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Research on air pollution by fine particles in tourist locations in the Ivano-Frankivsk region

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Abstract. The revitalisation of tourism in the Ivano-Frankivsk region highlights the need for systematic monitoring of atmospheric air, particularly in terms of the content of fine aerosol particles, in order to assess the level of environmental safety in popular tourist destinations. The aim of the study was to comprehensively assess atmospheric air pollution by PM_{2.5} and PM₁₀ particles in locations with varying degrees of anthropogenic load, as well as to identify the factors that determine the spatial variability of their concentrations. During the empirical stage, a series of instrumental field measurements were carried out using portable monitoring equipment. The locations were classified into three groups: recreational areas (low load), tourist and recreational areas (medium load) and transport and trade hubs (high load). Multivariate analysis methods were used for statistical data processing, in particular fourth-order polynomial regression and regression modelling of the relationship between PM₁₀ and PM_{2.5} levels, taking into account the load typology. It was found that the average concentrations of PM_{2.5} and PM₁₀ in high-load zones were 14.63 µg/m³ and 34.63 µg/m³, respectively, which does not exceed the maximum permissible values set by national and international standards. The lowest levels were recorded in natural recreational areas, due to the natural filtration capacity of green spaces and the absence of traffic. In areas with medium load, intermediate levels of pollution were found, indicating the influence of both stationary and mobile sources of emissions. Regression analysis

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showed a nonlinear relationship between PM_{2.5} and PM₁₀ ($R^2 = 0.87$), indicating the dominance of the fine fraction in the total mass of aerosol dust. In addition, it was found that an increase in relative air humidity correlates with a decrease in the concentration of fine particles, which is important for predicting air pollution levels depending on weather conditions

Keywords: environmental monitoring; tourist load; atmospheric aerosols; spatial analysis; PM_{2.5}; PM₁₀; regression modelling

Introduction

The issue of the impact of tourism on the natural environment is becoming increasingly relevant in light of global climate change, intensification of anthropogenic processes and rapid growth in tourist flows. In modern conditions, the tourism industry, on the one hand, is an important factor in the economic development of territories, and on the other hand, significantly increases the load on ecosystems, changing natural balances and threatening biodiversity (Stryzhak, 2022).

A. Dias *et al.* (2024) paid special attention in their scientific research to the impact of tourism on the quality of atmospheric air as one of the basic components of the environment that directly affects human health and ecosystem stability. According to modern approaches, the indicators of air quality in tourist locations are recognised as concentrations of fine particles (PM_{2.5}, PM₁₀), levels of carbon dioxide (CO₂), formaldehyde (HCHO) and basic meteorological parameters (temperature, relative humidity). Research into the impact of tourist flows on air quality is important for assessing the environmental sustainability of regions and developing strategies for their adaptation to new challenges.

The relationship between tourism and the state of natural resources is the focus of current scientific research at both the global and regional levels. In particular, G. Miller & A. Torres-Delgado (2023) argued that the rapid and unregulated growth of tourist flows causes systematic depletion of the natural environment. The authors emphasised that the degradation of ecosystems, the deterioration of air, water and soil quality, and the overloading of infrastructure directly affect the

tourist attractiveness of territories and the capacity of regions for sustainable development.

In recent scientific research, A. Dias *et al.* (2024) paid particular attention to the impact of tourist activity on air quality as one of the key elements of environmental stability in a region. Atmospheric air not only serves as a physical environment, but also plays a critical role in maintaining biotic balance, ensuring comfort and forming the health-preserving potential of recreational spaces. The deterioration of air quality due to increased tourist flows is accompanied by a local increase in anthropogenic emissions, in particular from transport infrastructure, accommodation facilities and entertainment establishments. Within the framework of environmental monitoring of tourist locations, the main indicators of air quality are the concentrations of fine aerosol particles PM_{2.5} and PM₁₀, which have the ability to penetrate deep into the respiratory system, carbon dioxide (CO₂) levels as a marker of ventilation activity and traffic density, formaldehyde (HCHO), which is formed as a result of incomplete combustion of organic substances, as well as basic meteorological parameters – air temperature, relative humidity, atmospheric pressure.

D. Yıldırım *et al.* (2023) emphasised the need for regular and spatially adapted monitoring of atmospheric air quality, especially in regions with high tourist traffic density. The authors argued that global warming and climate change are causing transformations in the distribution, duration and concentration of harmful substances in the air, which poses additional risks to public health, reduces the recreational potential

of territories and disrupts the ecosystem balance. In this context, atmospheric air monitoring within tourist destinations is seen as one of the key tools for ensuring environmental safety, adaptive management and forecasting the sustainability of ecological systems under the influence of intensive anthropogenic activity. At the same time, the environmental impact of tourism should be considered not only through the prism of air pollution, but in a broader ecosystem context, which includes the impact on marine and coastal environments, the state of flora and fauna, hydrological balances and landscape structure. Tourism, especially in regions specialising in coastal recreation, exerts multidirectional pressure on natural complexes through the generation of large amounts of solid waste, disruption of the natural rhythms of wild species, degradation of soil cover, erosion processes and transformation of biotopes.

A study by S. Barik *et al.* (2024) demonstrated that unregulated growth in tourist flows leads to significant pollution of coastal areas with household waste, in particular plastic products, packaging, textile residues and organic matter. Such pollution negatively affects the state of biodiversity, both marine and coastal species, disrupts the functionality of ecosystems, and reduces the attractiveness of beaches for recreational use. In addition, the accumulation of waste in the marine environment leads to the formation of secondary microplastics, which threaten food chains and the health of marine organisms.

In turn, the study by M. Ben-Haddad *et al.* (2024) focused on another specific manifestation of anthropogenic pressure - the blooming of macroalgae, which, in a changed marine environment, trap large amounts of plastic on the coast, creating an additional environmental burden and complicating the operation of tourist areas. The massive accumulation of algae enriched with plastic not only causes aesthetic and sanitary discomfort, but also increases the risk of pathogenic environments, which complicates the maintenance of infrastructure in proper sanitary

and hygienic condition. Such processes require the implementation of integrated coastal management models that synchronise environmental monitoring, spatial planning and the participation of local communities in maintaining ecosystem balance. Thus, to ensure the environmental sustainability of tourist regions, especially in coastal areas, it is necessary to comprehensively rethink approaches to managing tourist flows, taking into account the impact on all components of the environment - from air and water to biodiversity and soil and vegetation cover.

The issue of integrating tourism into the paradigm of sustainable development was analysed in detail in the work of S.M. Rasoolimanesh *et al.* (2023). The researchers emphasised that declarative support for environmental safety is not enough to ensure the sustainability of tourist areas - it is necessary to apply a system of quantitative indicators that allow the social, economic and environmental consequences of tourist activity to be verified. The authors also developed an evaluation structure based on a multidimensional analysis of the impact of tourism on the achievement of the Sustainable Development Goals.

Of considerable interest in the context of the greening of tourist areas is the study by A.I. Osman *et al.* (2023), which examined the prospects for the use of renewable energy in tourist infrastructure. The authors argued that the introduction of solar, wind and hybrid energy systems not only reduces overall greenhouse gas emissions but also improves the environmental image of destinations. At the same time, they drew attention to the need for economic justification of such decisions to increase their adaptability at different levels of management.

At the regional level, especially in Ukraine, the issue of sustainable tourism development and environmental protection is becoming particularly relevant. The work of B.O. Shulika *et al.* (2023) analyses the potential of ecotourism as an effective tool for biodiversity conservation and local community activation. The authors showed that the development of ecotourism

practices aimed at preserving landscape diversity also contributes to the formation of an environmentally-oriented worldview and improves the environmental literacy of tourists.

At the same time, O. Tabenska & A. Prylut-skyi (2023) emphasised the regulatory and institutional dimension of sustainable tourism. In their work, they proved the need to form a national strategy for the development of eco-tourism, which should include components of environmental education, active community participation in decision-making, and the adaptation of international experience in managing tourist flows, taking into account local environmental conditions. Thus, the analysis of the literature indicates a systematic awareness by the scientific community of the challenges associated with the ecological transformation of tourist areas, as well as the relevance of developing tools for monitoring, spatial planning and evaluation of the load on natural components of the environment. In this context, the applied analysis of air quality under conditions of varying intensity of tourist activity becomes particularly important, which determines the relevance of the research presented in this article.

The issue of studying the relationship between the level of tourist load and the concentrations of fine particles in the air is becoming increasingly important. PM_{2.5} and PM₁₀ are recognised by the World Health Organisation as some of the most dangerous pollutants for human health due to their ability to penetrate deep into the respiratory system, causing serious diseases. In view of this, a quantitative assessment of PM_{2.5} and PM₁₀ concentrations in different types of tourist locations (from natural and recreational to transport and commercial areas) allows not only to identify risk areas, but also to justify measures to optimise tourist activities.

In this context, instrumental monitoring of air quality in tourist locations in the Ivano-Frankivsk region, followed by their differentiation according to levels of anthropogenic load and the application of mathematical methods for analysing

pollution factors, is of particular scientific and practical importance. The aim of the study was to comprehensively model the relationship between the level of tourist load and the concentrations of PM_{2.5} and PM₁₀ particulate matter in the air to identify the leading factors in the formation of dust load in recreational areas.

Materials and Methods

The study was conducted using a comprehensive approach that combined theoretical analysis of contemporary scientific literature and field measurements of atmospheric air quality in tourist locations in the Ivano-Frankivsk region. The methodology ensured comprehensive coverage of the subject matter and representativeness of the data obtained. Field measurements were taken on 30 August 2024 within tourist locations in the Ivano-Frankivsk region. The selection of sites was based on the need to cover a variety of environmental conditions and levels of anthropogenic load, from natural recreational areas to urban and transport-commercial areas. The list of locations included: Underhill Earth History Park, forest area near Underhill, Pidhiria (residential area), Leybova Hora restaurant, transport area near Leybova Hora, parking area at the entrance to Leybova Hora, Shevchenko Square in Nadvirna, Hetmana Mazepy Street in Nadvirna, central market in Nadvirna, area near the fountain in the centre of Nadvirna, OKKO petrol station (Yaremche), souvenir market (Yaremche), MORVA Premium Spa Resort (Yaremche), the Stanislavsky Hotel (Yaremche), the shopping area near the railway track (Yaremche), Svobody Street (Yaremche), Car Park №1 (Polianytsia), Lake of Youth (Bukovel), the Ferris wheel (Bukovel), the Syayevo restaurant (Bukovel), Car Park №2 (Bukovel), entrance to Bukovel, ski area (Bukovel), remote area of Bukovel. The selection of sites was based on the need to cover a variety of environmental conditions and tourist traffic intensity.

The first stage of the study involved an analytical review of scientific publications on the impact of tourism on the environment, air

pollution by solid particles, sustainable tourism, and environmental monitoring. The information base consisted of peer-reviewed articles for the period 2020-2024. The literature was selected based on criteria of relevance, scientific novelty, and relevance to the research topic. The second stage involved the organisation and conduct of field measurements of atmospheric air in selected tourist locations, conditionally divided into three groups according to the level of anthropogenic load: low (recreational areas), medium (tourist and recreational areas) and high (transport and trade hubs). The measurements were carried out according to a single scheme at specific points at a height of 1.5 metres above ground level.

Three specialised devices were used to collect data. The CEM DT-9881M portable air quality analyser (brand CEM Instruments, country of registration and manufacture China) was used to measure concentrations of PM2.5 and PM10 fine particles, formaldehyde, as well as air temperature and relative humidity. The device operates on the basis of a diffusion sampling method and is equipped with a built-in battery and memory. To determine the concentrations of carbon monoxide (CO) and nitrogen dioxide (NO₂), a Walkom W-K-600 gas analyser (manufacturer Walcom Instruments, Italy) was used, known for its high accuracy in mobile monitoring of gaseous pollutants. The volume fraction of oxygen was determined using a CEM GD-3803 oxygen monitor (brand CEM Instruments, country of manufacture China). The use of several devices ensured a multifactorial assessment of the state of atmospheric air.

The third stage involved processing the obtained data using Microsoft Excel software for primary analysis: calculating average values, standard deviations, and coefficients of variation. For in-depth statistical analysis, regression analysis methods (fourth-order polynomial regression) were used to model the dependence of PM10 on PM2.5, taking into account load categories, as well as correlation analysis to establish the relationship between air pollution levels and

relative humidity. In order to identify the nature of the relationship between the concentrations of PM2.5 and PM10 particulate matter in the air at tourist locations in the Ivano-Frankivsk region, mathematical modelling methods, in particular regression analysis, were used. Given the empirical distribution of the studied variables and the need to take into account possible nonlinear dependencies, the linear model was found to be insufficiently informative to accurately reflect the relationship between these parameters. For a comparative analysis of the concentrations of fine particles in tourist locations in the Ivano-Frankivsk region, the standards approved by the current national documents in the field of atmospheric air protection were applied. In particular, the focus was on maximum permissible concentrations (MPCs).

In view of this, it was appropriate to use fourth-order polynomial regression, which allows higher degrees of the PM2.5 variable to be taken into account to model its impact on PM10 levels. In addition, the model included a categorical variable "Load Category", represented as two binary predictors: for areas with low and medium levels of anthropogenic load. The high load zone is the base (reference) category. That is why fourth-order polynomial regression was used to build the model:

$$PM10 = \beta_0 + \beta_1 PM2.5 + \beta_2 PM2.5^2 + \beta_3 PM2.5^3 + \beta_4 PM2.5^4 + \beta_5 (\text{Low load}) + \beta_6 (\text{Medium load}), (1)$$

where: β_0 – is a free term (constant) corresponding to the baseline level of PM10, β_1 is a linear coefficient showing how PM10 changes when PM2.5 changes, β_2 , β_3 , β_4 are polynomial coefficients reflecting the nonlinear effect of PM2.5 on PM10, β_5 – correction of the PM10 level for low load, β_6 – correction of the PM10 level for medium load.

Regression analysis results = Coefficient of determination $R^2 = 0.87$ (the model explains 87% of the variation in PM10). All polynomial coefficients are statistically significant ($p < 0.05$).

Results and Discussion

One of the main environmental problems in tourism is the accumulation of pollutants in the air due to the growth of tourist flows and the development of transport infrastructure in popular recreational areas. Fine particles, in particular PM_{2.5} and PM₁₀, are the main markers of anthropogenic load, as their excessive accumulation in the air negatively affects both the state of natural ecosystems and human health. The problem is compounded by the fact that most tourist regions are traditionally positioned as areas with “clean air”, which does not always correspond to the actual environmental situation in conditions of intensive exploitation of the territories.

Fine aerosol particles have the ability to penetrate deep into the human respiratory system, causing a wide range of negative effects, including respiratory and cardiovascular diseases and an increase in overall mortality risk. At the same time, the accumulation of PM_{2.5} and PM₁₀ in tourist regions leads to a decrease in the ability of vegetation to naturally purify the air, impairs the photosynthetic activity of green spaces and accelerates soil degradation due to particle deposition.

It is particularly important to analyse the distribution of fine particles depending on the level of anthropogenic load: from areas with a predominantly natural environment to areas with developed transport infrastructure. As part of the study, the concentrations of fine particles PM₁₀ and PM_{2.5} in the air of tourist areas in the Ivano-Frankivsk region were determined, with subsequent classification

of observation objects according to the level of anthropogenic load into three categories:

- recreational areas (low load);
- tourist and recreational areas (medium load);
- transport and trade hubs (high load).

Areas with minimal anthropogenic impact include natural parks, forest areas, and areas with low building density and limited traffic. The dominant sources of PM₁₀ and PM_{2.5} fine particles are natural processes, in particular soil dust and biogenic emissions. Concentrations of pollutants in such conditions remain the lowest due to effective natural filtration of the atmosphere by vegetation.

Tourist and recreational areas are characterised by a moderate level of anthropogenic impact. The main factors of pollution include tourist activity, commercial activity, and traffic flows near recreational facilities. The concentration of solid particles in these areas is intermediate between the levels recorded in recreational and transport and commercial areas, as the influence of natural and man-made sources is combined here. City centres, transport hubs, commercial areas, markets, bus stations, car parks and petrol stations are characterised by the highest level of anthropogenic impact. The main sources of pollution are motor vehicle exhaust gases, industrial emissions and aerosols generated by economic activity. The high intensity of traffic flows and commercial processes leads to increased concentrations of PM₁₀ and PM_{2.5}, which negatively affects the quality of atmospheric air and the ecological state of the region (Table 1).

Table 1. Air quality indicators in different locations of Ivano-Frankivsk region (August 2024)

Nº	Location	Load category	PM _{2.5} (µg/m ³)	PM ₁₀ (µg/m ³)	HCHO, ppm	O ₂ , %	CO ₂ , ppm	°C	Relative humidity, %
1	Earth History Park “Underhill”	Low load	11.6	28.0	0.0	20.4	455	23.1	65
2	Forest area near Underhill	Low load	10.8	26.0	0.0	20.4	450	22.9	65
3	Pidhiria, residential district	Low load	11.2	24.0	0.0	20.4	454	23.3	64
4	Leibova Hora Restaurant	Medium load	12.0	25.0	0.01	20.2	435	23.9	61

Table 1. Continued

N ^o	Location	Load category	PM2.5 (µg/m ³)	PM10 (µg/m ³)	HCHO, ppm	O ₂ , %	CO ₂ , ppm	°C	Relative humidity, %
5	Transport zone near Leibova Hora	Medium load	12.5	29.0	0.01	20.2	435	24.1	61
6	Parking area near the entrance to Leibova Hora	Medium load	13.0	31.0	0.01	20.2	435	24.1	61
7	Shevchenko Square, Nadvirna	High load	13.0	32.0	0.0	20.4	444	23.5	67
8	Hetman Mazepa Street, Nadvirna	High load	13.5	33.6	0.0	20.4	439	23.5	70
9	Central Market, Nadvirna	High load	14.0	40.0	0.0	20.4	439	23.5	70
10	Area near the fountain in the centre of Nadvirna	Medium load	13.2	41.0	0.0	20.4	444	23.5	67
11	OKKO Petrol Station, Yaremche	High load	13.0	39.0	0.0	20.3	576	28.7	50.2
12	Souvenir Market, Yaremche	High load	13.0	35.0	0.0	20.4	502	29.1	49.2
13	MORVA Premium Spa Resort, Yaremche	Medium load	14.0	38.0	0.01	20.3	494	29.3	42.6
14	Hotel Stanislavsky, Yaremche	Medium load	13.0	40.0	0.02	20.4	499	29.4	47.7
15	Shopping area near the railway line, Yaremche	High load	13.5	37.0	0.02	20.4	480	29.4	47.5
16	Svobody Street, Yaremche	High load	13.8	38.5	0.02	20.4	440	29.4	47.9
17	Car Park N ^o 1, Polianytsia	High load	19.0	39.2	0.02	20.4	442	24.7	50.7
18	Lake of Youth, Bukovel	Medium load	12.0	30.0	0.01	20.4	412	26.0	46.3
19	Ferris Wheel, Bukovel	Medium load	11.0	25.0	0.01	20.2	420	30.1	49.3
20	Syaevo Restaurant, Bukovel	Medium load	8.0	22.0	0.01	20.2	424	29.8	48.5
21	Car Park No. 2, Bukovel	High load	17.0	23.0	0.01	20.2	456	29.8	48.9
22	Entrance to Bukovel	High load	16.5	29.0	0.01	20.2	429	29.8	48.2
23	Ski area, Bukovel	Medium load	10.5	28.5	0.01	20.2	424	29.8	48.5
24	Remote area, Bukovel	Low load	9.0	24.0	0.01	20.2	438	29.8	48.5

Source: compiled by the authors

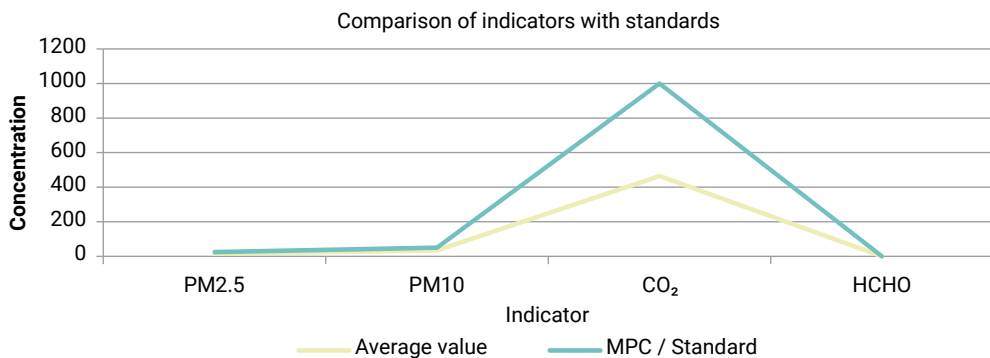
Background concentrations are determined in accordance with Order of the Ministry of Ecology and Natural Resources of Ukraine No. 286 (2001), as amended in 2021. The document has been in force since 1 March 2000 and defines the basic standards for the permissible

content of chemicals in the air, in particular components that are hazardous to human health, such as PM2.5, PM10, formaldehyde, carbon monoxide and nitrogen dioxide, established and recommended by the World Health Organisation (2021). (Table 2, Fig. 1).

Table 2. Comparison with permissible standards

Indicator	Average value (high load)	Standard in Ukraine (MPC)	Conclusion
PM2.5	14.63 $\mu\text{g}/\text{m}^3$	up to 25 $\mu\text{g}/\text{m}^3$ (daily average)	Within the normal range
PM10	34.63 $\mu\text{g}/\text{m}^3$	up to 50 $\mu\text{g}/\text{m}^3$ (daily average)	Within the normal range
CO ₂	464.7 ppm	approximately up to 1,000 ppm (ventilation recommendations)	Within the normal range
HCHO	≤ 0.02 ppm	up to 0.035 ppm	Within the normal range

Source: compiled by the authors based on Order of the Ministry of Ecology and Natural Resources of Ukraine No. 286 (2001)

**Figure 1.** Comparison with permissible standards

Source: compiled by the authors based on Order of the Ministry of Ecology and Natural Resources of Ukraine No. 286 (2001)

Thus, the average PM2.5 value was 14.63 $\mu\text{g}/\text{m}^3$, which is significantly lower than the daily maximum permissible concentration of 25 $\mu\text{g}/\text{m}^3$. The recorded value indicates that there is no excess of fine dust, which can adversely affect the respiratory system. A similar trend can be observed for PM10, whose concentration was 34.63 $\mu\text{g}/\text{m}^3$ with a permissible level of 50 $\mu\text{g}/\text{m}^3$. Both indicators remain within sanitary and hygienic standards, which confirms the absence of critical levels of particulate matter pollution. The average carbon dioxide level was 464.7 ppm, which corresponds to the recommended standards for areas of mass human presence. The formaldehyde content was within the range of 0.00–0.02 ppm, not exceeding the maximum permissible value of 0.035 ppm.

A comparative analysis showed that none of the indicators exceeded the established standards.

Accordingly, the atmospheric air in tourist locations in the Ivano-Frankivsk region is characterised by a relatively favourable ecological state, despite the increased recreational and transport load. Fourth-order polynomial regression was chosen as the most suitable tool for modelling the dependence of the concentration of PM10 suspended particles on the level of PM2.5 fine dust, given the empirical nature of the data distribution and the need to take into account non-linear relationships that are not covered by the linear model. The additional inclusion of the categorical variable “Load category” in the form of binary predictors made it possible to take into account the influence of the intensity of anthropogenic pressure on the concentration of PM10, where a high level is the baseline. The dependence is shown in (Fig. 2):

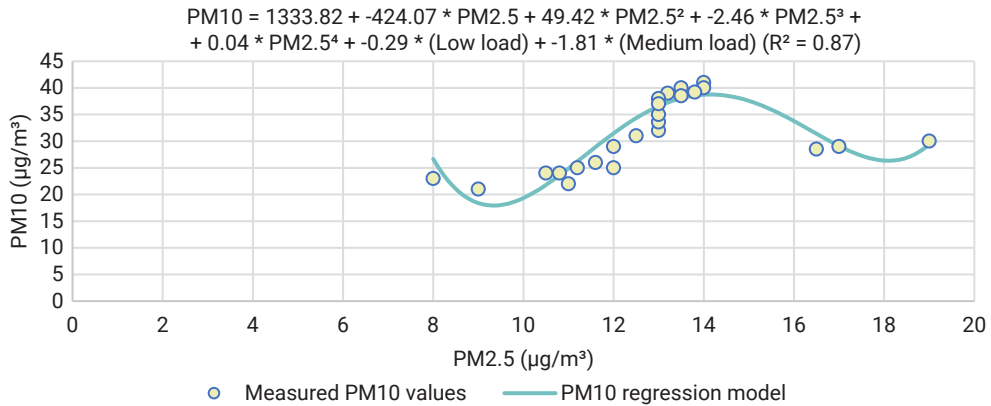


Figure 2. Dependence of PM10 concentration on PM2.5 in tourist locations in Ivano-Frankivsk region

Note: 4th order polynomial approximation, $R^2 = 0.87$

Source: compiled by the authors

Considering that relative humidity influences the behaviour, aggregation and deposition of aerosol particles, analysing its relationship with PM2.5 concentration is justified for a deeper understanding of the mechanisms of air quality formation in tourist areas. An increase in relative humidity can promote the condensation of water vapour on the surface of PM2.5 particles, increasing their size and changing their

deposition properties, which in turn affects the concentration of particles in the air. On the other hand, excessive humidity can cause particles to be washed out of the atmosphere, reducing their content. Therefore, establishing the nature of the interdependence between these parameters is necessary to assess the environmental status of tourist areas and the potential risk to human health (Fig. 3).

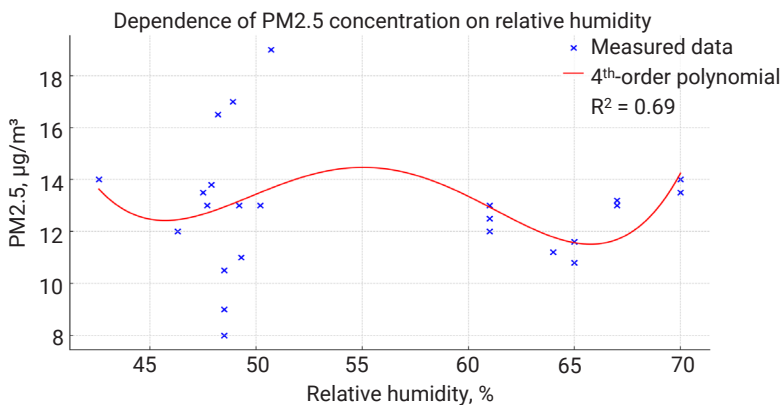


Figure 2. Polynomial regression of PM2.5 concentration on relative humidity in tourist locations of Ivano-Frankivsk region

Source: compiled by the authors

The results of the regression analysis showed that the coefficient of determination

$R^2 = 0.69$, which indicates a fairly strong dependence between the concentration of fine particles

PM2.5 and the level of relative humidity in the atmospheric air of tourist locations in the Ivano-Frankivsk region. The value of the coefficient of determination indicates that approximately 69% of the variation in PM2.5 concentration can be explained by changes in humidity, which indicates the presence of a significant nonlinear relationship between these indicators. Analysis of the constructed polynomial model demonstrates the nonlinear nature of the relationship. In particular, as relative humidity increases, there is a tendency for the concentration of fine particles in the air to decrease, which may be due to the physical and chemical processes of aerosol deposition under the influence of hygroscopic growth of droplets and gravity towards the Earth's surface. However, when a certain threshold level of humidity is reached, a change in the trend is recorded - a secondary increase in PM2.5 concentrations is possible, which is probably explained by the mechanisms of particle aggregation into larger aggregates, a decrease in their precipitation rate, or the formation of secondary particles due to heterogeneous reactions on the surface of water aerosols.

The results obtained emphasise the role of relative humidity as one of the key meteorological factors influencing the spatial and temporal variability of fine dust in tourist regions. Under conditions of medium and high anthropogenic load, typical for recreational and tourist areas, fluctuations in air humidity can significantly modify the quality of the atmospheric environment, intensifying or mitigating the impact of pollution sources. The results of the conducted research allow for the formation of substantiated conclusions regarding the impact of anthropogenic load on the spatio-temporal distribution of fine aerosol concentrations of PM2.5 and PM10 in the atmospheric environment of tourist locations in the Ivano-Frankivsk region. The obtained indicators demonstrate significant variability depending on the level of technogenic pressure, which fully correlates with the conclusions made in the work of S.Yu. Adamenko *et al.* (2024), where the patterns of PM10 particle accumulation in the urban

environment of Ivano-Frankivsk were studied. In particular, in transport and commercial areas, particle concentrations exceed the corresponding values recorded in recreational areas with minimal urbanisation, indicating a direct relationship between the nature of land use and the level of atmospheric dustiness.

The coefficient of determination $R^2 = 0.87$, obtained in the process of approximating the dependence between PM2.5 and PM10 using fourth-order polynomial regression, confirms the existence of a pronounced nonlinear relationship between the two main markers of aerosol pollution, which was also recorded in a study of PM2.5 concentrations in various natural and territorial conditions in the Ivano-Frankivsk region (Adamenko *et al.*, 2024). The inclusion of a categorical variable reflecting the level of anthropogenic load in the model allowed for a deeper understanding of the spatial dynamics of pollution and its dependence on the functional purpose of tourist areas.

Changes in PM2.5 particle content also showed a noticeable dependence on the level of relative air humidity, which is consistent with the conclusions presented in international publications by J.S. Rodríguez-Alcántara *et al.* (2024) and M. Pásková *et al.* (2024), which emphasised the role of atmospheric moisture as a factor influencing particle aggregation, hygroscopic growth and deposition. The analysis found that an increase in humidity to a certain threshold level contributes to a decrease in the concentration of fine particles due to the intensification of deposition processes. At the same time, at high humidity levels, a change in trend is observed, which is probably due to the secondary formation of aerosol aggregates or a slowdown in their deposition, which is characteristic of heterogeneous chemical transformations in a humid environment.

It should be emphasised that the results of the study are relevant in the context of the scientific community's growing attention to the impact of environmental indicators on the quality of tourism services and the attractiveness of destinations. The work of C. Eusébio *et al.* (2022)

indicates that air quality is one of the critical factors in choosing tourist routes, especially in the ecotourism segment. A decrease in environmental comfort due to increased concentrations of PM10 and PM2.5 during periods of intense tourist traffic can negatively affect the perception of the region, which is strategically important for areas with high recreational potential.

The detected PM2.5 and PM10 concentrations in tourist locations demonstrate a close relationship between air quality and environmental comfort, which, according to a number of studies, directly affects the intensity of tourist flows. In particular, a spatial econometric analysis in China demonstrated a negative relationship between air pollution levels and the number of foreign visitors (Deng *et al.*, 2017), while regression models showed a significant reduction in inbound tourism in conditions of increased concentrations of harmful pollutants (Dong *et al.*, 2019). Air quality in the region of origin also determines the demand for outbound tourism, with disposable income acting as an integrating factor (Wang *et al.*, 2018).

In parallel with changes in anthropogenic load, special attention should be paid to meteorological factors, in particular relative humidity, which modifies the chemical composition of atmospheric aerosols and their deposition processes. This is confirmed by monitoring observations in Tehran, where significant fluctuations in PM1, PM2.5 and PM10 particle levels have been detected under the influence of dust storms and local pollution (Jaafari *et al.*, 2017; Naddafi *et al.*, 2019).

In a global comparative context, a correlation has been established between air pollution levels and the Human Development Index, allowing the HDI to be considered a marker of environmental quality (Santra, 2014). Indoor pollution problems in low-income countries, associated with inadequate ventilation and the dominance of traditional energy sources, are considered a critical public health challenge (Bruce *et al.*, 2000). Air quality in rural areas is often overlooked in environmental policy, but it has a significant impact on vulnerable population groups (Majra, 2011).

In general, the identified patterns of change in PM2.5 and PM10 concentrations indicate the need to establish a systematic monitoring system for the air environment in tourist regions, adapt environmental policy to the intensity of tourist traffic, and implement preventive measures to reduce anthropogenic impact, especially in areas with a high density of transport and commercial facilities. The study confirms that monitoring atmospheric air quality is a key element in ensuring the sustainable development of recreational areas, and integrating monitoring results into spatial planning practices can significantly improve the environmental safety and tourist attractiveness of the region.

Conclusions

Thus, the results of the study show that the atmospheric air in tourist locations in the Ivano-Frankivsk region is in satisfactory ecological condition, despite the presence of differentiated anthropogenic load. It has been established that the average concentrations of fine particles PM2.5 and PM10 in areas with high tourist and transport loads do not exceed the maximum permissible concentrations specified by national and international regulatory documents, but show a steady upward trend compared to natural recreational areas.

Regression modelling revealed a high level of nonlinear dependence between PM2.5 and PM10 concentrations (coefficient of determination $R^2 = 0.87R$), which indicates the importance of fine fractions in the formation of overall atmospheric pollution. It has been established that the increase in PM2.5 levels largely determines the increase in the total mass of PM10 dust, regardless of the type of anthropogenic load, which confirms the universality of the physicochemical processes responsible for the formation of aerosol pollution in tourist regions.

Additional analysis of the influence of meteorological factors showed the significant role of relative humidity in the variation of fine particle levels. Polynomial modelling of the dependence of PM2.5 on air humidity showed a coefficient of

determination $R^2 = 0.69R^2$, indicating a noticeable non-linear relationship between these indicators. An increase in humidity to a certain optimal level contributes to a decrease in PM2.5 concentrations due to the effect of particle precipitation, while excessive humidity can cause a secondary increase in pollution due to aerosol aggregation and heterogeneous reactions.

Prospects for further research include conducting multi-season measurements, expanding the set of analysed indicators (in particular, organic and inorganic gases), integrating spatial pollution models based on geoinformation technologies, and studying long-term trends in the

impact of tourism on the state of the atmospheric environment in the context of climate change.

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Conflict of Interest

None.

Reference

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Дослідження забруднення повітря дрібнодисперсними частками у туристичних локаціях Івано-Франківської області

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Анотація. Активізація туристичної діяльності в Івано-Франківській області актуалізує потребу у системному моніторингу атмосферного повітря, зокрема у частині вмісту дрібнодисперсних аерозольних часток, для оцінки рівня екологічної безпеки в популярних туристичних осередках. Метою дослідження була комплексна оцінка забруднення атмосферного повітря частками PM_{2.5} та PM₁₀ у локаціях із різним ступенем антропогенного навантаження, а також ідентифікація факторів, що детермінують просторову варіативність їх концентрацій. У межах емпіричного етапу було здійснено серію інструментальних польових вимірювань із застосуванням портативного моніторингового обладнання. Локації класифіковано на три групи: рекреаційні території (низьке навантаження), туристично-рекреаційні зони (середнє навантаження) та транспортно-торговельні вузли (високе навантаження). Для статистичної обробки даних використано методи багатовимірного аналізу, зокрема поліноміальну регресію четвертого порядку та регресійне моделювання залежності між рівнями PM₁₀ і PM_{2.5} з урахуванням типології навантаження. Встановлено, що середні концентрації PM_{2.5} та PM₁₀ у зонах високого навантаження становили відповідно 14,63 мкг/м³ та 34,63 мкг/м³, що не перевищує гранично допустимі значення, визначені національними та міжнародними нормативами. У природних рекреаційних зонах зафіксовано найнижчі показники, що зумовлено природною фільтраційною здатністю зелених насаджень і відсутністю транспортного трафіку. У зонах із середнім навантаженням виявлено проміжні рівні забруднення, які вказують на вплив як стаціонарних, так і мобільних джерел викидів. Проведений регресійний аналіз засвідчив наявність нелінійного зв'язку між PM_{2.5} і PM₁₀ ($R^2 = 0,87$), що свідчить про домінування дрібнодисперсної фракції у загальній масі аерозольного пилу. Додатково встановлено, що підвищення відносної вологості повітря корелює зі зниженням концентрацій дрібнодисперсних часток, що має значення для прогнозування рівня забруднення повітря у залежності від метеоумов

Ключові слова: екологічний моніторинг; туристичне навантаження; атмосферні аерозолі; просторовий аналіз; PM_{2.5}; PM₁₀; регресійне моделювання