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Assessing the Effectiveness of Air Quality Improvements in Polish Cities Aspiring to Be Sustainably Smart

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Abstract: Environmental and climate protection is one of the areas of development of modern smart cities intensively exposed in the literature. Nevertheless, it often remains only a scientific postulate or a strategic record of city authorities. With these circumstances in mind, this article addresses conceptual assumptions with actual achievements in improving air quality in 16 Polish cities aspiring to be smart. In this way, an answer is sought to the following research problem: To what extent do Polish cities aspiring to be smart and operating in a developing economy realize the climate quality improvement goals exposed today by the smart city concept and the environmental requirements of the European Union? The research was conducted in a long-term perspective covering the period from 2010 (entry into force of EU air quality standards) to 2022. In addition, with reference to contemporary urban environmental studies, special attention was paid to the impact of the COVID-19 pandemic on air quality in the surveyed cities. In the course of the study, data on PM10 concentrations were used and statistically analyzed using measures of variability and cluster analysis as an unsupervised classification method. The results allow the formulation of the following key conclusions: (1) PM10 levels were systematically reduced in all 16 cities studied, which allows a positive assessment of the municipal authorities' efforts to improve urban air quality; (2) the leaders in the effectiveness of PM10 reduction are Warsaw and Wrocław; and (3) after the COVID-19 pandemic, most of the cities studied managed to maintain or improve urban air quality. The originality of the considerations and analysis undertaken is due to the following considerations: (1) to fill the research gap in terms of the long-term assessment of the effectiveness of air quality improvement in cities aspiring to be smart and located in developing or emerging economies; (2) to make a cognitive contribution to the environmental research stream on smart city development (gaining knowledge on the effectiveness of cities' actions to improve air quality); and (3) to conduct an analysis of the impact of the COVID-19 pandemic on air quality in Polish cities located in various provinces.

Keywords: Polish smart cities; environmental and climate protection in smart cities; urban air quality; effectiveness of measures to improve urban air quality

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1. Introduction

The smart city concept has been developing steadily since the end of the last century and is a response to the search for ways to improve the quality of life and increasing urbanization [1]. Initially, it was primarily associated with the use of modern information technology (IT) and information and communication technology (ICT) in the urban environment to improve the functioning of cities [2–4]. Over time, increasing attention has been paid to the social and environmental aspects [5] of smart city development, which is intended to make modern cities more humane and sustainable [6–8]. In addition, it is also intended to respond to the objections of adversaries of the smart city concept regarding, among other things: the promotion of excessive consumerism, meeting only the commercial needs of technology providers, social and economic exclusion (of seniors, people with disabilities, less affluent members of the urban community), and the negative impact of urbanization on the environment in cities and their immediate surroundings. Among other things, the lack of connection between smart urban solutions and urban ecological policy is criticized [9]. In addition, SC assessment methods fail to take into account stakeholder involvement [10] and the concept itself focuses on the unions of tech barons, city mayors, and entrepreneurs [11]. Excessive technicalization adapted to social needs is also subject to criticism [12]. Another problem is the issue of exclusion [13] and social marginalization [14].

In the context of the above circumstances, more and more social and environmental themes are emerging in the literature and in the practice of smart city management [15–21]. Nevertheless, they are still not dominant in the stream of considerations and research on smart city concepts. In many cases, they are also limited to presenting single solutions or selected case studies [22–25]. This, in turn, does not allow a holistic and long-term view of environmental and climate issues in cities that are or aspire to be smart.

In addition, efforts to improve environmental quality are a particularly difficult task for cities operating in emerging and developing economies, where the basic livelihood needs of urban communities are still not fully met [26–28]. At this point, it is worth adding that a developing economy is understood as a country that has not yet reached full socio-economic development. It is distinguished by a lower quality of life than in a fully developed economy, a low degree of industrialization, a lack of financial resources, and a relatively low level of Gross Domestic Product per capita. Nevertheless, in a developing economy, the rate of economic growth, and thus pro-development aspirations, are usually higher than in developed economies. In these economies, government attention and financial resources are focused on economic, social, and often political priorities, causing environmental and climate problems to be downplayed by both policymakers and urban communities [29–31].

In the European Union, within the framework of climate policy coherence, collective actions for environmental protection have been undertaken for many years [32,33]. Their real dimension is the systematically tightened regulations in force in all member states [34,35]. They are oriented toward maximizing the use of renewable energy sources and a closed-loop economy, which is expected to make all EU economies zero carbon by 2050 [36,37].

The European Union also focuses on the systematic reduction in industrial pollution in the air. An expression of this is the introduction in 2009 of the Air Quality Directive, setting acceptable air quality standards, including the permissible content of PM10 in the air. Meeting the standards set out in this Directive has been and is a real challenge for today's dynamically urbanizing cities.

With the above circumstances in mind, this article attempts to answer the following research problem: To what extent do Polish cities aspiring to be smart and operating in a developing economy realize the goals related to improving climate quality exposed today within the smart city concept? The above problem relates directly to the effectiveness of municipal authorities in the field of environmental protection, and its solution is intended to contribute to urban studies and assessment of the implementation of the smart city concept in Polish cities.

To solve the such-posed problem, 16 Polish cities from various provinces were examined from 2010 to 2022. In assessing the effectiveness of air quality improvement in cities, measurements of PM10 particulate matter are used, analyzing their value in the context of the applicable standards and the scale of change over time.

The originality of the proposed research results from the following circumstances:

- An assessment carried out concerning the effectiveness of improving air quality in Polish cities in the long term and comparatively;
- Indication of the scope for achieving environmental quality improvement goals in cities aspiring to be smart;
- Identification of the cities that best fit with the environmental priorities of the European Union and the smart city concept;
- Embedding research in a developing economy characterized by problems in meeting environmental goals;

- To fill the research gap in terms of holistic (non-case study) analyses of the environmental aspects of smart city development, with a particular focus on the impact of the COVID-19 pandemic on air quality in Polish cities (such studies have not been conducted so far and are part of the international research trend from 2019 to 2022).

The description of further analyses was arranged in such a way as to answer the research question posed above. They begin with a literature study of environmental and climate protection in cities located in EU developing economies with a particular focus on urban air quality issues. Based on these, the research gap is identified. Next, the adopted research methodology is presented, including data sources, characteristics of the analyzed cities, and statistical tools used to assess the dynamics and comparative analysis of the studied phenomena. Research results are described from the perspective of air quality standards, the extent of air quality improvement in individual cities, and the ranking of the most environmentally effective cities. Based on the identified trends and comparisons, a discussion is carried out addressing the results and achievements of previous research with the conclusions obtained by the author of the article, and recommendations are made to the studied cities. The entire discussion closes with a summary containing key insights, research limitations, and directions for further research.

2. Literature Overview

This section reviews the literature with two key issues related to urban environmental and climate protection in mind. The first refers to the role of environmental determinants of smart city development in emerging and developing economies. The second covers detailed issues related to the effectiveness of improving the quality of urban air. Both literature threads were used to identify the research results to date and to define the existing research gap.

2.1. Environmental and Climate Issues in Smart Cities of Developing and Emerging Economies

As already mentioned, environmental and climate issues are not priority issues in developing economies. What matters most to them is economic development to catch up with developed economies [38,39]. This is also what citizens, including urban residents, want. This is due to the hierarchy of needs, according to which material, subsistence needs are met first, including, above all, individual needs [40]. Meanwhile, environmental and climate protection is a collective need, and its satisfaction is for the benefit of present and future generations, which does not directly involve any tangible benefits of its own [41–43].

Emerging and developing economies are also having a lot of trouble with green energy transition [44,45]. This is the result of years of using traditional energy resources, which are more readily available and cheaper to use. The energy transition now being advocated requires them to have access to the latest technologies, significant capital investment, and public acceptance of the higher costs of obtaining electricity and heat [46,47]. Changes in energy sources in developing and emerging economies evoke social resistance mainly for economic reasons and established habits. [48,49]. The circumstances described above, albeit on a smaller scale, carry over to the local level and impinge on the approach and implementation of environmental goals.

Meanwhile, as Cepeliauskaite et al. (2021) [50] pointed out, the existence and level of environmental awareness of both authorities and local communities play a key role in environmental and climate protection in smart cities. Their research shows that in Europe's emerging economies (Lithuania, Latvia, Estonia), the level of this awareness is far lower than in developed economies (Germany), as residents of Kaunas, Riga, and Tartu are far more difficult to persuade to give up individual car transportation (in favor of public or bicycle transportation) than those in Berlin.

The result of adverse financial and social conditions is the poor state of the environment in the cities of European emerging and developing economies. According to research conducted by Kopackova (2019) [51] in Prague, Ostrava, Budapest, Miskolc, and Warsaw, residents have a very poor opinion of urban air quality. They also perceive virtually no interest and involvement of city authorities in environmental and climate protection activities.

Similar conclusions were reached by Erős et al. (2022) [52] analyzing case studies of Romanian cities aspiring to be smart. The authors concluded that far too little attention is paid to climate, environmental protection, and waste management in the development strategies adopted and implemented by the city study. This confirms earlier observations about the marginalization of environmental issues in developing and emerging economies.

Kronenberg et al. (2020) [53] attempted to identify the reasons for the low interest of municipal authorities in environmental issues. Their assessment was highly critical. They considered extreme individualism and the associated lack of social solidarity as one of the reasons for the observed state of affairs. They also placed the blame on municipal authorities, who disregard social needs and show extreme irresponsibility for the public interest. The authors also indicated the reasons for the disrespectful attitude of the municipal authorities. Among them they mention: the long-standing system of a centrally planned economy, which was characterized by a lack of trust in authority and a false and illusory understanding and realization of the public interest. Nonetheless, today these remnants represent a serious obstacle to the sustainability of smart cities in Europe's emerging and developing economies.

In the context of the findings of Kalbarczyk and Kalbarczyk (2022) [54], the above observations may be surprising. After all, the authors examined the scope and quality of municipal environmental and climate protection development plans in 44 Polish cities and concluded that they were very well designed. They took into account the desired goals and the means of achieving them, and, in addition, analyzed the uncertainty associated with the variability in environmental and climate conditions. Interestingly, however, the research perspective of the aforementioned authors took into account only the declarative aspect because they did not study the results of the planned activities, they focused only on the written intentions. The degree to which the stated goals were achieved and the extent of measures actually taken to achieve them were not examined.

As a counterpoint to the environmental challenges and problems described above, it is worth citing at least a few achievements and successes in the sustainability of the smart cities analyzed. Thus, Lewandowska and Szymańska (2021) [55], based on the author's synthetic environmental assessment index, noted the systematic greening of Polish cities. Their study of 65 cities shows that environmental and climate quality improved by an average of 6% over 13 years. This indicates a positive, albeit slow, development trend.

On the other hand, Serbanica and Constantin (2017) [56] emphasized that thanks to EU solidarity policies, a number of interesting pro-environmental projects have been implemented in emerging and developing economies. In the Czech Republic, for example, green transportation modes have been implemented. In Romania, the recycling of raw materials was successfully launched and the use of water resources for energy was activated. In Slovakia, eco-innovations were implemented in iron and steel production. In Slovenia, modern heating systems and biomass and biomaterials began to be used. Hungary invested in sustainable agriculture and renewable and clean energy. Poland began producing energy-efficient structures, and took steps toward smart, green transportation and the use of modern technologies in food production.

Thus, it can be concluded that the analyzed economies are making efforts to be smart organically; however, these efforts are not always successful and there is still a lot of catching up to do compared to developed economies. As a result, most of the cities aspiring to be smart in emerging and developing economies are in the early stages of developing the smart city concept. These are generation 1.0 or 2.0 cities, and their distinguishing feature is lower attention to social and environmental issues, and consequently lower sustainability and poorer implementation of modern assumptions of the smart city concept [57,58].

Given these circumstances, there is a legitimate rationale for undertaking research on the effectiveness of improving urban environmental quality in European emerging economies. Among them, it is important to mention:

- The need to monitor environmental and climate progress;
- Exposing the importance of environmental priorities in the smart city concept;
- The need to evaluate the effectiveness of municipal policies to take care of air quality;
- The lack of studies documenting the effects of environmental goals in smart cities in a long-term and comparative perspective.

2.2. Air Quality in Smart Cities

In this article, environmental issues have been narrowed down to those related to air quality, so this subsection focuses attention on a review of the literature in this area.

In general, progressive urbanization is not conducive to improving the quality of the urban environment [59–61], as it is associated with increased transportation, the development of industrial plants, and intensive exploitation of urban space. This is also confirmed in a study by Lin and Zhu (2018) [62], who found that in the initial phase of intensive urbanization, the urban environment is negatively affected by population density, the increasing number of private cars, and average air temperature. Beyond a certain level, the negative impact of urbanization on environmental quality can decrease under the condition of optimizing the industrial structure and promoting harmonious development of the economy and environment [63–65].

In the course of detailed research on air quality in smart cities, there are mainly publications on the use of modern technologies to measure and monitor its quality [66–68]. This approach fits into the mainstream of smart city considerations related to the use of IT and ICT for information management in urban infrastructure [69].

Studies of comprehensive and integrated approaches to air quality management are also appearing in the literature, exposing the importance of proper planning and monitoring of the state of the environment in cities. Molina et al. (2020) [70]—analyzing air quality management programs in Singapore and Mexico—noted that both cities have significantly reduced air pollution levels using systemic and long-term management plans. Although cultural and economic differences influenced the decision-making process in the two entities studied, they did not reduce the effectiveness of environmental and climate protection measures. The conclusions obtained contribute to the evidence that cities in developing economies—with the right environmental management strategy—can also be successful in the face of environmental challenges and are not always doomed to failure in this area for economic reasons.

Similar—albeit less enthusiastic—insights emerge from the findings of Pisoni et al. (2019) [71]. The authors analyzed the impact of 642 European urban sustainable mobility plans on levels of PM2.5 particulate matter and nitrogen dioxide (NO_2). The results they obtained show a moderate impact of the implementation of these plans on urban air quality, as PM2.5 emissions were only reduced by about 2% and NO_2 by about 4% per year.

An unsatisfactory level of air pollution reduction was also reported by Rodriguez-Rey et al. (2022) [72] studying the impact of private car restrictions on NO_x emissions in Barcelona. The researchers noted that individual city government actions have very limited impact on urban air quality. They also suggested combining transportation restrictions with upgrading (renewing) urban transportation, which would produce a better integrated synergistic effect. Ultimately, they also concluded that the current actions of Spanish cities are insufficient to meet EU requirements for air quality standards.

Li et al. (2019) [73] arrived at interesting and valuable conclusions about the impact of subway station expansion on air quality. According to the authors' calculations, an increase in the density of the subway network by one standard deviation improves urban air quality by 2%. Furthermore, they enriched their study by estimating the health benefits (reduced morbidity and mortality from diseases caused by poor air quality) associated with the construction of 14 new subway stations, which would amount to about USD 1.0–3.1 billion over a 20-year period.

As mentioned in the previous subsection, the quality of the environment and climate is also affected by factors of a psychological and social nature, such as environmental awareness and the behavior and habits of residents. Research results by Borbet et al. (2018) [74] show that systematically provided information (reports) on air quality can modify residents' attitudes and behavior. The propensity to change behavior and the level of environmental awareness is higher in their study for: urban residents, the elderly, better-educated respondents, and respondents informed about air quality measurement results. This allows one to conjecture that the authorities of smart cities monitoring air quality are able to effectively influence the pro-environmental psychological and social parameters of residents, and thus increase the effectiveness of improving environmental and climate quality.

Moreover, the impact of the COVID-19 pandemic on urban air quality has received considerable attention in the past three years. Rodríguez-Urrego and Rodríguez-Urrego (2020) [75], studying 50 of the world's most polluted cities, found that successive lockdowns contributed to significant reductions in PM2.5. Thus, they had a positive impact on urban quality of life and reduced the risk of serious lung diseases caused by air pollution.

Adam et al. (2022) [76] confirmed the above conclusions in terms of the positive effect of COVID-19 on reducing outdoor air pollutants in the form of PM10 and PM2.5 particulate matter, carbon monoxide, and nitrogen dioxide and sulfur dioxide. However, they pointed out the accompanying pandemic increase in ozone and secondary particulate matter levels. They also stressed the need for a parallel study of the state of the air outside and inside urban infrastructure.

Zangari et al. (2022) [77] noted, however, the short-term nature of the observed improvement in air quality during the COVID-19 pandemic. Their study looked at PM2.5 particulate matter and carbon dioxide concentrations in New York City just after the subsequent lockdowns ended. The results they obtained showed a significant reduction in air pollution. Nevertheless, after applying a linear model with a time lag, it turned out that the concentration levels of the above-mentioned substances were close to the values characteristic of the pre-pandemic period covering 2015–2019. Given the obtained conclusions, the authors suggested conducting long-term analyses that would provide a basis for more objective conclusions about the scale of air quality improvement as a side effect of the COVID-19 pandemic.

On a broader geographic scope (analyzing more cities) and subject matter (analyzing more pollutants), the results of the above studies were confirmed by Kumari and Toshniwal (2020) [78]. Emissions of the substances they studied (PM10; PM2.5; NO_2) managed to be reduced by tens of percent as a result of lockdowns, but this was a short-term phenomenon, accompanied by the aforementioned increase in ozone levels.

Analyzes of air pollution were also carried out in the Polish trend of research on the smart city. Danek and Zaręba (2021a) [79] presented a detailed analysis of data provided by low-cost sensors (LCS) in Kraków. This analysis covers PM1, PM2.5, and PM10 emissions. The obtained results indicate a significant improvement in air quality in Kraków, achieved after the introduction of a restrictive prohibition on the use of fossil fuels. The city began legislative activities in 2012 when the concentration of PM2.5 was about 160 $\mu g/m^3$. As a result of systematically introduced restrictions, in 2020 the level of PM2.5 emissions was only 24 $\mu g/m^3$. The authors also point out the important role of environmental education and the information campaign in the process of improving the quality of urban air. This observation confirms the importance of social and managerial determinants in the greening of cities. Additionally, Danek and Zaręba (2021b) [80] suggested that the current legal and environmental regulations in Poland are insufficient to effectively improve the quality of urban air.

Badyda et al. (2022) [81] conducted their research on air quality in the COVID-19 pandemic in Warsaw. They showed that during the lockdown in March–April 2020 in the capital of Poland, NO_2 emissions decreased by about 35–40%. This was the result of a reduction in the intensity of transport. At the same time, the emission of PM2.5 and PM10 increased due to residents remaining in isolation and increased generation of these pollutants by households.

Slightly different conclusions on PM2.5 and PM10 were formulated by Filonchyk et al. (2021) [82]. Their research shows that during the COVID-19 pandemic (April–May 2020), the level of above pollutants significantly decreased compared to the corresponding months in 2019. Therefore, restrictions on movement had a positive impact on the air quality in the cities they studied: Warsaw, Wrocław, Łódź, Kraków, and Gdańsk.

In the context of the conclusions and recommendations on directions for further research resulting from the above literature review, this article focuses on completing the postulated and missing research threads involving analyses of the effectiveness of air quality improvement: (1) in the long-term research perspective; (2) in cities of a developing economy (Poland); and (3) considering the impact of the COVID-19 pandemic on changes in urban air quality and their persistence over time.

3. Materials and Methods

This section is an introduction to the research and is divided into two parts. The first recalls the research intentions and describes a four-stage approach to assessing the effectiveness of air quality improvement in the examined cities. The second part describes the studied Polish cities.

3.1. Research Intentions, Data, and Methods

The study of urban air quality used concentrations of PM10 particulate matter, which is a mixture of particulate matter and liquid droplets with a diameter of 10 µm (10 µm) or less. It can contain toxic substances from the group benzopyrene, dioxins, and furans that contribute to respiratory diseases. The main source of particulate matter emissions into the atmosphere in Poland are fuel combustion processes in the municipal and household sector, related to heating buildings with the use of solid fuels. In 2018, emissions from this source accounted for approximately 44% of total PM10 emissions. The second largest source of PM10 emissions is road transport. PM10 emissions from the energy sector (5% of the national emission), production processes (10%), and combustion processes related to industrial processes (14%) have a much smaller impact on the occurrence of exceeding the permissible levels of PM10 dust than the aforementioned emissions related to heating buildings and transport [83]. Nevertheless, it is worth adding that the values given above may change over time, and transportation has a greater impact on particulate matter emissions in the summer.

In 2009, the European Union introduced the Air Quality Directive, setting acceptable air quality standards. This Directive sets the standard for PM10 at 40 $\mu g/m^3$. It is also worth mentioning that the World Health Organization (WHO) advocates maintaining a lower standard of 20 $\mu g/m^3$.

In connection with the research gaps identified in the previous section, the research seeks to answer the question: To what extent do Polish cities aspiring to be smart and operating in a developing economy realize the climate quality improvement goals exposed today within the smart city concept and the environmental requirements of the European Union? In order to obtain an answer to such a formulated question, the research was divided into 4 stages:

1. The first stage assessed the level of compliance with PM10 standards set by the European Union and WHO (in this respect, a comparison of institutional standards with indicators reported by individual cities was used, the assessment was carried out with two criteria: "compliance with the requirements" or "non-compliance with the requirements").
2. In the second stage, the obtained data were compared with additional measures for assessing the effectiveness of PM10 reduction, which were taken as:
    - P90 percentile indicating up to which limit 90% of daily PM10 concentration measurements were in;
    - maximum values of daily PM10 concentrations;

- the number of days on which PM10 concentrations exceeded the daily average value.

The indicators listed above were used to deepen the assessment of effectiveness. Meeting the standards in one narrow scope does not guarantee a real improvement in air quality, and thus in the quality of life. The measurement itself can also be aimed at meeting defined requirements. Hence the need to observe non-standardized PM10 values.

3. In the third stage, a comparative analysis of the surveyed cities was carried out using the level of change in PM10 concentrations in 2010–2022 and the average annual rate of change, and the surveyed units were grouped using cluster analysis (unsupervised learning method). The clustering of the examined cities allowed for the selection of the cities with the worst and the best efficiency in terms of improving the quality of urban air. This, in turn, made it possible to develop more precise recommendations for each of the selected groups. Cluster analysis was used as an unsupervised machine learning method in the clustering process. It detects dependencies between objects only based on the data assigned to them. In the clustering process, the Euclidean distance was adopted and the Wards method was used.
4. In the fourth stage, a comparative analysis of the effectiveness of air quality improvements during and after the COVID-19 pandemic was conducted (this analysis was based on the calculation and comparison of the percentage range of PM10 reduction in 2010–2022).

The analysis was conducted for 2010–2022, taking the following years as cut-off dates:

- 2010—the start of EU air protection standards;
- 2015—the first 5 years of EU air protection standards providing a medium-term perspective for assessing the effectiveness of air quality improvements;
- 2020—the next 5 years of EU air protection standards providing a long-term perspective for assessing the effectiveness of air quality improvements, and additionally the opportunity to assess the impact of the COVID-19 pandemic on PM10 concentration levels;
- 2022—date to compare the sustainability of changes in PM10 concentrations during the pandemic period with the period of normal economic operation.

The source of data for the analysis carried out in the article was the database of the Chief Inspectorate of Environmental Protection—a government portal on air quality monitoring in Poland [84]. Due to the lack of data, only PM10 was included in the study because the time series for this pollutant was complete.

3.2. Research Sample Characteristics

Sixteen provincial cities were surveyed in accordance with the stages described above. These are the largest Polish cities that are familiar with the smart city concept and are implementing smart city solutions. Their geographical distribution is shown in Figure 1, and general numerical characteristics including number of inhabitants, area, and population density are included in Table 1. It should also be noted that 2 of the 16 units analyzed, Wrocław and Warsaw, are the Polish cities most frequently mentioned in international rankings of smart cities.

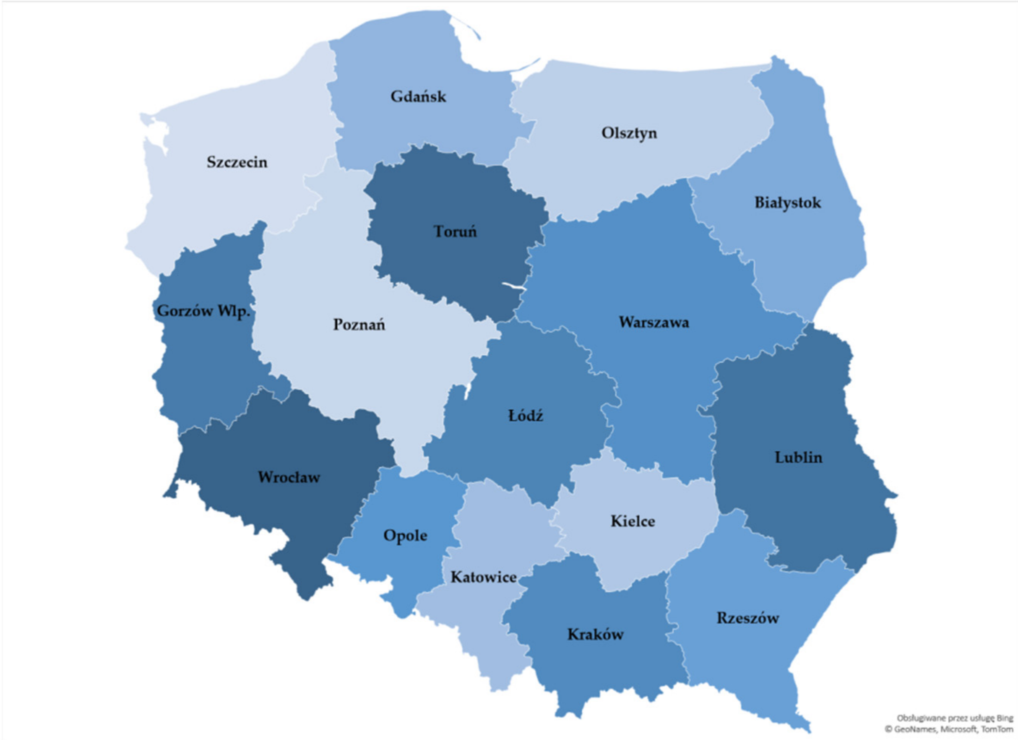

Figure 1. Location of the surveyed cities.

Table 1. Characteristics of the surveyed cities.

City	Inhabitants	Surface	Population Density
Białystok	296,000	102 km^2	2902 persons/km^2
Gorzów Wlk.	120,087	86 km^2	1400 persons/km^2
Gdańsk	471,000	263 km^2	1787 persons/km^2
Katowice	292,000	165 km^2	1756 persons/km^2
Kielce	192,500	110 km^2	1686 persons/km^2
Kraków	782,000	327 km^2	2450 persons/km^2
Lublin	338,000	147 km^2	2270 persons/km^2
Łódź	670,42	293 km^2	2287 persons/km^2
Olsztyn	170,622	83 km^2	1932 persons/km^2
Opole	127,839	149 km^2	858 persons/km^2
Poznań	532,000	262 km^2	2031 persons/km^2
Rzeszów	198,609	129 km^2	1539 persons/km^2
Szczecin	396,472	301 km^2	1319 persons/km^2
Toruń	197,812	116 km^2	1511 persons/km^2
Warsaw	517,000	517 km^2	3466 persons/km^2
Wrocław	643,000	293 km^2	2298 persons/km^2

4. Results

The analysis of the obtained results began with an individual assessment of the effectiveness of improving the air quality in the cities studied. Then, a comparative analysis and clustering were carried out in order to select the most effective municipal entities.

4.1. Assessing the Effectiveness of Air Quality Improvement

According to the research methodology outlined in the previous section, the first stage of the analyses involved assessing the effectiveness of air quality improvements individually for each of the cities studied. The first part of the assessment took into account the EU standard that annual average PM10 concentrations must not exceed 40 µg/m^3 and the WHO standard of 20 µg/m^3. The results for the analyzed periods (2010; 2015; 2020; 2022) are shown in Table 2.

Table 2. Values of annual average PM10 concentrations in the studied cities in 2010, 2015, 2020, and 2022 (in µg/m^3).

City	Years			
	2010	**2015**	**2020**	**2022**
Białystok	27	25	19	17
Gdańsk	30	36	19	17
Gorzów Wlk.	26	19	21	20
Katowice	52	46	34	31
Kielce	42	37	28	26
Kraków	48	52	30	29
Lublin	32	29	21	19
Łódź	61	42	31	32
Olsztyn	22	25	18	19
Opole	32	31	25	22
Poznań	38	27	20	21
Rzeszów	40	30	20	21
Szczecin	34	26	25	21
Toruń	43	29	23	21
Warsaw	56	33	22	22
Wrocław	62	28	23	24

—compliance with the WHO requirements; —non-compliance with the EU requirements. Source: [84].

According to the data in Table 2, the less stringent EU air quality standards were exceeded in the surveyed cities only in 2010 and 2015. The worst situation was in Katowice, Kraków, and Łódź. It was slightly better in Toruń, Warsaw, and Wrocław. In the longer term, covering 2020 and 2022, none of the surveyed cities exceeded the normative EU average annual PM10 concentration of 40 µg/m^3.

Therefore, given the above observations, we can conclude that all the analyzed cities have been effective in improving air quality with regard to PM10 particulate matter and, both during and after the COVID-19 pandemic, have been complying with European Union standards.

However, the situation does not look so favorable in the context of the standards set by the WHO. In 2010, none of the surveyed cities met the postulated PM10 concentration standard of 20 µg/m^3. In 2015, Gorzów Wielkopolski was the only city to meet it. In 2020, the standards were met by Białystok, Gdańsk, Olsztyn, Poznań, and Rzeszów. In 2022, Lublin joined the above group, and 11 out of the 16 cities surveyed did not meet the stricter air quality standards. At this point, it should be explained that among the "green" cities listed, it was certainly easier for those units that are less industrialized and operate in a more agricultural part of Poland to achieve normative results—these are: Białystok, Olsztyn, and Rzeszów. Nevertheless, the indicated group also included Gdańsk and Poznań—more industrialized cities, which deserves special mention.

In Table 2, it is also worth noting the involvement of Warsaw and Wrocław (the Polish entities most frequently mentioned in international lists of smart cities) in efforts to improve air quality. In 2010, these cities had the highest PM10 concentrations in the analyzed research group, which they had already managed to significantly reduce in 2015, and in 2020 and 2022 their value approached the standard postulated by the WHO. The significant reduction in PM10 was certainly contributed to by the tightening of environmental regulations at the state level, which is perfectly illustrated by the example of Krakow as described in the literature studies (Danek and Zaręba (2021a); Danek and Zaręba (2021a)).

Since the value of the arithmetic mean is burdened with many disadvantages (extreme variables may distort its final value; all variables are equally significant; is mostly useful in assessing a homogeneous population with a low degree of differentiation) and does not reflect the full structure and course of the studied phenomenon, in the next stage, in the evaluation of the effectiveness of air quality improvement, the following were also used:

- P90 percentile indicating up to which limit 90% of daily PM10 concentration measurements were in;
- The maximum values of daily PM10 concentrations;
- The number of days on which PM10 concentrations exceeded the daily average value.

The results of the above measurements for the analyzed periods are shown in Figures 2–4.

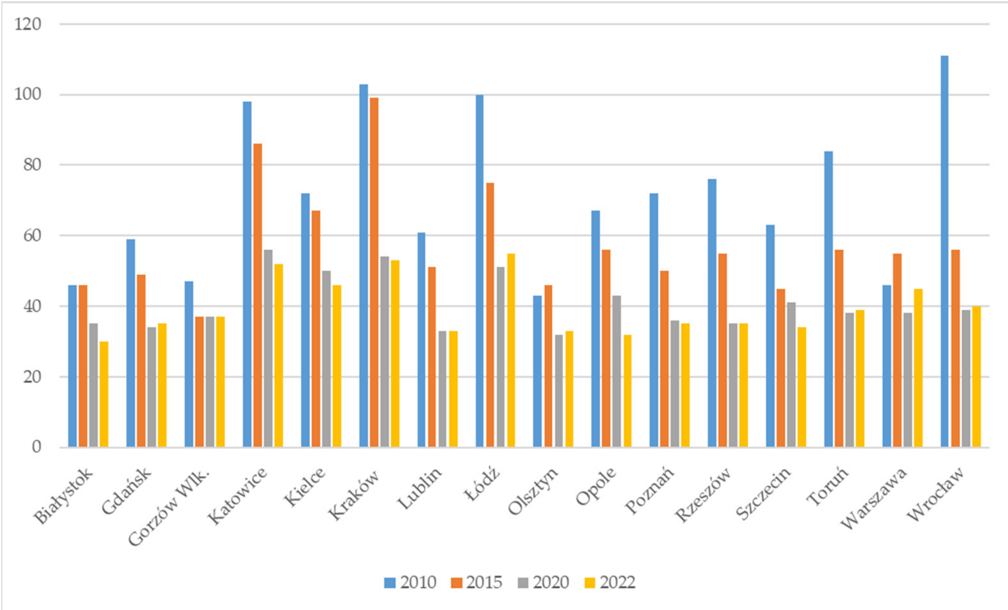

Figure 2. P90 percentile of PM10 concentrations in the surveyed cities in 2010, 2015, 2020, and 2022. Source: [84].

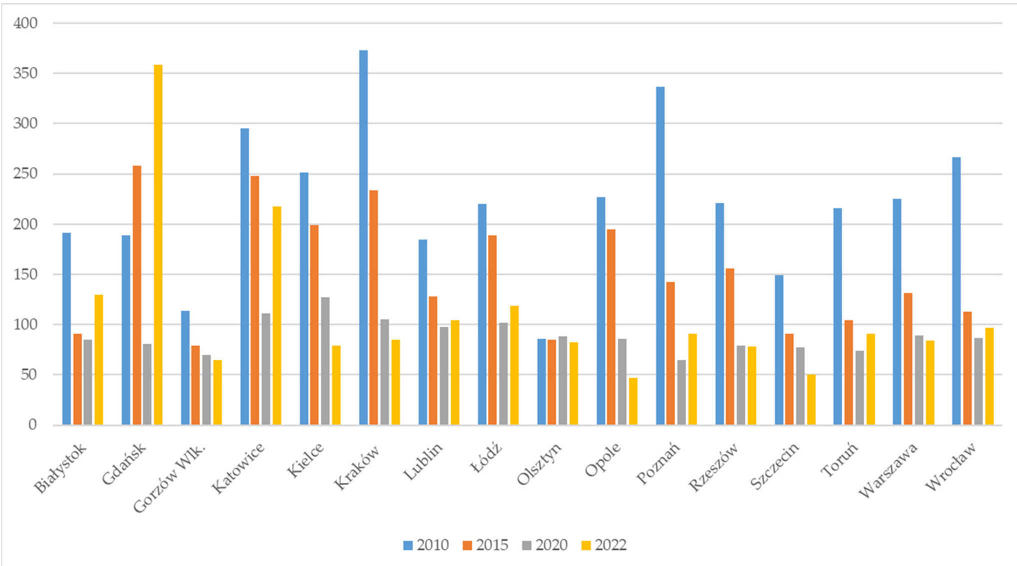

Figure 3. Maximum values of daily PM10 concentrations in 2010, 2015, 2020, and 2022. Source: [84].

From the data presented in Figure 2, it can be seen that the value of PM10 particulate matter steadily decreased in all cities, and this was true not only for the annual average, but for 90% of daily measurements. In most of the cities surveyed in 2020 and 2022, the dominant part of the indications were already below the EU standard of 40 μg/m^3, which indicates good effectiveness in terms of measures to improve urban air quality. The following cities failed to meet the challenge: Katowice, Kielce, Kraków, Łódź (both in 2020 and 2022), as well as Opole (in 2020) and Warsaw in 2022. Katowice, Kraków, and Łódź should be remembered as cities that also failed to meet the EU standard for average PM10 concentrations in 2015, indicating their problems in maintaining the desired air quality. Nevertheless, it should be noted that these are also cities where the P90 percentile had the highest values in 2010 and 2015, and eventually managed to reduce it quite significantly in subsequent periods.

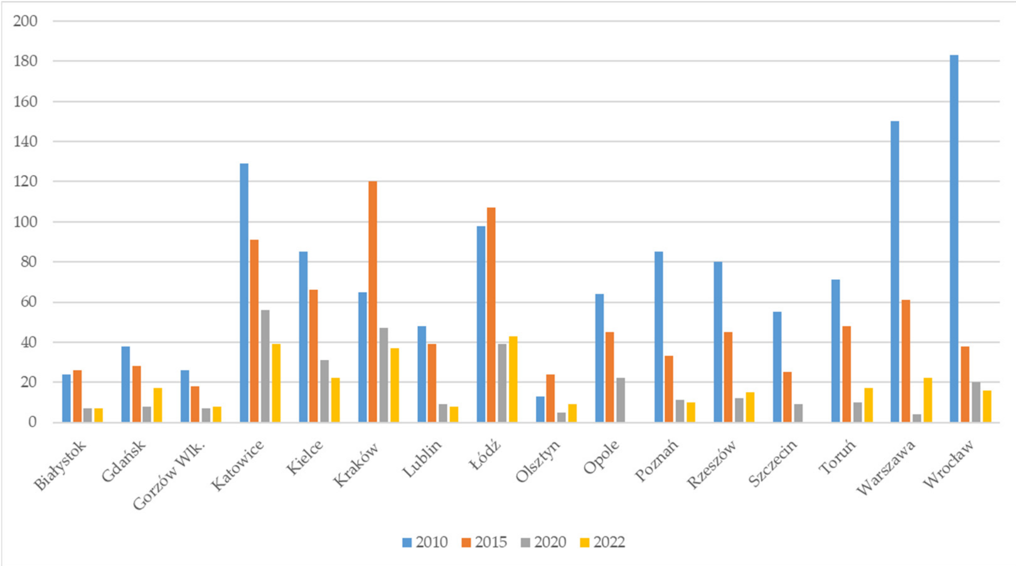

Figure 4. Number of days on which PM10 concentrations exceeded the daily average value in 2010, 2015, 2020, and 2022. Source: [84].

Taking into account the stricter PM10 standard recommended by the WHO, one must conclude that none of the analyzed cities managed to even approach the P90 percentile value to the optimum of 20 µg/m^3. This means that 90% of daily measurements of PM10 concentrations over the entire study period were above the indicated value.

According to Figure 3, the maximum values of PM10 concentrations in the analyzed cities exceeded 50 µg/m^3 throughout the study period, and were therefore higher than the EU and WHO standard. The reduction in the values of maximum concentrations in 2020 and 2022 clearly confirms previous observations about the good efficiency of cities in improving air quality. Here, Olsztyn (a city located in the Masurian Lake District in a forest–agricultural area) stands out from the surveyed units, having managed to maintain low PM10 values throughout the analyzed period.

The systematic improvement in the effectiveness of air protection in the studied cities is also confirmed by an analysis of the number of days on which PM10 concentrations exceeded the daily average value (Figure 4). In all the studied cities, their number significantly decreased in 2020 and 2022. Noteworthy in this regard are Białystok, Gdańsk, Gorzów Wielkopolski, and Olsztyn, where both the average and the number of days with exceedances were low. In addition, the efforts of Warsaw and Wrocław are notable as they managed to significantly reduce the number of days in which PM10 concentrations exceeded the daily average values.

Summarizing the considerations presented in this subsection, it should be stated that the Polish cities studied in the period 2010–2022 managed to significantly improve air quality in the context of the analyzed PM10 concentrations. In 2020 and 2022, all analyzed units met the EU standards for daily average concentration, and several cities additionally met the more stringent WHO requirements as well. The above observations are also confirmed by changes in the P90 percentile indicating up to what limit 90% of daily PM10 concentration measurements were in, the maximum value of daily PM10 concentrations, and the number of days on which PM10 concentrations exceeded the average daily value.

4.2. Benchmarking the Effectiveness of Urban Air Quality Improvements

In addition to assessing effectiveness at the individual level, this paper attempts to compare effectiveness within the study group of cities and in the context of the COVID-19 pandemic. The results of the study documenting this step are presented in this subsection.

The comparative analysis of cities used two relative measures of performance evaluation: (1) the reduction in average PM10 concentrations in 2022 compared to 2010; and (2) the average annual rate of change in PM10 concentrations. The results of the aforementioned parameters are shown in Table 2.

The best results in terms of the total reduction and average annual reduction of PM10 concentrations were achieved by Warsaw and Wrocław, which illustrates the aspirations of these cities to be smart not only in the area of modern technology but also in terms of improving environmental quality and climate. Significant improvements compared to the original state also occurred in Toruń, Rzeszów, and Łódź.

On the other hand, the lowest values of change over time occurred in Olsztyn, Gorzów Wlk., and Opole. Nevertheless, we should add that in the mentioned cities the initial level of PM10 concentrations was low (Olsztyn, Gorzów Wlk, Poland) or average (Opole, Poland) compared to the other cities studied, which undoubtedly influenced the lower extent of the final and average annual reduction.

In the following analysis, the grouping of the studied cities was carried out taking into account the two parameters presented in Table 3 (reduction in average PM10 concentration in 2022 compared to 2010 and the average annual rate of change in PM10 concentration), and, in addition: the level of PM10 concentration in 2010 and the number of days on which PM10 concentration exceeded the average daily value in 2010. It is oriented to a breakdown that takes into account the effectiveness of the improvements made to urban air quality. The results are presented in Figure 5.

Table 3. Reduction in average PM10 concentration in 2022 compared to 2010 and the average annual rate of change in PM10 concentration.

Cities	Parameters	
	Reduction in Average PM10 Concentration in 2022 Compared to 2010	**The Average Annual Rate of Change in PM10 Concentration**
Białystok	37.04%	3.50%
Gdańsk	43.33%	4.28%
Gorzów Wlk.	23.08%	2.00%
Katowice	40.38%	3.90%
Kielce	38.10%	3.62%
Kraków	39.58%	3.80%
Lublin	40.63%	3.93%
Łódź	47.54%	4.84%
Olsztyn	13.64%	1.12%
Opole	31.25%	2.84%
Poznań	44.74%	4.46%
Rzeszów	47.50%	4.84%
Szczecin	38.24%	3.64%
Toruń	51.16%	5.36%
Warsaw	60.71%	6.93%
Wrocław	61.29%	7.04%

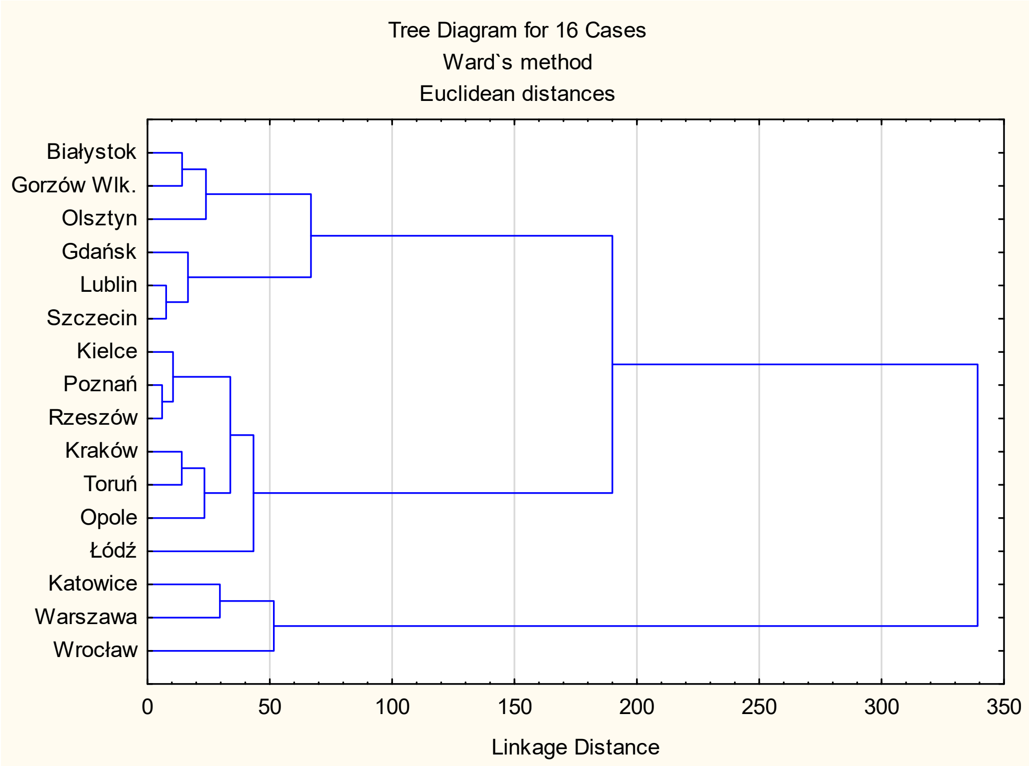

Figure 5. Grouping of surveyed cities by effectiveness of urban air quality improvement from 2010 to 2020.

Assuming a distance of no more than 100, 4 groups can be distinguished:

1. Białystok, Gorzów Wlk., Olsztyn—these are cities with low initial PM10 concentrations and a low number of days in which PM10 concentrations exceeded the daily average value; therefore, they are characterized by a low value of changes in total PM10 concentrations (in 2010–2020) and a low average annual rate of change in this parameter;
2. Gdańsk, Lublin, Szczecin, Kielce, Poznań, Rzeszów, Szczecin, Kraków, Toruń—these are cities with average baseline parameters and average effectiveness in terms of total and average annual PM10 reduction;
3. Opole, Łódź, Katowice—these are cities with fairly high initial PM10 concentrations and a small number of days when PM10 concentrations exceeded the average daily value, which have achieved good—though not the highest—results in terms of improving air quality;
4. Warsaw, Wrocław—these are the cities with the highest baseline PM10 levels and the largest range of PM10 reductions over time, both overall and on an annual average basis.

Given the above classification and description, the most effective in taking care of air quality are the cities in groups 1 and 4. With the first group, the level of PM10 concentration was low so it was enough to reduce it only to a minimum extent. In the fourth group, on the other hand, due to the very high value of the initial parameters, considerable effort was needed to achieve the final result. Groups 2 and 3 included cities with average results in improving air quality, with slightly more effective results for units assigned to the third group.

The final stage of the study involved assessing the sustainability of changes in PM10 reductions after the end of the COVID-19 pandemic. To do so, the baseline PM10 concentration of 2010 was compared first with its 2020 value—characteristic of pandemic lockdowns, and then with its 2022 value—after the opening of the economy. The results of these comparisons are shown in Table 4.

Table 4. Level of change in PM10 concentrations during and after the COVID-19 pandemic: a comparative analysis.

City	Change Level			
	PM10 Average Concentration (Reduction)		Number of Days on Which PM10 Concentrations Exceeded the Daily Average Value (Reduction)	
	2020/2010	2022/2020	2020/2010	2022/2010
Białystok	29.63%	37.04%	70.83%	70.83%
Gdańsk	36.67%	43.33%	78.95%	55.26%
Gorzów Wlk.	19.23%	23.08%	73.08%	69.23%
Katowice	34.62%	40.38%	56.59%	69.77%
Kielce	33.33%	38.10%	63.53%	74.12%
Kraków	37.50%	39.58%	27.69%	43.08%
Lublin	34.38%	40.63%	81.25%	83.33%
Łódź	49.18%	47.54%	60.20%	56.12%
Olsztyn	18.18%	13.64%	61.54%	30.77%
Opole	21.88%	31.25%	65.63%	100.00%
Poznań	47.37%	44.74%	87.06%	88.24%
Rzeszów	50.00%	47.50%	85.00%	81.25%
Szczecin	26.47%	38.24%	83.64%	100.00%
Toruń	46.51%	51.16%	85.92%	76.06%
Warsaw	60.71%	60.71%	97.33%	85.33%
Wrocław	62.90%	61.29%	89.07%	91.26%

—better performance during the COVID-19 pandemic.

The data in Table 4 on the PM10 particulate matter concentration standard show that 12 out of the 16 cities studied saw a further reduction in this pollutant in the air after the COVID-19 pandemic, i.e., in 2022. This means that the improvement in urban air quality in the analyzed context in 2020 was not only the result of the shutdown of the economy, and was of a permanent nature sustained in subsequent periods. The above observation does not apply to Łódź, Olsztyn, Poznań, and Wrocław. In these cities, the PM10 reduction in 2022 was lower than in 2020 (the reference point for both periods was 2010). Nevertheless, the observed increase in PM10 concentrations in these cities did not exceed 2%, so it can be assumed that the favorable trend in improving air quality will also be maintained in these cities.

In order to deepen the conclusions about the impact of the COVID-19 pandemic on urban air quality, changes in the number of days on which PM10 concentrations exceeded the daily average value were additionally analyzed. As shown by the data in Table 4, in this case, the number of cities in which the value of this indicator increased again was seven (Gdańsk, Gorzów Wlk., Łódź, Olsztyn, Rzeszów, Toruń, Warsaw). The identified differences allow us to conclude that, after the economy was restored to full capacity in the cities mentioned, the reduction in the number of days on which PM10 concentrations exceeded the average daily value could not be successfully maintained (the reduction value of this parameter was lower in 2022 than in 2020—the pandemic year).

Summarizing the above observations, it can be concluded that in the studied group of 16 provincial cities, there were 5 cities (Warsaw, Wrocław, Katowice, Opole, Łódź), that at the beginning of the analysis were characterized by high levels of PM10 emissions. However, these cities intensively and successfully pursued its reduction, becoming leaders in efficiency in improving air quality. During the COVID-19 pandemic, the cities' air protection effectiveness was higher in several cases, with a broader focus on the number of days in which PM10 concentrations exceeded the daily average value, and less on maintaining EU PM10 standards.

5. Discussion

As part of the discussion, reference was made to the existing literature studies and research results. Recommendations regarding actions to improve air quality in the surveyed cities were also formulated.

The research carried out in the article suggests that despite the environmental problems of developing economies signaled by Wang and Wei (2015) [18], Cezarino (2021) [38], and Almeshqab (2019) [40], the cities within them are able to effectively, and in the long term, improve environmental and climate quality. The above statement confirms the results of Molina's (2019) [70] research about the possibility of also taking thoughtful and effective environmental measures in economically and socially less developed regions.

Nevertheless, it should be noted that the pro-environmental transformation in the surveyed cities has been relatively slow. The most frequently observed average annual reduction in PM10 dust was between 1 and 3%. A similar scale of air quality improvement was previously observed by Pisoni et al. (2019) [71] and Lewandowska and Szymańska (2021) [55]. Nevertheless, it should be added that the examples of Warsaw and Wrocław, which reduced PM10 levels by 6–7% annually, indicate that faster action to improve urban air quality is also possible. Another excellent example of effective PM10 reduction is Kraków, analyzed by Danek and Zaręba [79,80], where, as a result of restrictive municipal legal and environmental regulations, the air quality was significantly improved. In further research, it would therefore be worthwhile to identify the actions that made such success possible, in line with the approach proposed by others, such as Rodriguez-Rey et al. (2022) [72] and Li (2019) [59].

Regarding the literature threads on the impact of the COVID-19 pandemic on air quality, it can be said that the research carried out in this article confirms that, with the closure of the economy in 2020 in the 16 provincial cities studied, all analyzed parameters related to PM10 were successfully reduced. This is consistent with previous observations by Rodríguez-Urrego and Rodríguez-Urrego (2020) [75] and Adam and Tran (2021) [76]. The obtained conclusions are also consistent with the results of research conducted in Poland by Filonchyk et al. (2021) [82]. However, they do not confirm the observations made by Bady et al. (2022) [81], which indicated the lack of a positive effect of the COVID-19 pandemic on the reduction in PM10 in Polish cities.

Nevertheless, the results obtained on the example of Polish cities and particulate matter do not fully support Zangari et al.'s (2020) [77] and Kumari Toshniwal's (2020) [78] conclusions about the short-term nature of improvements in urban air quality and reductions in its pollutants. Indeed, the present study shows that after the opening of the economy, most of the cities studied managed to maintain or improve the indicators related to PM10 concentrations, which indicates that the effects of improving urban air quality can be sustained in a post-pandemic perspective. Notably, this persistence was to a greater extent related to the average value of PM10 concentrations and to a lesser extent to the number of days on which PM10 concentrations exceeded the daily average value.

Given that none of the surveyed cities in 2020 and 2022 met the PM10 concentration standard set by the WHO, it should be concluded that there are still many challenges in improving urban air quality in Poland. The following recommendations from this research paper and previous studies may be helpful in addressing them:

- Develop long-term plans for protecting the city's environment and climate, and then systematically analyze their results and improve them, as Kalbarczyk and Kalbarczyk (2020) [54] and Erős et al. (2022) [52] pointed out;
- Conduct air quality monitoring and keep residents informed of the results, which, according to Borbet et al.'s (2018) [74] findings, can activate residents and positively influence the effectiveness of air quality improvements, and perhaps offset the lack of public involvement in environmental and climate protection reported by Kronenberg et al. (2020) [53];

- Promote pro-environmental behavior among residents in line with the best practices of smart cities in developing economies, as, for example, called for by Kopackova (2019) [51] and Cepeliauskaite (2021) [50].

6. Conclusions

This study shows that PM10 levels have been steadily reduced in all 16 cities surveyed, giving a positive assessment of the municipal government's efforts to improve urban air quality. Additional detailed conclusions are as follows:

- In 2020 to 2022, all of the cities surveyed on an annual basis met the EU standard for permissible PM10 air concentrations of 20 μg/m^3; in addition, 5 of the 16 cities met the more stringent WHO standard of 40 μg/m^3 during this period;
- The above conclusion is also confirmed by favorable changes in: the P90 percentile indicating up to what limit 90% of daily PM10 concentration measurements were in, the maximum value of daily PM10 concentrations, and the number of days on which PM10 concentrations exceeded the average daily value;
- The leaders in terms of the effectiveness of PM10 reduction are Warsaw and Wrocław—the Polish cities most often mentioned in international rankings as smart cities, which illustrates their sustainability efforts and ability to effectively care for environmental and climate quality;
- After the COVID-19 pandemic (in 2022), most of the studied cities managed to maintain or improve air quality in the context of PM10 concentrations, which implies the sustainability of the studied environmental results;
- The sustainability of the environmental results after the COVID-19 pandemic is more broadly related to the EU PM10 standard, and less to the number of days on which PM10 concentrations exceeded the daily average value.

The originality of the considerations and analysis undertaken is due to the following contributions:

(1) Closing the research gap in the long-term evaluation of the effectiveness of air quality improvements in cities aspiring to be smart and located in developing or emerging economies;
(2) A cognitive contribution to the environmental research stream on smart city development (gaining knowledge on the effectiveness of cities' actions to improve air quality);
(3) The onducting of an analysis of the impact of the COVID-19 pandemic on air quality in Polish provincial cities.

The main research limitations of the analyses carried out are that the focus was only on PM10 and other air pollutants were omitted, and the use of a rather simple research approach (covering four research stages and simple indicators). Nevertheless, the proposed approach makes it possible to capture and easily identify the research idea and replicate the research procedure in both comparative studies and urban practical analyses.

Accordingly, further studies could address other normative air pollutants, such as PM2.5, benzene, BaP, SO_2, or NO_2. They could and should also include a qualitative analysis of the city government's environmental and climate protection measures in cities in terms of their effectiveness. It would also be worthwhile to compare the effectiveness of planned and realized environmental effects, given the abundance of publications on city government declarations and plans and the small number of articles in which authors have undertaken an assessment of the performance of environmental intentions.

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