improving air quality has already been confirmed by the results of the implementation of the anti-smog resolution for Krakow. Similar measures are being taken in communes such as Niepołomice, Krzeszowice, Skawina, Rabka Zdrój (spa resort area) and Czarny Dunajec and the towns of Oświęcim and Nowy Targ (city centre). However, the local anti-smog resolutions adopted only prohibit, as of 2030, the use of coal and do not prohibit the use of other solid fuels [49].

The implementation of the measure can be financed under the "Clean Air" (Pol. Czyste Powietrze), "Stop Smog" and "LIFE" programmes and through the budgets of communes, districts and the province. Today, funding is being mobilised for the replacement of boilers by the requirements of the anti-smog resolution for the Małopolska Province [10]. The postponement of the deadline for the replacement of boilers in the Małopolska Province by almost 1.5 years also has a negative impact on air quality in Krakow (TABLE 8).

TABLE 8

SWOT analysis for the ban on burning solid fuels in municipalities neighboring Krakow

Strengths	Weaknesses
– reducing the inflow of pollutants to Krakow – improving the air quality in Krakow and the surrounding municipalities – reducing the exposure of the population to diseases related to air pollution – lower financial outlays on healthcare	– high cost of replacing boilers and furnaces with other heating sources – possible increase in heating costs after changing
Opportunities	**Threats**
– co-financing of old boiler replacement – heating subsidies – development of RES – thermal modernisation of buildings – development of heating networks	– energy crisis – residents' protests – too slow pace of replacing boilers

4.2. Clean transport zone

Another proposed solution is the establishment of a Clean Transport Zone (CTZ) in Krakow under Resolution No. C/2707/22 of the Krakow City Council of 23 November 2022 on the establishment of a Clean Transport Zone in Krakow [58,59]. The CTZ would cover the entire city, except for the A4 motorway, the S7 express road and national roads (7, 44, 75, 79, 94) beyond the 4th Krakow bypass. The resolution envisaged the introduction of restrictions on the movement of vehicles in 2 stages [60]:

– Stage I – after 1 July 2024, only vehicles that meet the Euro 1 standard for petrol engines or the Euro 2 standard for diesel engines will be able to enter the city. Thus, approximately

1% of vehicles, which account for approximately 1% of emissions of nitrogen oxides, would be prohibited from entering the city after that date.

– Stage II – after 1 July 2026, only vehicles that meet the Euro 3 standard for petrol engines or the Euro 5 standard for diesel engines would be able to enter the city. Thus, approximately 27% of vehicles, which account for approximately 48% of emissions of nitrogen oxides, would be prohibited from entering the city after that date.

Exceptions would include, among others, motorcycles and vehicles driven by individuals who turned 70 before 1 March 2023 or individuals with disabilities [60].

Clean transport zones have been introduced or are currently being introduced in European cities such as London, Rotterdam and Paris. However, the restrictions imposed there are greater since the vehicles permitted to enter the clean transport zones in those cities have to or will have to meet higher Euro emission standards compared to the vehicles that are planned to be permitted to enter the Clean Transport Zone in Krakow (TABLE 9). According to forecasts, the establishment of the Clean Transport Zone in Krakow will cut NO_x emissions by 48% and will reduce the emissions of PM10 and PM2.5 by 82%. The base year used for projections is 2019 [61]. The cost of the introduction of the Clean Transport Zone in Krakow is estimated at PLN 850 thousand and will mainly be covered through the budget of the Krakow municipality [10].

TABLE 9

SWOT Analysis for the Clean Transport Zone

Strengths	Weaknesses
– covering the entire city with CTZ – reducing NOx and dust emissions into the air – improving air quality – reducing residents' exposure to diseases related to air pollution	– lack of funding for changing vehicles – difficulties in entering the city for vehicles from outside Krakow – expected ecological effect only after 2026
Opportunities	**Threats**
– development of public transport – creation of new bicycle routes – development of railway lines – creation of P+R parking lots	– lower requirements of EURO standards than recommended in POP 2020 – insufficient number of vehicle inspections entering CTZ – possibility of abuse – increase in public transport ticket prices

4.3. Hydrogen vehicles

The last proposal, which also relates to transport, is the replacement of combustion vehicles with hydrogen-powered vehicles. Hydrogen vehicles use fuel cells, in which the oxidation of H from the fuel tank and the reduction of oxygen from the air take place. The reaction generates electricity. Hydrogen vehicles produce only water and do not produce any pollutants. In addition, for example, Toyota Mirai, a hydrogen car, is fitted with an active carbon filter, which removes between 90% and 100% of pollutants such as NO_x, SO_2 and PM2.5 from the air drawn. The car purifies approximately 0.47 m^3 of air per kilometre driven (www.toyota.pl). The EU's 2035 ban on the sale of new CO_2-emitting cars can be the biggest incentive to use hydrogen technologies in transport [62]. The possibility of implementing this solution for passenger cars is limited due to an insufficient number of hydrogen filling stations. Krakow plans to use hydrogen technology in public transport and intends to buy more hydrogen buses [63,64]. Another obstacle is the high price of such vehicles (TABLE 10).

TABLE 10

SWOT Analysis for Hydrogen Vehicles

Strengths	Weaknesses
– no pollutant emissions – purification of collected air – hydrogen production in the Małopolska province – hydrogen refuelling station for public transport buses	– high vehicle prices – lack of public hydrogen refuelling stations – conventional hydrogen for refuelling
Opportunities	**Threats**
– possibility of implementing hydrogen technologies in public transport – plans to create new hydrogen refuelling stations in Poland – development of hydrogen technologies – plans to produce low-emission hydrogen – sales of only zero-emission vehicles in the EU after 2035	– displacement by cheaper electric cars – high cost of the catalyst (platinum) – insufficient promotion

5. Conclusions

Our analysis of air concentrations of pollutants in Krakow over 12 years, from 2010 to 2021, showed the following:

1. The annual mean concentrations of PM10, PM2.5, NO_2, SO_2 and B[a]P decreased by 42%, 40%, 6%, 50% and 60%, respectively, and the annual mean concentration of ozone increased by 21.2%.
2. The concentrations of PM10, PM2.5, B[a]P and SO_2 in heating seasons decreased by 56%, 55%, 71% and 75%, respectively.
3. The legal limit values for the annual mean concentrations of SO_2 and NO_2 were met in each of the years analysed, the limit value for PM10 was met from 2019 through to the end of the period analysed, whereas the target/limit values for PM2.5, B[a]P and the maximum daily 8-hour mean ozone concentration were exceeded in each of the years analysed.
4. The hourly and daily limit values and information thresholds for SO_2 and NO_2 were not exceeded.
5. The number of exceedances of the daily mean limit value, information threshold and alert threshold for PM10 decreased by 51%, 95% and 101%, respectively.
6. The contribution of the municipal and residential sector to PM10, PM2.5 and B[a]P emissions decreased significantly.
7. NO_2 levels decreased slightly (by more than 8%), with the largest decrease seen in non-heating seasons.
8. In non-heating seasons, the largest increase was seen in ozone concentrations (31%).

Despite the anti-smog resolution introduced in Krakow, air quality in the city remained poor, especially during the heating seasons. The objectives for reducing pollution emissions as set out in the APP were not met. This was mainly due to the large and growing contribution of road transport to emissions and pollution transport into Krakow from the surrounding communes. While the objectives for reducing PM10, PM2.5 and B[a]P emissions were not met, the reductions in emission levels achieved in Krakow were significantly better than those seen for the entire Małopolska Province. This undoubtedly results from the gradual reduction in the number of solid fuel furnaces and boilers in Krakow, which in turn led to large reductions in particulate and B[a]P emissions from the municipal and residential sectors. Our analyses showed that while the measures taken yielded good results, it is necessary to introduce other solutions to further reduce air pollution in the city.

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