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TECHNIQUES AND DEVICES FOR MITIGATING ENVIRONMENTAL POLLUTION IN COTTON PROCESSING INDUSTRIES

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Abstract: This article analyzes the issue of atmospheric pollution caused by particulate matter (PM2.5, PM10) in cotton processing enterprises. The efficiency of conventional dust collection devices—cyclones, cartridge filters, and HEPA filters—is scientifically compared, and their limitations in ensuring environmental safety are identified. Furthermore, the theoretical and practical integration of IoT (Internet of Things)-based smart sensors and GIS (Geographic Information Systems) platforms into industrial monitoring is substantiated. The study develops a block-diagram approach for real-time data acquisition, network-based transmission, and spatial visualization to determine pollution dynamics. Based on the analysis of local and international practices, it has been demonstrated that smart-filter systems can reduce atmospheric pollution by up to 90%. The findings provide a solid foundation for formulating scientifically grounded recommendations on the implementation of digital technologies in the field of industrial ecology.

Keywords: cotton industry enterprises; atmospheric particulate pollution; IoT technologies; GIS systems; smart filters; environmental monitoring; particulate matter (PM2.5, PM10); industrial ecology; real-time control; smart sensors.

Introduction. In recent years, scientific research aimed at ensuring the environmental safety of industrial production systems has been intensifying worldwide. Studies in modern industrial systems addressing environmental protection are expanding rapidly at the global scale. In particular, air pollution caused by particulate matter $PM_{2.5}$ and PM_{10} has been identified in developed countries as a leading cause of cardiovascular and respiratory diseases. The 2021 report of the World Health Organization provided an in-depth analysis of these risks, substantiating that particulate pollution constitutes one of the most critical environmental threats to human health. In this regard, real-time GIS-based monitoring and management systems have been widely implemented in the United States, European Union countries, and other technologically advanced nations. These systems make it possible to identify the volume, composition, and geographic distribution of industrial emissions, thereby serving as an essential tool for detecting and predicting environmentally hazardous areas. In the context of Uzbekistan, the primary cotton processing industry is regarded as a key sector that determines the export potential of the national economy. At the same time, this sector requires particular attention as an environmentally hazardous segment of production. Specifically, particle emissions generated during the drying, separation, pneumatic transport, and pressing stages directly affect technological stability, environmental quality, and human health. Currently applied dust collection systems—cyclones, cartridge filters, and mechanical separators—not only increase energy consumption but also lack sufficient capacity to effectively capture $PM_{2.5}$ and smaller particles. This leads to the dispersion of emissions beyond industrial zones, undermining ecological sustainability. Therefore, our research is directed toward developing alternative technological approaches for monitoring and controlling the spread of particulate emissions in cotton processing industries. Among these, the design of integrated environmental management models based on real-time GIS monitoring systems, smart filtration technologies, mechatronic control elements, and sensor devices is identified as one of the most pressing challenges.

Within the economic structure of the Republic of Uzbekistan, the cotton industry represents a strategic sector, contributing significantly to the national GDP and serving as one of the main sources of export revenue. According to official statistics, approximately 3 million tons of raw cotton are produced annually in the country, more than 70% of which is directed to primary processing stages (State Committee on Statistics, 2024). The initial technological processes in cotton production—particularly drying, lint cleaning, pneumatic transport, and separation—emit large quantities of particulate matter into the air. Fine-fraction aerosols, such as $PM_{2.5}$ (particles smaller than 2.5 micrometers) and PM_{10} (particles up to 10 micrometers), are considered especially hazardous to human health due to their morphological structure and size, which allow them to penetrate the respiratory system, reach the lungs, and in some cases enter the circulatory system. These particles can remain suspended in the air for 4–12 hours, disperse over long distances, and pose threats not only to the environment but also to human health.

Among the currently used dust separation devices, cyclones and cartridge filters are the most common. However, their efficiency against $PM_{2.5}$ is considerably low, leaving them unable to fully meet environmental safety requirements. Under these conditions, modern high-efficiency particulate air (HEPA) filters and smart filtration systems are regarded as promising alternatives. Smart filters integrate Internet of Things (IoT) technologies, enabling real-time measurement of dust concentration and adaptive adjustment of operations through automated control systems. $PM_{2.5}$ particles, in particular, can penetrate deep into the pulmonary alveoli, causing cardiovascular and respiratory diseases. Existing industrial filtration systems are not sufficiently effective in mitigating this problem. For example, while conventional cyclones can capture particles larger than 20 micrometers, their efficiency for $PM_{2.5}$ remains limited to only 30–50%. The table below compares the efficiency levels of different filtration technologies.

Table 1. Efficiency of Different Filter Types in Capturing $PM_{2.5}$ and PM_{10} Particles

Filter Type	PM_{10} Efficiency (%)	$PM_{2.5}$ Efficiency (%)	Emission ($PM_{2.5}$,kg/ton)
Cyclone	60	30	0.035
Cartridge Filter	75	50	0.025
HEPA Filter	90	85	0.008
Smart-filtr (IoT based)	95	92	0.004

As shown in the table, smart-filter systems demonstrate the highest efficiency in capturing $PM_{2.5}$ particles, achieving a rate of 92%. These systems reduce emissions to as low as 0.004 kg per ton of raw cotton, which represents up to a nine-fold improvement compared to HEPA filters (0.008 kg/ton) and conventional cyclone devices (0.035 kg/ton). In addition to their filtration capacity, smart filters are distinguished by their automatic response capability, energy efficiency, and reduced human error. For these reasons, they are considered the most promising technological solution for ensuring environmental safety.The integration of such filter systems with Geographic Information System (GIS) technologies in cotton industry enterprises enables the establishment of regional ecological monitoring. This approach allows the identification of critical zones, real-time mapping of pollution levels, and timely decision-making in environmental management. From a regulatory perspective, despite the adoption of Resolution No. 168 of the Cabinet of Ministers of the Republic of Uzbekistan on March 29, 2021, which set maximum permissible concentrations of harmful substances in the atmosphere, monitoring data reveal that these standards are frequently violated in many industrial areas. In certain cotton-cleaning enterprises, dust concentrations range from 85 to 120 $\mu g/m^3$, which is nearly ten times higher than the WHO-recommended annual limit of 10–12 $\mu g/m^3$. This ecological burden in the cotton industry carries not only technical but also social significance, as many cotton-processing facilities are located near residential areas. Consequently, windborne dust particles are observed to reach nearby settlements, posing health risks particularly to children, the elderly, and individuals prone to respiratory diseases.

Furthermore, the accumulation of dust within machinery increases friction, reduces heat dissipation, and lowers energy efficiency. All of these factors negatively impact production performance and raise operational costs. Advanced international practices—particularly in Germany, France, Hungary, China, and South Korea—demonstrate the successful implementation of real-time GIS monitoring, dust pollution mapping, and AI-assisted automated control systems. Adapting such technologies to the industrial context of Uzbekistan could significantly improve environmental safety, facilitate real-time identification of critical zones, and promote ecological sustainability in production processes.

Accordingly, our research is directed toward developing a comprehensive, interdisciplinary integrated system aimed at reducing dust pollution, protecting human health, and enhancing industrial efficiency in the cotton industry. Current filtration systems do not provide sufficient solutions to these challenges. For instance, widely used cyclones are only effective in capturing particles larger than 20 micrometers, with an efficiency of merely 30% for $PM_{2.5}$. Compared with HEPA or IoT-based smart filters, such devices fail to meet contemporary technical and ecological requirements. From the perspective of environmental legislation, Resolution No. 168 of the Cabinet of Ministers of the Republic of Uzbekistan (2021) defines permissible thresholds for pollutant concentrations. However, practical observations indicate that these thresholds are consistently exceeded in most industrial areas. In some cotton enterprises, dust concentrations have been recorded at 85–120 μg/m³, which is 8–10 times higher than the WHO annual guideline of 10–12 μg/m³. Most cotton-processing plants in Uzbekistan lack the necessary sensor systems and GIS platforms required for real-time monitoring, resulting in inadequate ecological surveillance and complications in state environmental control and certification processes.

Presidential Decree No. PQ-172 (2023) emphasizes the need to enhance environmental safety in industrial enterprises, introduce air-monitoring systems, and implement modern technologies under the "Yashil Makon" ("Green Space") initiative. Based on this, the integration of GIS technologies with real-time dust concentration monitoring, automatic data transmission to filtration systems, and mechatronic control mechanisms is regarded as an innovative solution for reducing ecological risks in cotton industry enterprises.Additionally, dust particles contribute to equipment corrosion, increased friction, and reduced energy efficiency. These issues directly affect production efficiency, shorten service life, and lead to higher operational costs. Consequently, the development of automated management systems based on comprehensive, interdisciplinary approaches has become an urgent priority to ensure environmental safety, safeguard human health, and maintain production efficiency in the cotton industry.

Our research, for the first time in Uzbekistan, is focused on integrating GIS monitoring and smart-filtration technologies within a mechatronic control model to enhance environmental safety in cotton-processing enterprises. This provides a scientifically grounded framework for advancing technological modernization in the sector under national conditions.

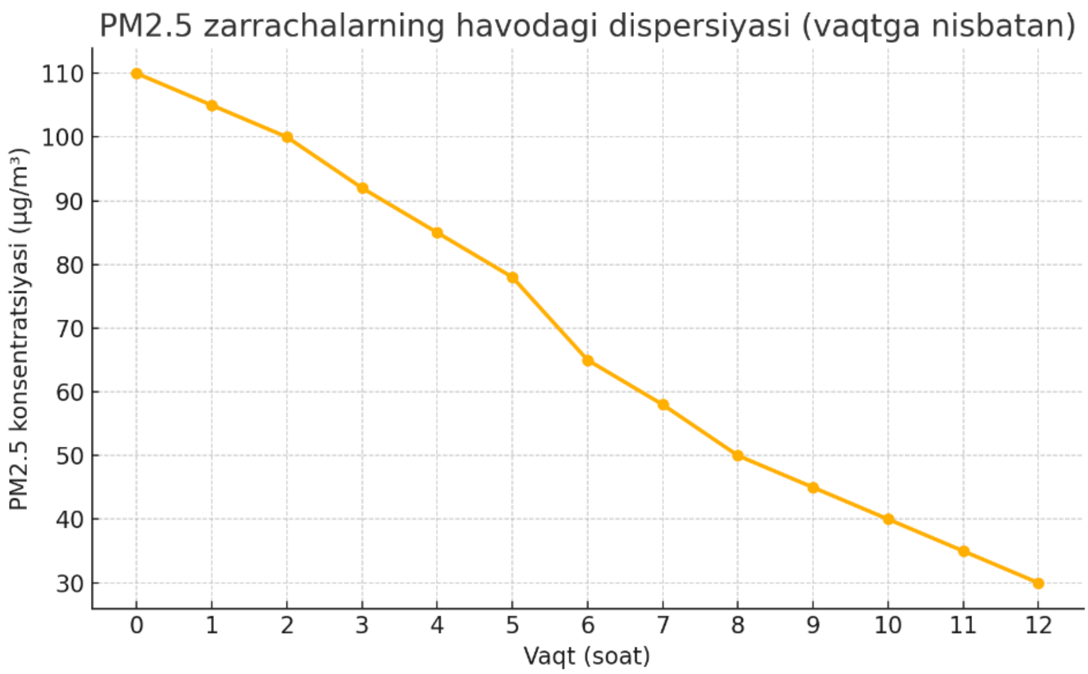

Figure 2. $PM_{2.5}$ Dispersion Graph.

In many enterprises, the absence of dust analysis devices prevents real-time monitoring of air quality. This, in turn, creates obstacles in obtaining permits and certifications from state environmental authorities. Under such circumstances, the implementation of GIS technologies and the integration of mechatronic systems to enable intelligent control capabilities have become an urgent necessity. In particular, GIS tools can be employed to map dust dispersion areas, while sensor-generated data are collected in real time and automatically transmitted to smart filter systems. Through this mechanism, enterprises can enhance ecological safety, certify industrial facilities as "eco-zones," and establish an environmental monitoring system in compliance with international standards. In the near future, such solutions are expected to become decisive factors for ensuring the sustainable development of industry.

The consequences of pollution originating from primary cotton processing lines extend beyond the internal industrial environment, exerting negative impacts on the surrounding social infrastructure. Since many cotton-cleaning plants are located in close proximity to residential areas, airborne micro-particles ($PM_{2.5}$) dispersed by variable wind currents pose health risks to the local population. The World Health Organization (WHO) has particularly emphasized the growing incidence of pulmonary diseases among vulnerable groups, such as children, the elderly, and individuals with chronic respiratory illnesses.

In line with the Presidential Decree of the Republic of Uzbekistan dated May 12, 2023, "On Expanding the National Project 'Green Space' and Ensuring Environmental Safety," industrial enterprises are mandated to strengthen environmental responsibility and adopt modern technologies for air quality monitoring. From this perspective, the real-time detection of dust pollution in cotton industry facilities, the storage of measurement data in digital GIS databases, and the automated management of filtration systems are recognized as advanced approaches.

One of the key advantages of smart monitoring systems is their ability to independently activate mechatronic filter modules whenever the concentration of airborne particles exceeds established thresholds. This reduces human error, shortens automatic response times, and ensures the rational use of energy resources. Moreover, GIS-based control systems enable quarterly assessments of industrial zones' environmental status, provide graphical representations of trends, identify problematic areas, and transmit data to state regulatory agencies. Such an integrated approach not only enhances ecological safety within cotton industry enterprises but also broadens their capacity to participate in environmental monitoring, auditing, and certification systems. Consequently, enterprises gain the opportunity to align with the ISO 14001:2015 environmental standard.

In general, without the adoption of modern technologies, ensuring ecological safety in cotton industry facilities will remain a persistent challenge. Particulate pollution arising from cotton processing plants poses a serious threat to environmental security, undermines the efficiency of industrial technologies, and adversely affects public health. Therefore, the integration of mechatronically controlled smart filters and GIS-based monitoring technologies is regarded as a vital technological solution for maintaining ecological balance in the cotton industry.

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