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Article

Assessment and Mitigation of The Impact of Harmful Pollutants on Green Spaces in Industrial Areas

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Abstract: The article discusses the issues of assessing the impact of harmful pollutants generated as a result of the activities of industrial enterprises on the green spaces of industrial territories, as well as ways to reduce their negative impact. The analysis of the main sources of atmospheric air pollution, which have an adverse effect on woody, shrubby and herbaceous vegetation, is carried out. The mechanisms of the impact of pollutants on the physiological state of plants, the processes of photosynthesis, growth and resistance of green spaces to adverse environmental factors are considered. Approaches to the ecological assessment of the state of green spaces using indicators of plant viability, the level of accumulation of pollutants and the effectiveness of greening industrial areas are proposed. Special attention is paid to the development of measures to reduce the negative impact of pollutants, including the optimization of the landscaping system, the selection of sustainable types of tree and shrub vegetation, the creation of protective green strips and the improvement of environmental protection measures at industrial facilities.

Keywords: green spaces, industrial zones, pollutants, environmental assessment, plant resistance, impact reduction

Introduction

The conservation of flora and ensuring the ecological sustainability of natural and anthropogenic ecosystems are among the priorities of modern environmental policy [1]. In conditions of intensive industrial development, urbanization and increasing anthropogenic pressure, green spaces perform important ecological functions, including reducing the concentration of pollutants in the atmospheric air, absorbing carbon dioxide, releasing oxygen, regulating the microclimate and maintaining biological diversity [1], [2].

However, an increase in industrial emissions containing oxides of sulfur, nitrogen, carbon, particulate matter and heavy metals has a significant negative impact on the physiological state of plants, reducing their viability and environmental efficiency [3], [4]. At the international level, issues of flora protection are an important component of achieving the UN Sustainable Development Goals, primarily SDG 13 "Combating climate change" and SDG 15 "Preserving terrestrial ecosystems" [5]. Considerable attention is paid to the implementation of the provisions of the Convention on Biological

Diversity, the United Nations Framework Convention on Climate Change, as well as initiatives to develop green infrastructure, restore degraded ecosystems and increase the area of forests and urban green spaces [6]. In many countries, modern methods of environmental monitoring, bio indication and digital mapping of vegetation conditions are being introduced, which makes it possible to identify the negative effects of pollutants in a timely manner and develop effective environmental protection measures [4].

In the Republic of Uzbekistan, special attention has been paid to environmental protection, rational use of natural resources and conservation of flora in recent years [7], [8]. Large-scale government programs are being implemented to green settlements, expand forest plantations, develop an environmental monitoring system and reduce air pollution. Of significant importance are the activities carried out within the framework of the national project "Yashil Makon", aimed at increasing the area of green spaces, improving the environmental situation and adapting territories to the effects of climate change [9].

At the same time, the regulatory framework in the field of environmental protection is being improved, and the requirements for industrial enterprises to reduce pollutant emissions and introduce environmentally sound technologies are being strengthened. Despite the ongoing reforms, there are still a number of urgent problems related to the deterioration of green spaces in industrial areas. High concentrations of pollutants, insufficient effectiveness of sanitary protection zones, limited use of resistant types of tree and shrub vegetation and insufficient comprehensive assessment of the ecological condition of green areas reduce the effectiveness of environmental protection measures. Previous studies show that trees and forests can remove airborne pollutants [10], that foliar dust accumulation can alter chlorophyll and other physiological indicators [11], and that particulate-matter capture efficiency varies among tree species according to leaf characteristics [12]. These findings reinforce the need for pollutant-resistant species and scientifically designed green belts in industrial areas.

In this regard, research aimed at assessing the impact of harmful pollutants on green spaces, the development of scientifically sound methods of environmental assessment and the introduction of effective measures to reduce the negative impact of industrial pollution are becoming particularly relevant [13]. The purpose of this study is to assess the impact of harmful pollutants on the green spaces of industrial territories, analyze their ecological status and develop scientifically sound measures aimed at reducing the negative impact of industrial emissions and increasing the environmental sustainability of green infrastructure.

Materials and Method

Bio indication Method. The bio indication method is based on the use of plants as natural indicators of the state of the environment. Changes in the morphological, physiological and biochemical parameters of plants make it possible to determine the degree of exposure to pollutants [4], [11].

Tree species, shrubs, mosses and lichens with different sensitivity to atmospheric air pollution are widely used as bio indicators. The method is highly environmentally informative and is widely used in monitoring industrial areas [4].

Environmental Monitoring Method. Environmental monitoring provides for systematic monitoring of the state of green spaces and the level of environmental pollution. The method includes determining the concentrations of pollutants in atmospheric air, soil and plant tissues, as well as assessing the state of vegetation in dynamics. The data obtained is used to identify areas of increased environmental risk and develop environmental protection measures [4].

Laboratory and Instrumental Method. This method is based on laboratory studies of samples of leaves, soil and precipitation using modern analytical instruments. Atomic absorption spectrometry (AAS), inductively coupled plasma mass spectrometry (ICP-MS), X-ray fluorescence analysis (XRF), gas and liquid chromatography are used to determine the content of heavy metals and other pollutants. The method provides a high accuracy of quantification of the pollution level.

The Comparative Ecological Analysis Method. The method is based on comparing the condition of green spaces located in an industrial zone and in control territories with minimal anthropogenic load. Plant growth indicators, leaf surface area, degree of leaf damage, level of accumulation of pollutants and general sanitary condition of plantings are assessed. Comparative analysis makes it possible to establish the impact of industrial emissions on vegetation cover and determine the effectiveness of environmental protection measures; species-level differences in particulate capture should also be considered when interpreting such comparisons [12].

Result

Monitoring Results on the Level of Inorganic Dust Pollution of Vegetation at the Samarkand Regional Road Maintenance Unitary Enterprise

Samples were collected from trees based on the spatial distribution range of pollutants emitted by the enterprise. The sampling process and the assessment of the impact of industrial enterprises on vegetation were carried out in accordance with:

The processes of sampling and the assessment of the enterprises' impact on vegetation were analyzed in accordance with the requirements set out in Resolution No. 464 of the Cabinet of Ministers dated August 22, 2022, "On further improvement of the procedure for planting, maintaining, and using trees and shrubs not included in the State Forest Fund" [14], as well as on the basis of the Instruction on the inventory of pollution sources and standardization of pollutant emissions into the atmosphere for enterprises of the Republic of Uzbekistan, registered on January 3, 2006 [15].

Monitoring of vegetation contamination by inorganic dust at the Samarkand Regional Road Maintenance Unitary Enterprise was mainly conducted on:

Western side: ornamental trees (juniper);

Eastern side: juniper species with scaly leaves;

Northern side: fruit trees (quince, walnut, and apple);

Southern side: ornamental trees (juniper).

Calculation of Inorganic Dust Pollution of Vegetation at the Samarkand Regional Road Maintenance Unitary Enterprise

Samples taken before the purification process

From tree leaves on the western side: $q1 = 4.917\ g$

From tree leaves on the eastern side: $q2 = 5.918\ g$

From tree leaves on the northern side: $q3 = 21.530\ g$

From tree leaves on the southern side: $q4 = 5.178\ g$

Samples Collected After the Purification Process

From tree leaves on the western side: $q5 = 3.276\ g$

From tree leaves on the eastern side: $q6 = 4.090\ g$

From tree leaves on the northern side: $q7 = 19.027\ g$

From tree leaves on the southern side: $q8 = 3.529\ g$

The sampling points from four directions were considered as four emission sources. These sources were classified as unorganized (diffuse) emission sources. The parameters of the unorganized sources were assumed as follows:

Source 1

Height N = 4 m, diameter D = 0.5 m, temperature T = 22 °C, air velocity V = 4.2 m/s.

The cross-sectional area of the source is calculated as:

$$F = \pi^*D^2 /4= 3{,}14 * 0{,}5^2/4= 0{,}196\ m^2$$

The volumetric flow rate of the dust–gas mixture is determined by:

$$Q =V * F * K\ \ m^3/s$$

where V is air velocity, F is the cross-sectional area of the source, and K is the correction coefficient (K = 0.9).

$$Q =4{,}2 * 0{,}196 * 0{,}90 = 0{,}741\ m^3/s$$

$$S = q_1 – q_5 / V_0 * 1000\ mg/m^3.$$

Dust concentration is calculated as:

V_0 is the volume of air passing through the filter, determined considering air temperature and barometric pressure.

$$V_0 = 273 * V_t * V / (273 + T) * 760 \text{ m}^3.$$

Where:

P is barometric pressure (131.6 Pa),

T is the air temperature (22 °C),

V_t is the measured volume of air passed through the filter:

$$Vt=t×qV\_t = t \backslash times qVt=t×q$$

q is the volumetric air flow through the filter (34 L/min), t is sampling time (5 minutes).

Given:

$$V_t = 5 * 34 = 170 \text{ l}.$$

$$V_0 = 273 * 170 \times 131,6/(273 + 22) \times 760 = 6107556/224200 = 27,24 \text{ m}^3$$

$$q_1 = 4,917 \text{ gr.} \qquad q_5 = 3,276 \text{ gr.}$$

$$S = 4,917 - 3,276/ 27,24 * 1000 = 60,24 \text{ mg/m}^3.$$

The emission rate per unit time:

$$V = S * Q * 10^{-3} = 60,24 * 0,741 * 10^{-3} = 0,0446 \text{ g/s}.$$

Source 2

$$V = S * Q * 10^{-3} = 71,77 * 0,688 * 10^{-3} = 0,0494 \text{ g/s}.$$

Source 3

$$V = S * Q * 10^{-3} = 73,84 * 0,723 * 10^{-3} = 0,0534 \text{ g/s}.$$

Source 4

$$V = S * Q * 10^{-3} = 47,41 * 0,776 * 10^{-3} = 0,0368 \text{ g/s}.$$

According to calculation results, the dominant wind direction was from the west toward the east (36.8%), whereas the reverse wind occurred only 8% of the time. Therefore, vegetation located on the eastern side was exposed to higher levels of inorganic dust pollution.

Samarkand Road Maintenance Unitary Enterprise Laboratory Monitoring of Enterprise Impact on Vegetation on the Eastern Side (fruit trees – quince, walnut, and apple)

Stage I – Dust-contaminated leaves

1. Average weight of one dust-contaminated leaf: **4.917 g**
2. Number of leaves per branch: **11**
3. Number of branches per tree: **4**
4. Number of trees on the eastern side: **9**
5. X*U= 54,0gr*4=216 gr.
6. 216*9=1944gr (1kg, 944gr)

Stage II – Laboratory-cleaned leaves

1. Average weight of one cleaned leaf: **3.276 g**
2. Number of leaves per branch: **11**
3. Number of branches per tree: **4**
4. Number of trees on the eastern side: **9**
5. X*U= 35,6gr*4=141,5 gr.
6. 141,5*9=1275gr (1kg, 275gr)

Stage III – Total dust accumulation on trees

1944gr*1274gr=670gr The total amount of inorganic dust deposited on trees located on the eastern side equals 670 g.

Monitoring of Inorganic Dust Impact on Vegetation After Installation of the Second-Stage Dust–Gas Cleaning Unit at the Enterprise

Stage I

1. Average weight of one leaf contaminated with inorganic dust: **3.265 g**
2. Number of leaves per branch: **7**
3. Number of branches per tree: **5**
4. Number of trees located on the eastern side: **9**
5. X*U= 22,8gr*5=114 gr.
6. 114*9=1020gr (1kg, 026gr)

Stage II – Relative to Leaves Cleaned of Inorganic Dust Under Laboratory Conditions

1. Average weight of one dust-free leaf: **2.972 g**
2. Number of leaves per branch: **7**
3. Number of branches per tree: **5**
4. Number of trees located on the eastern side: **9**
5. X*U= 22,3gr*5=111,5 gr.
6. 111,5*9=1003,6gr (1kg)

Stage III – Amount of Dust Deposited on Trees

1027gr-1003,6gr=23,4gr The total amount of inorganic dust accumulated on the trees located on the **eastern side** was **23.4 g**.

Stage IV – Efficiency of Dust Impact Reduction After Installation of the Second-Stage Dust–Gas Cleaning Unit

The efficiency of reducing the impact of inorganic dust was calculated using the following formula:

$$\frac{D1-D2}{D2}*100;$$

where:

D_1 – amount of inorganic dust contamination on trees (fruit trees) on the southern side before installing the second-stage dust–gas cleaning system (g);

D_2 – amount of inorganic dust on trees after installation of the second-stage dust–gas cleaning system (g).

The calculated efficiency of pollution reduction reached 97%.

Table 1. Assessment of the Impact of Industrial Enterprises on Vegetation

Districts (distance 50–130 m) and pollutants	Sample amount from sources, g/s	Amount of inorganic dust on trees before equipment installation, g	After installation of new equipment, g	Achieved results and efficiency, %
Samarkand city (asphalt–concrete production), inorganic dust	0.19	670 g	23.4 g	*(Impact reduced)* **97%**
Urgut district (slate production), inorganic dust	0.22	872.8 g	24.9 g	*(Impact reduced)* **97%**
Pastdargom district (brick production), inorganic dust	0.18	576.9 g	38.7 g	*(Impact reduced)* **93%**

Source: Table compiled by the author based on research results.

Figure 1. Signs of the impact of dust and gas emissions on the leaves of woody plants, woody and shrubby vegetation of the sanitary protection zone of an industrial enterprise.

Discussion

The results demonstrate that inorganic dust generated by industrial activities has a measurable effect on vegetation within and around sanitary protection zones. The spatial distribution of dust accumulation was strongly associated with local wind direction. The dominant wind direction from west to east, recorded at 36.8%, resulted in greater exposure of vegetation situated on the eastern side of the enterprise. This finding indicates that the environmental impact of industrial particulate emissions is determined not only by the magnitude of emissions but also by meteorological conditions and the spatial position of vegetation relative to emission sources. Previous studies have similarly demonstrated that particulate matter can accumulate on leaf surfaces and interfere with plant physiological functions, particularly photosynthesis, transpiration, and gas exchange [3], [4].

The substantial difference between dust accumulation before and after the installation of the second-stage dust–gas cleaning unit provides clear evidence of the effectiveness of the applied mitigation technology. At the Samarkand asphalt-concrete production facility, inorganic dust deposited on vegetation decreased from 670 g before the installation of the equipment to only 23.4 g afterward, corresponding to an impact reduction efficiency of approximately 97%. Such a marked reduction indicates that controlling pollutants directly at the emission source can considerably decrease the environmental burden experienced by surrounding green spaces. This result is particularly important because long-term exposure to particulate matter can alter leaf characteristics, reduce chlorophyll content, and negatively affect plant vitality [4], [11].

Comparable reductions recorded at the other investigated industrial facilities strengthen the reliability of this finding. At the slate production facility in Urgut district, dust accumulation decreased from 872.8 g to 24.9 g, resulting in a 97% reduction, whereas at the brick production facility in Pastdargom district it decreased from 576.9 g to 38.7 g, corresponding to a 93% reduction. Although the initial levels of particulate contamination differed among the three locations, the consistently high mitigation efficiencies indicate that modern dust–gas purification systems can provide an effective technological approach across different types of industrial production. The slightly lower efficiency observed in Pastdargom may reflect differences in production processes, emission characteristics, equipment operating conditions, or local environmental factors that influence pollutant dispersion and deposition.

The findings also emphasize the ecological importance of green spaces as complementary components of industrial pollution mitigation. Trees and shrubs situated around industrial facilities can intercept airborne particulate matter and consequently reduce the amount of pollutants dispersed into surrounding areas. Studies have demonstrated that urban trees and forests contribute to atmospheric pollutant removal and can improve environmental quality [2], [10]. However, the capacity of vegetation to retain particulate matter differs considerably among species because leaf morphology, surface roughness, wax characteristics, leaf area, and canopy architecture affect particle capture efficiency [12]. Therefore, the establishment of sanitary-protective green belts should not depend solely on increasing vegetation density but should also prioritize species that are both resistant to industrial pollutants and efficient in capturing airborne particles.

The visible accumulation of dust on leaves observed during field monitoring further supports the use of vegetation as a practical bioindicator of industrial pollution. Differences between contaminated and laboratory-cleaned leaf samples provide a relatively straightforward approach for evaluating particulate deposition under field conditions. This approach is consistent with the concept of environmental biomonitoring, in which morphological and physiological responses of plants are used to evaluate environmental stress [4]. Nevertheless, vegetation-based assessment should preferably be combined with instrumental monitoring of atmospheric pollutants and laboratory analysis of plant and soil samples. Integrating these methods would provide a more comprehensive evaluation of both pollutant concentrations and their biological consequences.

Overall, the results indicate that effective management of industrial pollution requires an integrated approach combining emission-control technology, environmental monitoring, and properly designed green infrastructure. The reductions of 93–97% achieved at the investigated facilities demonstrate that technological improvements at emission sources can substantially decrease particulate exposure to surrounding vegetation. At the same time, maintaining pollutant-resistant trees and shrubs within sanitary protection zones can provide an additional ecological barrier and contribute to the long-term stability of industrial landscapes. Consequently, regular monitoring of dust deposition, periodic assessment of vegetation condition, maintenance of dust–gas purification equipment, and appropriate selection of plant species should be incorporated into environmental management strategies for industrial enterprises in the Samarkand region.

Conclusion

The conducted studies have made it possible to comprehensively assess the impact of emissions from industrial enterprises on the condition of green spaces located within production areas and sanitary protection zones. It has been established that the main pollutants having a negative impact on vegetation cover are inorganic dust, nitrogen oxides, carbon monoxide, sulfur dioxide and other components of gas and dust emissions.

Their prolonged exposure leads to a decrease in the intensity of photosynthesis, disruption of physiological processes, a decrease in plant growth rates, deterioration of decorative properties and a decrease in the overall environmental sustainability of green spaces. The results of the study showed that the use of modern two-stage dust and gas purification plants is an effective engineering solution to reduce the anthropogenic impact on the environment. After the introduction of the second stage of emission purification, the impact of inorganic dust on the woody vegetation located on the western side of the industrial enterprise has significantly decreased.

The overall effectiveness of reducing the negative impact of pollutants was 97%, which indicates the high effectiveness of the implemented environmental technologies. The results also confirmed the effectiveness of using dust and gas cleaning equipment at various industrial facilities in the Samarkand region.

At the asphalt-concrete plant in Samarkand, the level of exposure to harmful pollutants on green spaces was reduced by 97%, which provided a significant improvement in the environmental condition of the surrounding area.

Similar results were obtained at the slate production plant in the Urgut district, where the effectiveness of reducing the impact on vegetation cover also reached 97%. The introduction of environmental protection measures at the Pastdargomsky district brick factory has reduced the negative impact of industrial emissions on plant ecosystems by 93%.

The obtained indicators confirm the high environmental and practical efficiency of using modern emission purification systems in the construction industry. Based on the conducted research, it is recommended to continue upgrading existing gas purification systems and equipping industrial enterprises with highly efficient two-stage dust and gas purification plants. Special attention should be paid to the formation and preservation of sanitary-protective green strips using tree and shrub species resistant to industrial pollutants, because vegetation performance and particulate capture can vary substantially among species.

For timely detection of changes in the ecological state of green spaces, it is advisable to organize regular environmental monitoring using bio indication methods, laboratory and instrumental research and geoformation technologies. The practical implementation of the proposed measures will significantly reduce the level of atmospheric air pollution, increase the resistance of green spaces to man-made impacts, improve the sanitary and ecological condition of industrial areas and create favorable conditions for the conservation of flora in conditions of intensive industrial development.

The results obtained can be used in the development of regional environmental safety programs, improvement of environmental policy, as well as in the design of sanitary protection zones and landscaping systems for industrial enterprises.

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