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DEFINING DUST LOAD PATTERNS AND ASSESSING HEALTH RISK TO PEOPLE FROM TRAFFIC FLOWS NEAR A QUARRY

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This study investigates atmospheric dust pollution generated by quarrying activities, particularly the impact of traffic on access roads. The task addressed relates to the lack of a comprehensive assessment of dust levels and associated health risks, considering the actual operation of quarry infrastructure and seasonal variability.

Emissions from quarrying during 2020–2024 have been analyzed, which made it possible to evaluate anthropogenic pressure. PM2.5 and PM10 measurements were conducted along the access road to the Rybalskyi quarry (Ukraine); the results were used for statistical processing and dust load modeling.

Correlation-regression models were built to assess the impact of environmental and transport factors, identifying key pollution drivers. A mathematical model of the spatial distribution of concentrations was constructed, including an evaluation of health risks for people.

Maximum recorded PM10 concentrations reached 312 μg/m³, thereby exceeding the permissible limit by 6.2 times. Considering meteorological conditions, vehicle types, as well as traffic intensity enabled quantitative assessment of each factor's contribution to dust load and identification of high-risk zones.

The results are attributed to the high sensitivity of dust concentrations to local changes, confirmed by determination coefficients and spatial modeling outcomes. The proposed approach is suitable for environmental protection measures aimed at reducing dust emission impact on the environment and public health. It could be applied to plan sanitary-protection zones, regulate traffic, and optimize logistics according to local conditions. This approach requires the availability of meteorological data and traffic information to provide reliable forecasts

Keywords: dust pollution, quarry access roads, correlation-regression analysis, health risk assessment, environmental safety

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1. Introduction

The granite industry is considered a potentially stable one due to the high demand for mining materials from the construction sector. However, the process of granite mining is accompanied by emissions of particulate matter and other pollutants into the air, which poses significant risks to the health of people living near quarries, as well as to the existence of animals and plants.

Dust generated during the development of deposits is a serious threat to workers and local residents because of its negative impact on the respiratory system. Studies confirm the increase in concentrations of suspended particles $PM_{2.5}$ and PM_{10} in the ambient air near granite quarries [1, 2]. The harmful effects of fine dust are emphasized with the risk of developing diseases of the respiratory and cardiovascular systems, as well as chronic inflammatory and neurological disorders [3, 4].

There is an increasing international and national environmental requirements for the mining sector, as well as a growing need to implement mechanisms for monitoring and forecasting the level of environmental pollution. In this context, comprehensive studies aimed at quantitatively assessing the dust load caused by the operation of quarries and their infrastructure facilities, in particular access roads, are of particular importance, as well as building mathematical models to determine the volume of emissions and spatial-temporal distributions of concentrations of fine particles $PM_{2.5}$ and PM_{10} in atmospheric air.

The results of dust pollution studies are of important practical importance as they allow for environmental planning and risk management in the area affected by quarries.

They make it possible to predict the level of air dust depending on weather conditions and traffic load, implement effective occupational safety measures, and minimize the negative impact on public health. The results also contribute to the adaptation of mining enterprises to the requirements of environmental safety and the principles of sustainable development, ensuring compliance with regulatory requirements and reducing environmental impact.

Thus, scientific research related to the assessment and forecasting of dust levels in the quarry development area is highly relevant as it contributes to devising effective emission control measures and increased occupational safety. It could also minimize the impact on public health and the environment and ensure sustainable development and functioning of the mining sector.

2. Literature review and problem statement

In [5], conventional engineering measures, namely, surface irrigation, the use of water cannons, and the installation of mechanical barriers, were analyzed in detail. These measures showed a certain reduction in PM_{10} concentrations in the granite quarry area, which confirms their partial effectiveness. At the same time, the authors did not take into account the impact of the more dangerous $PM_{2.5}$ fraction, which has a significant penetrating ability into the respiratory tract and causes chronic respiratory diseases. The study also lacks an analysis of the impact of meteorological parameters, in particular wind speed, air temperature, humidity, which significantly affect the spatiotemporal distribution of dust. The authors focus their research on industrial areas without assessing the impact of dust on nearby areas and people, especially near access roads to quarries, where the dust load is often maximum.

In [6], PM_{10} emissions from quarrying and mining operations in Malaysia were simulated using AERMOD. Scenarios with and without dust suppression measures were considered for two sites: quarry crushing and iron ore production. High efficiency of the measures was established: for the first site, the reduction in concentrations was 99.9%, for the second – 60.24%. At the same time, the study did not take into account the fine-dispersed fraction of $PM_{2.5}$, the influence of meteorological conditions; field measurements were not carried out to confirm the accuracy of modeling, and the risk assessment for public health was not performed.

The authors of [7] performed modeling of the dispersion of suspended particles (TSP) from seven quarries in the Artvin region (Turkey) using AERMOD. It was found that the maximum hourly concentrations of TSP reached 75.17 $\mu g/m^3$, the minimum – 9.87 $\mu g/m^3$; the spatial distribution depended to a large extent on topographic factors, in particular, altitude, distance to the source, and forest canopy. The use of regression and neural network models showed that MLR explains 25–54% of the variations, and MLP, respectively, 65–87%. However, the study lacks analysis of fine particulate matter (PM_{10}, $PM_{2.5}$), real measurements to verify the modeling results and assess the impact on public health.

Modern approaches to monitoring and forecasting pollution increasingly involve the use of digital technologies and artificial intelligence. In [8], an integrated system is proposed that combines sensors for determining $PM_{1.0}$, $PM_{2.5}$, and PM_{10} levels with machine learning algorithms, in particular Random Forest, for predicting concentrations in real time. This approach makes it possible to draw risk maps and quickly respond to changes in dust load. However, the study is limited by a short time period, which does not allow the authors to assess seasonal and climatic fluctuations, and it does not take into account the impact of traffic on access roads, which is often a significant additional source of dust.

In [9], examples of applying the BREEZE AERMOD model to analyze the impact of weather conditions on dust dispersion are given, but the need for more accurate local meteorological data is emphasized, especially in cases of temperature inversions and unstable atmospheres. An important area of modern research is the analysis of the spatial distribution of dust beyond the boundaries of quarries.

It is shown in [10] that the contribution of quarry dust is about 6% of the total $PM_{2.5}$ content in the air; its level significantly depends on seasonal fluctuations. Similar results are reported in study [11], which established the dependence of particulate matter concentrations on a combination of industrial and meteorological factors. At the same time, the authors do not consider the possibility of predicting the consequences for public health and do not take into account the additional dust load from traffic flows on access roads.

Paper [12] assessed the impact of dust pollution on the environment and workers at two granite quarries in Njuli (Southern Malawi). It was found that the average dust concentrations in the air at the quarries were about 1111 $\mu g/m^3$ in the dry season and 426 $\mu g/m^3$ in the wet season, which is well above the WHO recommended levels. Workers were exposed to high concentrations of PM, particularly in work areas near the crushing plants. The study focused on health risks: the main symptoms observed in workers were coughing, shortness of breath, and eye irritation. However, the study has limitations: it did not separate the PM_{10} and $PM_{2.5}$ fractions; there was no modelling of dust dispersion outside the quarry; the long-term risks to surrounding communities were not assessed.

Study [13] examined air quality in quarries in Congo. It was found that the average dust concentrations in the workplaces exceeded the maximum permissible levels, and the workers had frequent symptoms: cough – 67%, shortness of breath – 47%, and chronic bronchitis – 22%. The authors showed a statistically significant relationship between the duration of work in the quarry and the deterioration of respiratory indicators. The study confirms the high risks to the health of workers but, at the same time, it has certain limitations. A detailed differentiation by fractions of PM_{10} and $PM_{2.5}$ was not carried out; modeling of the spread of dust outside the quarry was not performed; the risks to people at the surrounding areas were not assessed.

In work [14], the air quality and health of women working in quarries in the city of Lubumbashi, Congo, were assessed. The average concentrations of $PM_{2.5}$ in the workplaces were found to be 205 ± 13.2 $\mu g/m^3$, significantly higher than the level of 31.3 ± 10.3 $\mu g/m^3$ in the control areas. Respiratory complaints were observed in 32.4% of the workers compared to 3.5% in the control group, and there was also a decrease in lung function tests. The study did not model the spread of dust outside the quarries, did not assess the impact of meteorological conditions, and did not make comparison with other sources of pollution, such as transport or industry.

The authors of [15] investigated the health effects of the Phuoc Tuong quarry in Da Nang, Vietnam. Statistically significant differences were found between groups living within 1 km of the quarry and those living 2–3 km from the pollution sources. There were significant differences in perceived air quality, skin diseases, and health satisfaction. Elevated concentrations of pollutants, including H_2S, CH^4, and TSP, were also found to be associated with higher health risks. However, the study did not conduct a detailed analysis of fine particulate matter $PM_{2.5}$, did not model the spread of pollution beyond the study area, and did not assess long-term health effects.

Study [16] assessed the impact of quarrying on air and water quality in Mukono District, Central Uganda. It was found that, despite the use of wet crushing and irrigation, dust levels ($PM_{2.5}$ and $PM_{1.0}$) exceeded the recommended limits, with variations between sites. Water pollution was characterized by elevated levels of nitrate, chromium and low pH, indicating significant water pollution as well. The study did not model the spread of dust outside the quarries, did not consider dust generation on access roads, did not take into account meteorological conditions and did not assess the health risks to people at the surrounding areas.

Paper [17] focused on the health risks associated with dust from stone crushing plants in Thailand. It was found that PM_{10} and TSP dust concentrations in areas with high density of such plants significantly exceed safe levels, with the highest values recorded in winter. Using the hazard quotient (HQ), the authors found a statistically significant association between high dust levels and increased health risks for local residents. This did not measure $PM_{2.5}$, did not account for the influence of meteorological conditions, did not assess long-term health effects on people, and did not consider dust generated on access roads to enterprises, focusing only on work sites.

In [18], the relationship between the cumulative dose of dust and impaired lung function in workers was investigated, showing a high level of abnormal lung function with prolonged exposure. At the same time, the issues of the impact of dust on nearby territories and people outside the enterprise, as well as the consideration of seasonal and meteorological fluctuations, remain unresolved. The reason for this may be the complexity of controlling external factors and the high cost of large-scale monitoring. To overcome these difficulties, it is advisable to combine field measurements with spatial modeling and forecasting of dust distribution.

The shortcomings of available studies indicate the need to build comprehensive models for predicting and dispersing dust along access roads to quarries, taking into account meteorological factors.

3. The aim and objectives of the study

The purpose of our study is to determine the patterns of formation and distribution of dust emissions from quarrying along access roads, which cause potential risks to the health of people in nearby territories.

To achieve this aim, the following objectives were accomplished:

– to analyze the dynamics and structure of emissions from quarrying according to statistical data for 2020–2024, perform a variance analysis, and assess the influence of such factors as “year” and “pollutant type”;

– to measure $PM_{2.5}$ and PM_{10} dust concentrations along the access road to the Rybalsky quarry, perform a correlation-regression analysis, and assess the risks to public health in the dust load zone;

– to build a mathematical model of the spatial distribution of dust in the area of influence of the quarry’s transport infrastructure, assess the risks to public health, and substantiate the need for environmental protection measures.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of our study is the dust load on the environment caused by the operation of the access road to the Rybalsky quarry in the city of Dnipro (Ukraine), as well as the level of chronic inhalation risk for people living in the affected area.

The hypothesis of the study assumes that establishing the patterns of formation and distribution of dust emissions along access roads to the quarry could make it possible to build models for predicting dust concentrations and assessing risks to public health.

The dust concentration can be quantitatively estimated based on a combination of field measurements and mathematical modeling.

The following assumptions were accepted within the framework of our study:

– the density of traffic on the road is constant during a working day;

– weather conditions during measurements are considered typical for the summer period.

Simplifications adopted in the work:

– the pollutant dispersion model does not take into account the secondary rise of dust due to air turbulence;

– the emission source is considered linear and evenly distributed along the length of the road.

4. 2. Instruments and methods used for the study

Field measurements of concentrations of suspended particles $PM_{2.5}$, PM_{10}, and meteorological parameters were carried out along the access roads to the Rybalsky quarry in the city of Dnipro (Fig. 1), where the dust load is formed due to the movement of freight transport, poor quality of road surface, and lack of dust suppression measures. The quarry provides crushed stone for a wide range of construction operations, including the production of concrete mixtures and asphalt concrete. The area of the land plot is 106.5 hectares, of which 40.9 hectares is an open area, where the deposit is developed in an open way using a transport system and external formation of dumps. A powerful source of dust emissions are dirt roads on the surface of the quarry (Fig. 1, item 1; Fig. 2, *a*, *b*), which are used by both residents of nearby areas and trucks transporting crushed stone of various fractions.

To determine the concentrations of $PM_{2.5}$ and PM_{10}, a multifunctional air quality detector GM8804 (China) was used, which provides simultaneous measurement of dust particle content, temperature, and relative humidity. The device does not require calibration and allows for operational monitoring.

To measure wind speed, a Peakmeter PM6252B anemometer (China) was used, a modern professional device with a large-diameter impeller, which is characterized by high sensitivity even at low air flow speeds.

All devices were installed at a height of 1.5 m from the road surface. Measurements were carried out over nine days in the summer period in the absence of mining operations to isolate the dust load specifically from access roads. Each day, six series of measurements were performed in two time intervals: from 11:00 to 13:00 and from 16:00 to 18:00. Concentrations were determined in three events: in the absence of motor vehicle traffic, during the movement of passenger cars, and during the movement of freight transport.

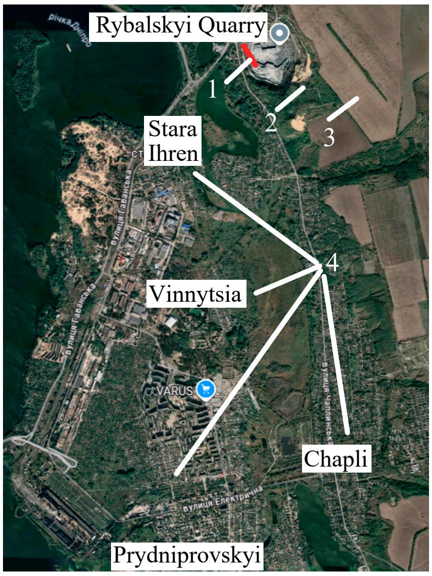


Fig. 1. Rybalskyi granite quarry (Google map): 1 — access road to the quarry, 2 — forest planting zone, 3 — agricultural land, 4 — residential area

a *b*

Fig. 2. Dirt road along the Rybalsky granite quarry: *a* — field measurements, *b* — dustiness when trucks drive along the access dirt road

Dust dispersion modeling was carried out on the basis of an analytical solution to the mass transfer equation in the Piton environment. To assess the risk of chronic inhalation exposure, the Chronic Daily Intake (CDI) risk calculation methodology was used in accordance with the USEPA (2009) recommendations. The resulting concentrations were compared with the maximum permissible levels established by the WHO (WHO, 2021).

Statistical processing of the results and verification of the reliability of the dependences were performed in the Microsoft Excel environment (USA) using the functions of variance, correlation, and regression analyses.

5. Results of investigating dust load on the environment in the area of influence of quarry development

5. 1. Analyzing the dynamics and structure of emissions from quarry development in 2020–2024

Since 2020, the State Statistics Service of Ukraine has been systematizing information on emissions of pollutants into the atmosphere by source categories, which significantly increases the accuracy of analysis of the impact of individual sectors of economic activity. A separate category "quarry development and mining of minerals (except coal)" gives an opportunity not only to estimate the total emissions of major pollutants but also track their dynamic changes over time, starting from 2020. This makes it possible to compare data for the period 2020–2024, identify stable trends, and draw reasonable conclusions about the effectiveness of the implemented environmental protection measures.

Our analysis of the structure of pollutant emissions (Fig. 3, *a*, *b*) reveals that the dominant components are dust fractions PM_{10} and carbon monoxide CO, the volumes of which exceed the levels of other substances SO_2, NO_2, NMVOCs, $PM_{2.5}$ by an order of magnitude. In particular, the average annual emissions of PM_{10} are about 4,000 t/year, varying from 2,500 t/year to over 6,000 t/year. This indicates seasonal and annual variability associated with the intensity of quarrying, meteorological conditions, and the effectiveness of dust suppression measures.

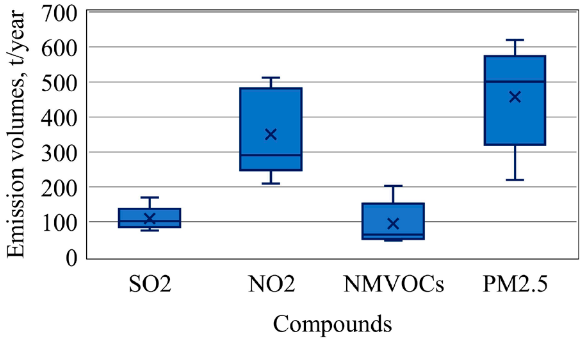
CO volumes also show consistently high figures at 1,200–1,800 t/year. Among fine-dispersed fractions, $PM_{2.5}$ occupies the leading place, about 500 t/year, which is a critical risk factor for public health due to the deep penetration of particles into the respiratory tract. Nitrogen dioxide NO_2 is emitted among other pollutants in volumes of 300–500 t/year and plays a key role in the formation of secondary pollution, namely, ozone and photochemical smog. Sulfur dioxide SO_2 is 100–150 t/year and NMVOCs – up to 200 t/year, i.e., they are characterized by lower emissions but pose a danger due to high toxicity and the ability to form secondary aerosols.

Since dust pollution has the largest volumes, it is advisable to conduct a structural analysis of the average volumes of pollutants from quarrying for 2020–2024 (Fig. 4) to assess the percentage value of the relevant emission components.

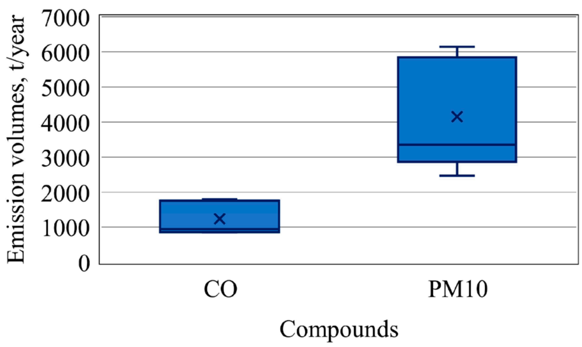
The largest share is occupied by PM_{10}, which accounts for almost two thirds of 64.9% of all emissions. This indicates the dominance of mechanical sources of dust, which are inherent in open-pit mining operations. In second place in terms of specific mass is carbon monoxide CO, the share of which is 19.3%. This indicates a significant contribution of transport and technological sources of fuel combustion to the volume of pollution. The share of $PM_{2.5}$ is only 7.2%, but even such a relatively small contribution has a disproportionately high environmental risk, which strengthens the arguments in favor of targeted monitoring of this fraction. The remaining pollutants, NO_2 – 5.5%; SO_2 – 1.7%; NMVOCs – 1.5%, have a small mass fraction, but remain influential because of high reactivity, participation in secondary pollution, and toxicological impact.

In the studies, a two-factor analysis of variance without repetitions was used to deepen the analysis, which makes it possible to simultaneously take into account the influence of two key factors, namely, "pollutant type" and "time period" ("year"), on the formation of the total volume of emissions. This approach makes it possible to identify whether the annual dynamics are statistically significant, as well as to assess how stable or variable the emissions are by these factors. This is important for further localization of sources of increased dust load. According to the results of the two-factor analysis of variance, the most significant factor affecting the change in emissions is the type of pollutant ($F = 32.0$, $P < 0.001$), while the annual variability is not statistically significant ($P = 0.091$).

This indicates the relative stability of emissions over the years, while emphasizing the dominant contribution of dust fractions PM_{10} and $PM_{2.5}$ to the total variation. The high dispersion for PM_{10} (over 2.5 million) indicates the unevenness of dust load sources, potentially related to non-organized sources, such as access roads to quarries.



a



b

Fig. 3. Volumes of pollutant emissions from quarrying in 2020–2024: *a* – gaseous compounds and $PM_{2.5}$ dust particles; *b* – carbon monoxide and PM_{10} dust particles

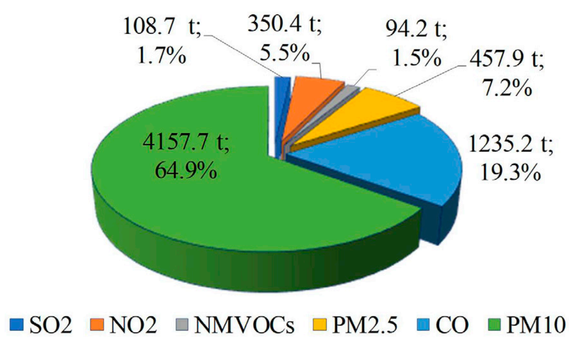


Fig. 4. Average and percentage values of pollutant emissions from quarrying in Ukraine over the period of 2020–2024

Despite the priority of the pollutant type, the two-factor analysis revealed the dominance of dust components in the emissions structure. Therefore, it is advisable to study in more detail the dynamics of changes in PM_{10} and $PM_{2.5}$ volumes in 2020–2024 (Fig. 5, 6). Based on the graphical data on $PM_{2.5}$ emissions over the period of 2020–2024, distinct non-linear dynamics are observed with peak values of 620 t/year in 2021 and the lowest volume of 220.9 t/year in 2022 (Fig. 5).

After a sharp decrease of 64.4% in 2022, there was a tendency for emissions to recover, with a further increase to 501.3 t/year in 2023, i.e., an increase of 126.9%. In 2024, there was a slight decrease of 16.2% and the volumes reach 419.9 t/year. The constructed trend curve demonstrates a projected increase in PM2.5 levels in 2025, which may reach 520 t/year, which may indicate the preservation of the technogenic load. Such a trend highlights the need for a more thorough analysis of the sources of fine dust and the implementation of effective strategies to minimize it. The dynamics of PM_{10} emissions for the period 2020–2024 have a general downward trend, although a peak value of 6,150 t/year was observed in 2021 (Fig. 6).

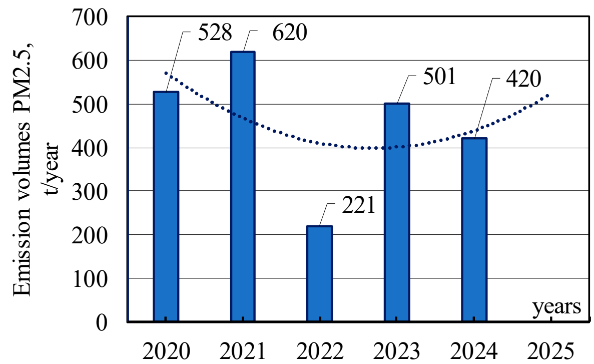


Fig. 5. Dynamics of changes in $PM_{2.5}$ emissions from quarry sources in 2020–2024

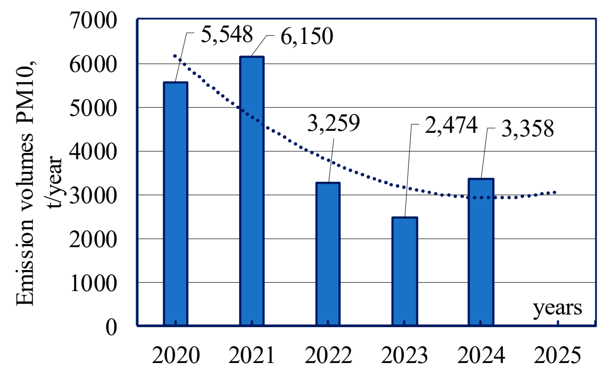


Fig. 6. Dynamics of changes in PM_{10} emissions from quarry sources in 2020–2024

In 2022, the volumes decreased by more than 47%, to 3258.9 t/year, and in 2023 the decline continued by another 24.1%, reaching a minimum level of 2474.3 t/year. However, in 2024, an increase of 35.7% was recorded, the volumes reached 3357.8 t/year. The constructed trend line demonstrates a slowdown in the rate of emission reduction, which may be due to changes in industrial and transport activity or the influence of seasonal and climatic factors. The forecast for 2025 indicates a likely stabilization or slight increase in emission levels, which requires increased monitoring of sources of coarse dust and assessment of the effectiveness of implemented environmental protection measures.

5. 2. Results of measuring $PM_{2.5}$ and PM_{10} dust concentrations and assessing health risks

The average results of measuring $PM_{2.5}$, PM_{10} concentrations, temperature, humidity, and wind speed are given in Tables 1–3.

The determined average concentrations of $PM_{2.5}$ and PM_{10} dust under different traffic conditions (Tables 1–3) allow us to clearly show the dynamics of their change and the relationship with the maximum permissible concentrations, shown in Fig. 7, 8.

Table 1

Results of measuring and calculating dust concentration along the access road to the Rybalsky quarry in the absence of vehicle traffic

Date	V, m/s	T,°C	φ, %	$C_{PM_{2.5}}$, µg/m³	$C_{PM_{10}}$, µg/m³	$C_{PM_{2.5}}$, µg/m³, calculation	$C_{PM_{10}}$, µg/m³, calculation
11.06.2025	2.6	16.4	49.4	24.4	65.2	26.0	63.8
19.06.2025	2.4	17.2	47.2	29.2	69.6	28.4	69.7
27.06.2025	1.9	18.3	46.1	30.6	73.2	29.8	74.3
08.07.2025	1.2	28.5	45.3	31.4	79.6	30.8	80.6
16.07.2025	0.8	30.1	42.7	32.8	89.2	33.8	88.3
24.07.2025	1.1	29.7	44.7	32.2	82.8	31.5	82.5
05.08.2025	1.6	27.3	45.1	31.2	78.2	30.9	79.3
13.08.2025	0.6	30.5	41.5	34.6	92.4	35.2	91.8
16.08.2025	2.2	26.4	44.8	30.8	77.6	30.9	77.4

Table 2

Results of measuring and calculating dust concentration along the access road to the Rybalsky quarry during the movement of passenger vehicles

Date	V, m/s	T,°C	φ, %	$C_{PM_{2.5}}$, µg/m³	$C_{PM_{10}}$, µg/m³	$C_{PM_{2.5}}$, µg/m³, calculation	$C_{PM_{10}}$, µg/m³, calculation
11.06.2025	2.8	18.2	48.2	51.2	140.2	54.3	141.3
19.06.2025	2.6	19.6	47.1	59.9	146.2	58.4	151.1
27.06.2025	2.2	20.3	46.8	64.3	157.4	64.4	158.8
08.07.2025	1.4	30.2	45.6	66.3	167.2	65.5	168.2
16.07.2025	1.5	29.6	46.1	65.9	162.8	63.4	163.5
24.07.2025	1.3	30.6	45.2	66.8	173.9	67.5	172.3
05.08.2025	1.8	26.6	46.4	62.4	168.1	62.4	160.3
13.08.2025	1.1	32.4	43.2	70.9	184.0	73.4	188.6
16.08.2025	2.4	20.4	44.6	68.7	176.8	67.1	172.5

Table 3

Results of measuring and calculating dust concentration along the access road to the Rybalsky quarry during the movement of trucks

Date	V, m/s	T,°C	φ, %	$C_{PM_{2.5}}$, µg/m³	$C_{PM_{10}}$, µg/m³	$C_{PM_{2.5}}$, µg/m³, calculation	$C_{PM_{10}}$, µg/m³, calculation
11.06.2025	3.0	18.4	48.6	92.2	259.3	95.8	260.3
19.06.2025	2.8	18.6	47.4	101.8	265.8	104.2	275.6
27.06.2025	2.1	20.1	46.2	115.7	291.2	114.9	288.4
08.07.2025	1.6	29.4	45.2	122.7	292.5	123.7	302.0
16.07.2025	1.8	28.6	46.8	118.6	291.6	112.8	281.1
24.07.2025	1.2	30.8	44.8	123.6	304.3	128.0	305.6
05.08.2025	2.0	23.3	46.4	119.4	291.8	114.2	286.1
13.08.2025	1.4	29.8	45.1	122.9	298.7	125.2	302.3
16.08.2025	2.6	22.2	44.6	123.6	317.2	121.6	311.0

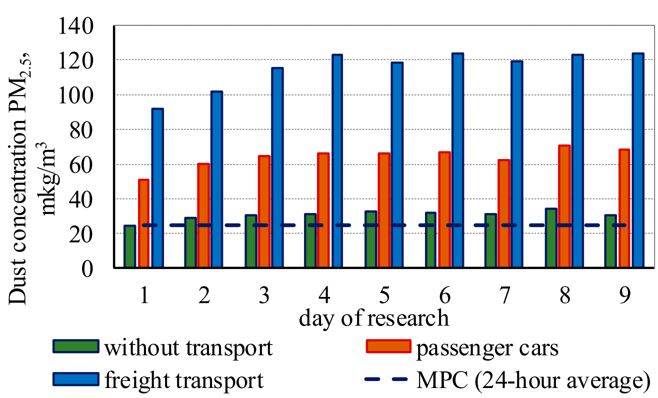


Fig. 7. Comparison of average $PM_{2.5}$ dust concentrations with maximum permissible concentrations (MPCs)

In the absence of traffic, dust concentrations remain relatively low (20–35 µg/m³), but close to the maximum permissible values of MPC = 25 µg/m³. The movement of passenger cars leads to an increase in concentrations by 2–3 times relative to background indicators, consistently exceeding MPC. The greatest contribution is observed from freight transport, during which $PM_{2.5}$ concentrations reach more than 100 µg/m³, i.e., 4–5 times higher than the norm.

Background values (excluding transport) are also at a level (~50–70 µg/m³) close to MPC = 50 µg/m³. Passenger transport causes a significant increase (approximately twice), concentrations are stable within 140–170 µg/m³. Freight transport is the main factor of pollution, PM_{10} levels exceed 250–300 µg/m³, which is 4–6 times higher than MPC.

For a clear comparison of the impact of wind speed, temperature, and humidity on the concentration of dust of different fractions ($PM_{2.5}$ and PM_{10}) under different types of transport, tabular data were plotted. That made it possible to visually assess the main trends and relationships between these factors and dust load (Fig. 9, 10).

As wind speed increases, dust concentrations decrease, with a slow decrease in PM_{10} concentrations and more intense dispersion of $PM_{2.5}$.

The increase in temperature is accompanied by an increase in dust concentrations, with a more significant increase observed for the PM_{10} fraction, while for $PM_{2.5}$ the intensity of this process is lower.

For a more detailed analysis of the influence of meteorological factors (wind speed, temperature, and relative humidity) on the formation of $PM_{2.5}$ and PM_{10} concentrations, correlation-regression models were constructed.

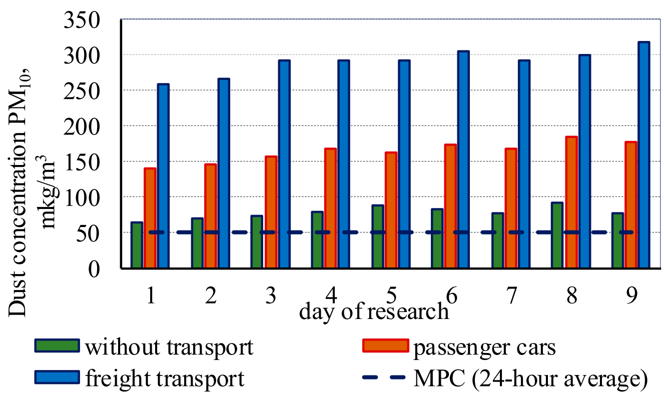


Fig. 8. Comparison of average PM_{10} dust concentrations with maximum permissible concentrations (MPCs)

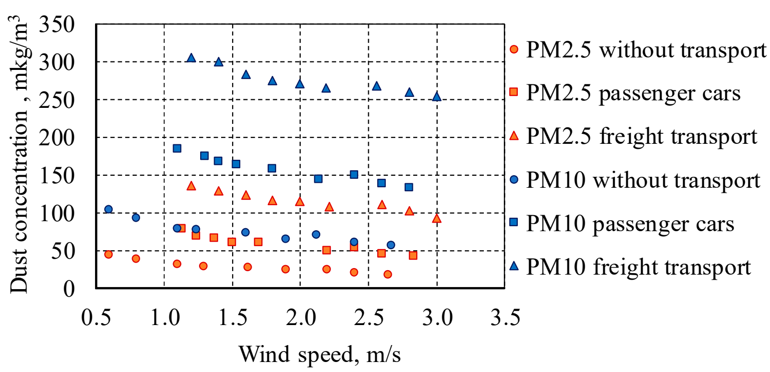


Fig. 9. Dependence of $PM_{2.5}$ and PM_{10} concentrations on wind speed along the access road to the Rybalsky quarry

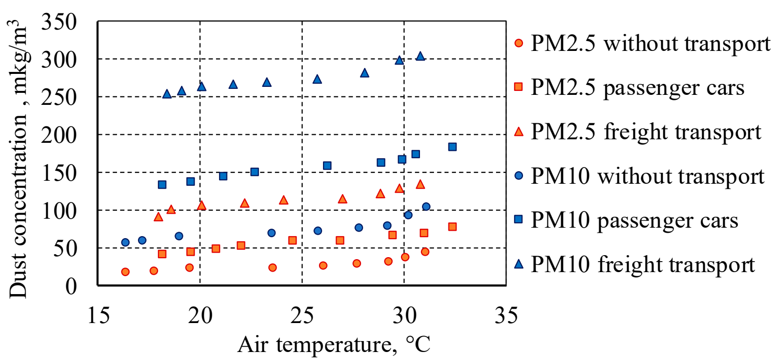


Fig. 10. Dependence of $PM_{2.5}$ and PM_{10} concentrations on temperature along the access road to the Rybalsky quarry

The coefficients of the regression equations were obtained in their natural form (wind speed – m/s, temperature – °C, relative humidity – %). The ranges of variation of the input variables are given in Tables 1–3. To prevent multicollinearity, the correlation coefficients between the factor variables were calculated, which varied within 0.4–0.8, which confirmed the possibility of including all of them in the model.

The regression equations were constructed by the least squares method (LSM) in Excel using the Data Analysis package. The significance of the coefficients was checked by P-value (<0.05). Since the repeatability of experiments under field conditions could not always be ensured, the estimation of the error variance was carried out on the basis of deviations of experimental data from the model. To ensure the verifiability of the results, Tables 1–3 give the input data: speed, temperature, and humidity of the air, as well as the corresponding values of dust concentrations ($PM_{2.5}$ and PM_{10}) obtained during measurements.

In addition, the tables give the concentration values calculated using regression equations (1) to (6). As a result of the study, for the case of no traffic (Table 1) along the access road to the quarry, mathematical models for determining the concentrations of $PM_{2.5}$ and PM_{10} dust particles were built, which are described by linear regression equations (1) and (2)

$$C_{PM_{2.5}}(V,T,\varphi)=c_0+c_1\cdot V+c_2\cdot T+c_3\cdot\varphi, \quad (1)$$

where $C_{PM_{2.5}}$ – concentration of $PM_{2.5}$ dust particles, $\mu g/m^3$; V – wind speed, m/s; T – temperature, C°; φ – humidity, %. The corresponding regression coefficients in equation (1) are:

$$c_0 = 80.797,\ c_1 = -0.489,\ c_2 = -0.0217,\ c_3 = -1.081;$$

$$C_{PM_{10}}(V,T,\varphi)=d_0+d_1\cdot V+d_2\cdot T+d_3\cdot\varphi, \quad (2)$$

where $C_{PM_{10}}$ – concentration of PM_{10} dust particles, $\mu g/m^3$; V – wind speed, m/s; T – temperature, °C; φ – humidity, %. The corresponding regression coefficients in equation (2) are:

$$d_0 = 182.919,\ d_1 = -3.907,$$

$$d_2 = 0.167,\ d_3 = -2.261.$$

For both regression equations, all the coefficients found were statistically significant since the corresponding P-values are within ≤ 0.05. In particular, for equation (1), they are 0.0074, 0.0272, 0.0388, and 0.0379; and for equation (2) – 0.0002, 0.0325, 0.0317, and 0.0025.

This indicates their significant influence on the dependent variables $C_{PM_{2.5}}$ and $C_{PM_{10}}$. The coefficients of determination are $R^2_{PM_{2.5}}=0.908$, $R^2_{PM_{10}}=0.989$, which indicates a high correlation between the variables and confirms the adequacy of the models. Based on the results of the analysis of variance, $F_{PM_{2.5}}=5.027\cdot10^{-3}$, $F_{PM_{10}}=2.387\cdot10^{-5}$, which is less than 0.01, and therefore, the models are highly significant. The average value of the relative error of the forecast is $\Delta_{ave(PM_{2.5})}=2.42\%$, $\Delta_{ave(PM_{10})}=0.95\%$, which indicates a high accuracy of our models.

Based on the averaged data on the concentrations of fine dust on the access dirt road to the Rybalsky quarry under conditions of passenger vehicle traffic, a correlation-regression analysis was conducted. According to the results from data processing, linear regression equations (3), (4) were derived, which allow us to predict the dust load depending on the specified factors

$$C_{PM_{2.5}}(V,T,\varphi) = f_0 + f_1 \cdot V + f_2 \cdot T + f_3 \cdot \varphi, \quad (3)$$

where $C_{PM_{2.5}}$ – concentration of $PM_{2.5}$ dust particles, μg/m^3; V – wind speed, m/s; T – temperature, C°; φ – humidity, %. The corresponding regression coefficients in equation (3) are:

$f_0 = 257.0, f_1 = -15.763, f_2 = -1.501, f_3 = -2.723;$

$$C_{PM_{10}}(V,T,\varphi) = g_0 + g_1 \cdot V + g_2 \cdot T + g_3 \cdot \varphi, \quad (4)$$

where $C_{PM_{10}}$ – concentration of PM_{10} dust particles, μg/m^3; V – wind speed, m/s; T – temperature, C°; φ – humidity, %. The corresponding regression coefficients in equation (4) are

$g_0 = 579.371, g_1 = -15.569, g_2 = -1.246, g_3 = -7.714.$

For equations (3) and (4), all coefficients were found to be statistically significant: the corresponding P-values do not exceed the threshold level of 0.05. Namely, 0.0022, 0.0119, 0.0147, 0.0206 for equation (3), 0.0019, 0.0437, 0.0457, 0.0076 for equation (4).

This indicates a significant influence of factor variables on the concentrations of $PM_{2.5}$ and PM_{10} particles. High values of the coefficients of determination indicate good agreement of the models with empirical data. The results of the analysis of variance, regarding the Fisher coefficient, demonstrate a high level of significance of the constructed dependences. The average relative errors of calculations, namely 2.31% for $PM_{2.5}$ and 1.85% for PM_{10}, indicate a high accuracy of our predictive models.

In the case of freight transport, equations (5) to (6) were derived, which reflect the trends of dust accumulation under conditions of significant mechanical load on the road surface, which contributes to the lifting of dust from the surface (the effect of secondary dusting). Compared to the situation in the absence of traffic or the presence of only passenger transport, the regression dependences demonstrate a higher sensitivity to wind and temperature conditions, which indicates an increase in dustiness precisely due to the movement of heavy machinery

$$C_{PM_{2.5}}(V,T,\varphi) = m_0 + m_1 \cdot V + m_2 \cdot T + m_3 \cdot \varphi, \quad (5)$$

where $C_{PM_{2.5}}$ – concentration of $PM_{2.5}$ dust particles, μg/m^3; V – wind speed, m/s; T – temperature, C°; φ – humidity, %. The corresponding regression coefficients in equation (5) are:

$m_0 = 413.255, m_1 = -4.3283, m_2 = 0.0465, m_3 = -6.2824;$

$$C_{PM_{10}}(V,T,\varphi) = n_0 + n_1 \cdot V + n_2 \cdot T + n_3 \cdot \varphi, \quad (6)$$

where $C_{PM_{10}}$ – concentration of PM_{10} dust particles, μg/m^3; V – wind speed, m/s; T – temperature, C°; φ – humidity, %. The corresponding regression coefficients in equation (6) are:

$n_0 = 899.7764, n_1 = 5.8349, n_2 = -0.3164, n_3 = -7.714.$

For equations (5) and (6), the independent variables demonstrated a significant effect on the variation of $PM_{2.5}$ and PM_{10} concentrations ($P < 0.05$), namely 0.0052, 0.0257, 0.0443, 0.0168 for (5) and 0.0028, 0.0368, 0.0437, 0.0097 for (6).

The values of the coefficients of determination $R^2 = 0.8886$ for $PM_{2.5}$ and $R^2 = 0.8467$ for PM_{10} indicate a strong relationship between the input parameters and the level of dust load. A variance analysis was performed, and accordingly the value of the Fisher coefficient F lies within 10^{-3}, which demonstrates the high statistical validity of our dependences. The accuracy of the models is confirmed by small average relative errors of the forecast, namely $\Delta_{ave(PM_{2.5})} = 2.69\%$, $\Delta_{ave(PM_{10})} = 1.94\%$, which makes it possible to use these equations for practical purposes of monitoring and forecasting dustiness in areas with intensive heavy transport traffic.

The assessment of the risk to public health due to dust pollution along the access road to the Rybalsky quarry was carried out using the chronic inhalation exposure method (USEPA), using the average concentrations of $PM_{2.5}$ and PM_{10} obtained on different days of the summer period in the absence of work of the quarry itself.

The methodology for assessing public health risk (Risk Assessment) consists of several main stages:

1. Exposure characteristics (selection of pollution indicators).

Pollutants: $PM_{2.5}$ – fine dust that penetrates the alveoli of the lungs; PM_{10} – dust that settles in the respiratory tract.

2. Determination of exposure dose.

To assess chronic risk, the calculation of the average daily dose of dust intake is used, taking into account concentration, exposure time, and physiological parameters

$$ADD = (C \cdot IR \cdot EF \cdot ED) / (BW \cdot AT), \quad (7)$$

where ADD – average daily intake dose, μg/m^3; C – average dust concentration in the air, μg/m^3; IR – inhalation rate (volume of inhaled air, m^3/day; EF – exposure frequency, days/years; ED – exposure duration, years; BW – human body weight, kg; AT – averaging period, days.

3. Assessment of non-carcinogenic risk

$$HQ = ADD / RfD, \quad (8)$$

where HQ is the hazard factor, RfD is the acceptable reference dose, mg/(kg day), which is set for $PM_{2.5} = 0.008$ mg/(kg day), for $PM_{10} = 0.02$ mg/(kg day).

If $HQ > 1$, this indicates a potential negative impact on health.

Fig. 11 shows the calculated level of chronic inhalation risk to public health for three scenarios: without transport, with the movement of cars, and trucks. A clear increase in the risk to public health is observed with increasing transport load.

The highest risk level, up to 4 conventional units, is observed in the scenario with the movement of freight transport, which confirms its dominant role as a source of secondary dust. Even with short-term movement of heavy machinery, including quarry dump trucks, the inhalation risk values significantly exceed background levels.

Despite the fact that PM_{10} concentrations consistently exceeded $PM_{2.5}$, the calculated risk levels for both fractions are almost the same. This is explained by the higher toxicological hazard of $PM_{2.5}$ particles, which penetrate deeper into the respiratory tract and have a lower reference dose value RfD, which makes them comparable in terms of health effects with higher PM_{10} concentrations. HQ > 1, namely 3.98, i.e., there is a potential health threat with long-term exposure to the recorded concentration of $PM_{2.5}$ and PM_{10}. This can lead to respiratory diseases, allergies, chronic bronchitis, and damage to the cardiovascular system [18].

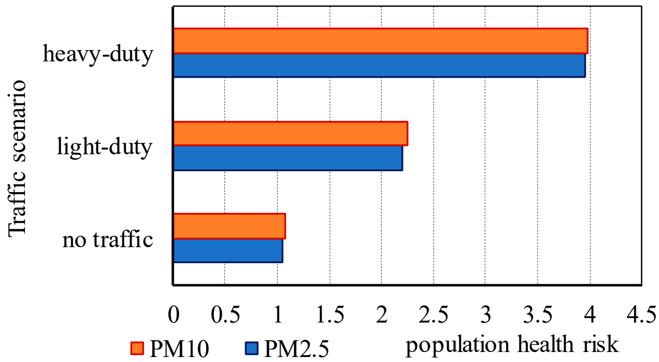


Fig. 11. The level of risk to public health due to dust pollution along the access road to the Rybalsky quarry was determined using the chronic inhalation exposure methodology

5. 3. Mathematical modeling of the dust concentration field in the area around the access road and health risk assessment

The spread of dust pollution is described by equation (9), which is the classical form of the mass transfer equation for impurities in the air. It comes from the general mass conservation equation in fluid mechanics and is widely used in environmental modeling [19].

The following simplifications were accepted when building the mathematical model: the propagation process was considered quasi-stationary; the problem was considered in two-dimensional space; the coefficients of the equation were considered constant

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}+\sigma C=\mu\Delta C+Q_l\delta\left(\left|\bar{r}-\bar{r}_0\right|\right), \quad (9)$$

where C is the dust pollution concentration integrated over height H of the surface layer, mg/m^3; u, v are the corresponding components of the air flow velocity in the directions Ox, Oy, m/s; σ is the dust deposition coefficient, m/s; Q_l is the power of the distributed dust source integrated over height H of the surface layer, mg/(m·s); $r=\sqrt{x^2+y^2}$ is the distance from the origin to the observation point (x, y), m; $r_0=\sqrt{x_0^2+y_0^2}$ is the distance from the origin to the location of the pollution source (x_0, y_0), m; μ is the turbulent diffusion coefficient, m^2/s; $\Delta=\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}$ is the Laplace operator; $\delta\left(\left|\bar{r}-\bar{r}_0\right|\right)$ is the Dirac delta function.

The analytical solution to equation (9) takes the following form (10)

$$C(x,y)=\frac{Q_l}{2\pi\mu}\exp\left[\frac{\bar{u}\cdot\left(\bar{r}-\bar{r}_0\right)}{2\mu}\right]\cdot KK_0\left(\lambda\cdot\left|\bar{r}-\bar{r}_0\right|\right), \quad (10)$$

where $KK_0\left(\lambda\cdot\left|\bar{r}-\bar{r}_0\right|\right)$ is the McDonald function; $\bar{u}=u\bar{i}+v\bar{j}$; $\bar{r}-\bar{r}_0=x\bar{i}+y\bar{j}$; $\bar{r}_0=x_0\bar{i}+y_0\bar{j}$; $\lambda=\sqrt{\frac{u^2+v^2+4\mu\cdot\sigma}{4\mu^2}}$. If we enter parameter $\xi=\lambda\left|\bar{r}-\bar{r}_0\right|$, then, to calculate the value of the McDonald function $KK_0(\xi)$, we can use the following approximation (11)

$$KK_0(\xi)=\sqrt{\frac{\pi}{2\xi}}\cdot e^{-\xi}\cdot\frac{MM(\xi)}{NN(\xi)}, \quad (11)$$

where $MM(\xi)$, $NN(\xi)$ are polynomials of the 4th power, namely:

$$MM(\xi)=\alpha_1+\xi\cdot\left(\beta_1+\xi\cdot\left(\gamma_1+\xi\cdot\left(\delta_1+\xi\cdot\varepsilon_1\right)\right)\right), \quad (12)$$

$$NN(\xi)=\alpha_2+\xi\cdot\left(\beta_2+\xi\cdot\left(\gamma_2+\xi\cdot\left(\delta_2+\xi\cdot\varepsilon_2\right)\right)\right). \quad (13)$$

The values of coefficients in the approximating polynomials (12), (13) are determined by the least squares method and are respectively equal to:

$\alpha_1=3273$, $\beta_1=115296$, $\gamma_1=398592$, $\delta_1=323584$,

$\varepsilon_1=65536$; $\alpha_2=8505$, $\beta_2=151200$, $\gamma_2=435456$,

$\delta_2=331776$, $\varepsilon_2=65536$.

The direction of the air flow in the calculations was assumed to be northeast, i.e., the wind comes from the northeast. The residential areas of Igren, Vinnytsia, and Chaply with private low-rise buildings are located along this direction. Also here is the Prydniprovsky district with multi-story residential buildings; there is a network of educational and preschool institutions, hospitals, supermarkets, sports and outdoor playgrounds.

This indicates that a significant number of people is constantly exposed to dust. Taking into account the given wind direction, the calculation area was 3.5 × 5.5 km, according to which a calculation grid with dimensions of 350 × 550 nodes was used in the numerical simulation.

In the calculations using equation (9) according to formula (10), the following parameters were used:

– dust deposition rate

$\sigma PM_{2.5}=0.003$ m/s, $\sigma PM_{10}=0.005$ m/s;

– diffusion coefficients: $\mu_x=200$ m^2/s, $\mu_y=100$ m^2/s, which corresponds to the atmospheric stability class B-C;

– components of the wind speed vector: $u=-0.8$ m/s (along the x axis), $v=-1.5$ m/s (along the y axis);

– dust emission intensity along the access road, the values of which are given in Table 4.

Table 4

Dust emission intensity along the access road to the Rybalsky quarry with different types of vehicle traffic

Q_i, g/(m·s)		
Type of traffic	$Q_{iPM_{2.5}}$	$Q_{iPM_{10}}$
Without motor vehicles	0.00052	0.00134
With passenger vehicles	0.00109	0.00279
With freight vehicles	0.00197	0.00493

Numerical experiments were performed according to the input data given in Table 1. For clarity, the simulation results for the traffic scenario involving trucks are given: spatial distribution of $PM_{2.5}$ (Fig. 12, *a*) and PM_{10} (Fig. 12, *b*) particulate matter concentration from the access road to the Rybalsky granite quarry.

The general configuration of the dust concentration fields is similar: maximum concentrations are observed directly near the source, within 90% of the maximum level, then a decrease in the concentration level is observed in the direction of air mass transfer.

At the same time, significant differences in the scale of the impact were established. The $PM_{2.5}$ fraction demonstrates a more significant range of distribution since the zone of increased concentrations covers a wider area and extends deeper towards residential areas. This is due to a lower deposition rate and higher mobility of fine particles. In the Prydniprovskyi district, which corresponds to the southern sector of the map, $PM_{2.5}$ concentrations exceed 20% of the maximum level, while PM_{10} in the same direction is almost completely deposited.

Thus, $PM_{2.5}$ dust is more environmentally hazardous because of its ability to be transported far and penetrate dense residential areas. Our results should be taken into account during environmental zoning, justification of sanitary protection zones, and development of measures to minimize dust load on adjacent territories.

Dust concentrations calculated using the mathematical model (9) to (13) were compared with the maximum permissible values established by WHO 2021 and national standards of Ukraine. The following values were taken as average daily indicative levels: for $PM_{2.5}$ = 0.025 μg/m^3, for PM_{10} = 0.05 μg/m^3. Exceeding these concentrations indicates a potentially harmful impact on public health. The most dangerous from this point of view is the residential area of Vinnytsia, where $PM_{2.5}$ concentrations exceed the permissible norm by 1.8–2.3 times, and PM_{10} by 2.3–2.9 times.

An assessment of chronic inhalation exposure to particulate matter was conducted for residential areas located near the access road to the Rybalsky granite quarry (Table 5).

The estimated levels of risk to public health from exposure to both $PM_{2.5}$ and PM_{10} are variable depending on the distance to the emission source and meteorological conditions. The highest risk values are observed in the Vinnytsia and Stara Igren districts where the combined contribution of $PM_{2.5}$ and PM_{10} exceeds the permissible level of HQ > 1 (Fig. 13).

Table 5

Dust concentrations and chronic inhalation risk for people near the access road to the Rybalsky quarry

Residential areas	$C_{PM_{2.5}}$, μg/m^3	$C_{PM_{10}}$, μg/m^3	Risk $HQ_{PM_{2.5}}$	Risk $HQ_{PM_{10}}$
Chapli	0.01156	0.01451	0.395895	0.198814
Prydniprovsk	0.02312	0.02902	0.791789	0.397628
Stara Igren	0.03468	0.08708	1.187684	1.192884
Vinnytsia	0.05781	0.11611	1.979473	1.590513

This indicates a potentially significant negative impact on the respiratory system of people permanently residing in these areas. In particular, $PM_{2.5}$ in all zones was more significant in terms of the overall risk, which is explained by its ability to penetrate deep into the lungs and a more pronounced toxicological effect.

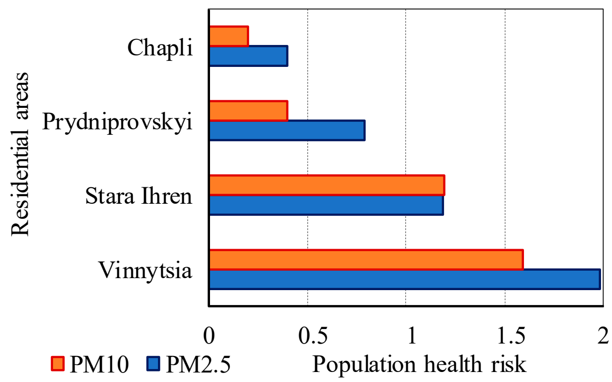


Fig. 13. Level of chronic inhalation risk from dust pollution near the access road to the Rybalsky quarry

Moderate risk levels were recorded in the Prydniprovsky residential area, while the Chaply area had the lowest risk, which is likely due to its remoteness from the pollution source and lower windage.

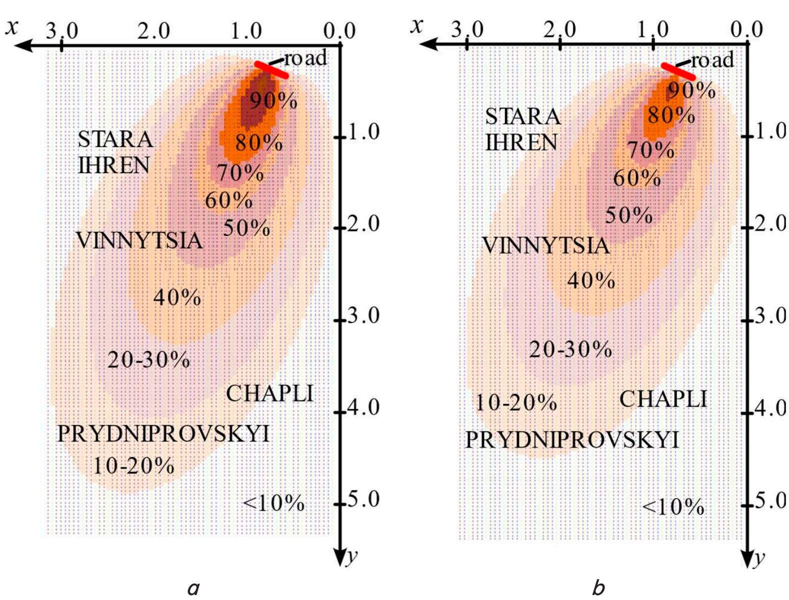


Fig. 12. Dust concentration field in the area around the access road to the Rybalsky granite quarry during the movement of freight transport, northeasterly wind, modeling area — 3.5 × 5.5 km: *a* — for the $PM_{2.5}$ fraction; *b* — for the PM_{10} fraction

The results obtained emphasize the importance of regular monitoring of fine dust, especially $PM_{2.5}$, as well as the need to take into account data on the dispersion of pollutants when planning development in areas of technogenic impact.

6. Results of investigating the dust load on the environment in the area of influence of quarry development: discussion

Our study of changes in the dynamics of dust fractions $PM_{2.5}$ and PM_{10} (Fig. 3) forms the basis for constructing predictive models and determining long-term trends, which in turn opens up opportunities for devising more effective environmental risk management strategies. The results obtained over a five-year period can become the basis for forming regional programs to reduce dust load, in particular in the territories of quarries and adjacent access roads, which are often overlooked by monitoring systems.

Parallel analysis of the specific mass of pollutants (Fig. 4) revealed the dominance of solid particles, primarily PM_{10}, in the structure of emissions. This approach makes it possible to assess the quantitative superiority of individual substances but does not reflect their temporal variation and differences between groups of pollutants in different years.

Unlike typical estimates of annual emissions without taking into account the structure of pollutants [8], the use of two-factor analysis allowed us to systematically take into account two factors at the same time: "year" and "type of substance", which increases the accuracy of identifying priority emission sources. This approach provides the advantage of being able to localize the most problematic groups of pollutants and separate the constant component from the variable, which is important for planning load reduction measures. The authors of [10] prove that emissions from quarries are seasonal in nature and are largely formed due to $PM_{2.5}$. Our study complements these conclusions by focusing on the types of pollutants as the main influencing factor and confirms the dominant role of PM fractions (Fig. 3, 4) in variations in the total emission level.

It was found that $PM_{2.5}$ volumes have nonlinear dynamics with a sharp decline in 2022 (–64.4%) and further growth, which indicates an unstable technogenic load (Fig. 5). PM_{10} emissions, on the other hand, demonstrate a general downward trend with a partial recovery in 2024 (+35.7%) (Fig. 6). The results are consistent with the conclusions of work [5], which showed the importance of assessing the dynamics of dust emissions for choosing optimal control measures.

The results of experimental monitoring of $PM_{2.5}$ and PM_{10} dust concentrations along the access road to the Rybalsky quarry in the period from June to August 2025 indicate a stable trend of exceeding the maximum permissible concentrations of MPC established for atmospheric air in populated areas. Measurements were carried out both in the absence of traffic, which makes it possible to isolate the influence of natural and climatic factors, and under the conditions of passenger and freight traffic (Fig. 7, 8).

The detected excess concentrations of suspended particles in periods of complete absence of traffic indicate a significant role of naturally occurring factors in the formation of dust. In particular, high air temperatures up to 30.5°C, low relative humidity up to 41.5%, and weak wind up to 0.6 m/s create conditions for drying the road surface, reducing dust deposition and its accumulation in the surface layer of air, which is noted in [10], which emphasizes the influence of weather conditions on dust in dry climates. Considering the potential risks, our study results indicate the need to implement dust load reduction measures, namely, compaction, wetting of the road surface, as well as continuous environmental monitoring, as recommended in EPA reports and studies [20].

Measurements conducted during the movement of passenger vehicles showed that, compared to periods without transport activity, a steady increase in dust load is recorded, which indicates a significant role of road traffic in the formation of secondary dusting of the road surface. The results obtained confirm that intensive freight traffic is a key factor in the formation of increased dust load in the quarry area, in particular on access dirt roads. Compared to periods without transport activity, a steady increase in $PM_{2.5}$ and PM_{10} concentrations was observed, which is consistent with the results of studies [21], where secondary dusting under transport load conditions is recognized as the main source of pollution.

Analysis of the influence of meteorological conditions on the level of dust concentration revealed a clear dependence. In particular, a decrease in wind speed and relative humidity, as well as an increase in temperature, is accompanied by an increase in dust concentrations due to a decrease in the efficiency of atmospheric dispersion and increased dust lift from the dry road surface (Fig. 9, 10). This is explained by the fact that at high temperatures dust resuspension from surfaces occurs, especially coarse particles. For fine particles ($PM_{2.5}$), the increase is less pronounced, as it is partly due to secondary chemical processes. An increase in relative humidity, on the contrary, promotes the aggregation and deposition of particles, which reduces their concentration in the air.

The key feature of our study is the combined analysis of weather conditions, type of traffic flow, and concentrations of $PM_{2.5}$ and PM_{10}, which allowed us to quantitatively show that the movement of passenger vehicles causes 2–2.5 times lower dust concentrations under similar weather conditions than the movement of freight vehicles. Most previous works focused mainly on total emissions in quarries or experimental conditions [7, 10, 21]. This study covers real conditions of traffic in the quarry area and contains a comparative assessment of vehicle types and weather scenarios.

That allowed us to more accurately assess the contribution of freight transport to secondary dusting and to substantiate the need to implement comprehensive measures to reduce dust emissions: stabilization of the road surface, regular irrigation, and air monitoring, which is also recommended in other works [2, 5].

In addition to the analysis of fine dust concentrations under different transport activity conditions, an important component of our study was the use of correlation-regression analysis, which allowed us to quantitatively assess the influence of meteorological factors on the variation of $PM_{2.5}$ and PM_{10} concentrations. Unlike papers [6, 7], which focused mainly on describing pollution levels or general trends, our study is aimed at establishing quantitative relationships. It builds mathematical models that describe linear relationships between dust concentrations and the main meteorological parameters: temperature, wind speed, and humidity.

The use of correlation-regression analysis confirmed with a high level of confidence that temperature and wind speed are key factors in the formation of dust load. Our results are consistent with previous studies [10, 21] but expand their practical application for assessing the conditions of real traffic load. Similar quantitative assessments were previously used mainly under open-pit mining conditions without taking into account the traffic component [7, 10], or for individual types of dust, for example, in coal mines.

The constructed regression equations (1) to (6) allow us to predict $PM_{2.5}$ and PM_{10} concentrations based on known environmental parameters and traffic flow characteristics. This makes it possible to assess the chronic impact on public health not only based on the results of direct measurements but also for different scenarios of access road operation, as well as extrapolate the calculations to other time periods and meteorological conditions, increasing the accuracy and practical significance of the forecast, which corresponds to the approaches described in [22, 23].

Based on the calculations, it was established that even in the absence of production activity, an increased dust load is observed. It forms a chronic inhalation risk for three scenarios: without transport, with the movement of passenger cars, and freight vehicles (Fig. 11).

Analysis revealed that in the absence of motor vehicle traffic, the chronic hazard index did not exceed one, which corresponds to an almost safe level of exposure. When only passenger cars were moving, it increased by about two times, while for freight transport it exceeded the baseline level by four times, which indicates a high degree of potential harm to human health. Similar patterns are consistent with the conclusions in [22, 23], which assessed the impact of dust pollution under quarry and road conditions.

The difference of our study is the combination of instrumental measurements under real operational conditions with a quantitative assessment of health consequences under three clearly defined traffic scenarios. This approach made it possible to determine in detail the contribution of each type of transport to the formation of dust load and the risks associated with it.

The results of the study show a characteristic spatial-concentration structure of pollution: maximum dust concentrations are recorded directly near the source, which corresponds to approximately 90% of the maximum level, with a further decrease in the direction of air mass transport (Fig. 12). This trend is consistent with classical models of atmospheric pollution diffusion [6, 7, 10]. However, a significant difference is the range of distribution of different dust fractions. The $PM_{2.5}$ fraction demonstrates a more widespread distribution, covering a much larger area and deeper penetration into residential areas, in particular in the Prydniprovskyi district, where $PM_{2.5}$ concentrations exceed 20% of the maximum (Table 5). At the same time, PM_{10} is almost completely deposited closer to the source, which is consistent with the physicochemical properties of the particles.

Exceedance of the regulatory concentrations established by the WHO and national standards of Ukraine ($PM_{2.5}$ – 0.025 μg/m^3, PM_{10} – 0.05 μg/m^3) was recorded in the residential area of Vinnytsia where $PM_{2.5}$ exceeds the permissible values by 1.8–2.3 times, and PM_{10} – by 2.3–2.9 times (Fig. 13). This indicates a high potential for negative impact on public health, which is also confirmed by the assessment of chronic risk (HQ > 1) in Vinnytsia and Stara Igren, where $PM_{2.5}$ is the dominant risk factor. In contrast, in the Chapli district, which is remote from the source and with less wind influence, the risk was minimal, which emphasizes the importance of taking into account local meteorological conditions.

Thus, our data emphasize the need for priority monitoring of fine $PM_{2.5}$ dust, as well as taking into account their dispersion in ecological zoning, the formation of sanitary protection zones, and the development of measures to minimize dust load on adjacent residential areas. The results of our study take into account the direction of the wind flow and seasonal conditions, which increases the accuracy of the forecast.

This is especially important for planning safe development in areas affected by quarrying activities and road infrastructure.

Compared with models [7, 10], this approach not only reproduces the spatiotemporal fields of pollution but also integrates them into the HQ calculation module for assessing long-term risk. Thus, the model acquires practical value for ecological spatial planning and the formation of sanitary protection zones.

From a practical point of view, the results of our study fill the gap related to constructing mathematical models for predicting and dispersing dust along access roads to quarries, taking into account meteorological factors.

In particular:

– a comprehensive risk assessment was carried out not only by average concentrations but also taking into account the spatial distribution and differences in the behavior of $PM_{2.5}$ and PM_{10};

– an integrated approach was applied, which makes it possible to move from mathematical models to a quantitative assessment of chronic risk;

– the need for spatial delimitation of territories by the degree of pollution was justified, taking into account the actual range of dust transport, which is critical for dense urban development.

However, the study has certain limitations that should be taken into account in practical application:

– the use of meteorological data for a limited period may not fully reflect interannual fluctuations;

– the model takes into account average source characteristics, while real emissions may be peak or intermittent;

– the impact of complex relief forms and local turbulent effects was not fully taken into account;

– the risk was assessed only by the inhalation route, without taking into account possible deposition and entry into food chains.

The shortcomings of the work include the lack of analysis of data on other seasons of the year, the lack of connection with medical statistics, which makes it impossible to directly confirm the correlation between pollution levels and morbidity rates in the studied areas.

Further development of the study involves conducting long-term monitoring taking into account seasonal fluctuations [24] and expanding the chemical analysis of particulate matter with the release of toxic and carcinogenic components [25]. In addition, it is planned to integrate the obtained data with medical statistics to quantitatively confirm the impact of dust pollution on public health. Additionally, it is advisable to model scenarios for reducing dust load through the introduction of dust suppression technologies and assess the effectiveness of such measures in reducing HQ [26].

7. Conclusions

1. Analysis of statistical data for 2020–2024 revealed that the total volume of emissions from quarrying was increasing by 15–22% depending on the year, with the largest contribution coming from $PM_{2.5}$ and PM_{10} particulate matter. The results of variance analysis showed a statistically significant effect of the factors “pollutant type” ($p < 0.01$) and “year” ($p < 0.05$) on the level of emissions. It was found that the growth of dust emissions outpaced the dynamics of gaseous emissions, which is due to the intensification of transport operations and unconsolidated roadbeds along access roads. This gave grounds to identify dust as a key factor for monitoring and minimizing negative environmental impacts, in contrast to common approaches where the main emphasis is on gaseous emissions.

2. Field measurements along the access road to the Rybalsky quarry showed that the average daily concentrations of $PM_{2.5}$ and PM_{10} exceeded the WHO recommendations by 1.8–2.3 and 2.3–2.9 times, respectively. Correlation-regression analysis revealed a strong relationship between dust levels and the intensity and type of traffic flow, $R^2 = 0.72$ for $PM_{2.5}$ and $R^2 = 0.68$ for PM_{10}, as well as between air humidity and wind speed. The HQ chronic risk assessment showed that the level of health hazard increases 4 times with freight traffic compared to no traffic. This confirms the priority of controlling heavy vehicles in residential areas near quarries.

3. Mathematical modeling of the spatial distribution of dust showed that the $PM_{2.5}$ fraction is characterized by a

larger radius of distribution compared to PM_{10}. The zone of more than 20% of the maximum concentration level extends to the residential areas of Prydniprovsky and Vinnytsia. In the indicated areas, the HQ value exceeds one, which indicates an increased risk to the respiratory system of people. Unlike most known models, which take into account mainly the point source of emissions, our models take into account the impact of traffic flow and meteorological conditions, which provides higher accuracy of the impact assessment. The results obtained confirm the need to introduce sanitary protection zones, as well as implement measures to reduce dust load, in particular, screening, greening, and moistening of the road surface.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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