E-ISSN: 2997-9382

SemantJournals

American Journal of Technology Advancement

https://semantjournals.org/index.php/AJTA

| Research Article

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Mechanisms for Monitoring Industrial Ecology Based on the Integration of Smart Filters and Scada Systems

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Annotation

This thesis presents the integration of a modern smart filter system into a cyclone separator, enhancing the efficiency of fine particle removal. Smart filters possess capabilities such as real-time detection of airborne particles, self-diagnostics, and automated assessment of cleaning conditions. Moreover, the system is integrated with a SCADA (Supervisory Control and Data Acquisition) automated control system, which enables continuous monitoring of air quality parameters, data collection, storage, and analysis, as well as remote management. Through SCADA, environmental conditions are monitored in real time, with automatic alerts and control signals generated when necessary. This integrated approach plays a crucial role in ensuring environmental safety at industrial enterprises, promoting the rational use of resources, improving the efficiency of technological processes, and safeguarding human health. The proposed integration method has been tested in practice and has demonstrated positive results.

Keywords: industrial air purification technologies, fine dust, cyclone dust collector, smart filter system, SCADA automated control system, environmental monitoring.

Today, the interdependence between human health, environmental conditions, and sustainable development has become increasingly evident. In industrialized regions in particular, maintaining the quality of atmospheric air has evolved into not only a technological challenge but also a social and ethical concern. The cleanliness of the air people breathe is directly linked to their quality of life, life expectancy, and overall well-being. Modern industrial enterprises emit significant amounts of dust, smoke, and harmful gases into the atmosphere, posing threats not only to ecological balance but also to public health at large. Consequently, the implementation of technologies capable of efficiently capturing dust-gas mixtures has become a pressing necessity. At the heart of this research lies the aim to improve human living standards, ensure environmental safety, and positively transform technological processes. Specifically, the study focuses on enhancing the efficiency of particle separation by complementing conventional cyclone devices with smart filter systems. Furthermore, integrating these systems with the SCADA control platform is intended to fully automate all monitoring processes. This approach contributes to maintaining a safe and healthy living environment, as environmental stability is not only a matter

of national policy but also a fundamental determinant of individual well-being and life quality. Traditional dust collection systems, such as cyclone separators, offer reliability and energy efficiency but struggle to efficiently capture smaller particles. Recent technological advances now allow for the integration of smart filtration systems and digital automation, presenting an opportunity to fundamentally improve dust collection and monitoring. This article investigates the enhancement of cyclone separators through the integration of a multi-functional smart filter system, further automated by SCADA technology. The main objectives are to:

- ✓ Increase particle removal efficiency, especially for fine dust;
- ✓ Enable real-time environmental monitoring and control;
- ✓ Provide scalable, practical solutions suitable for Uzbekistan and similar contexts.

Literature Review. Cyclone separators, baghouse filters, and electrostatic precipitators are among the most widely used technologies for industrial dust removal. Cyclones rely on centrifugal forces to separate heavier particles from airflow, while baghouses use fabric filters, and electrostatic precipitators charge and collect particles. Each method has advantages and limitations: cyclones are cost-effective and require little maintenance, but their efficiency drops for particles smaller than 5–10 μm [1][3][10]. SCADA systems provide centralized, automated monitoring and control of industrial processes. In air purification, SCADA enables remote tracking of air quality indicators, data logging, alarm management, and integration with other digital systems [2][4]. Modern SCADA platforms use a combination of wired and wireless sensors, real-time analytics, and user-friendly dashboards. Recent studies highlight the benefits of integrating smart filters with traditional dust collectors [3][6][7]. However, relatively few works have examined their combined effect in the context of SCADA-based automation, especially in developing countries. In Uzbekistan, the need for effective air quality control systems is pronounced, but the implementation of such integrated, modern solutions remains limited [4][5][6]. Among the various air purification systems, cyclone dust collectors (or devices for separating particles from gaseous media) are considered technologically simple, energy-efficient, and reliable. However, they are primarily effective in capturing large and medium-sized particles, while their efficiency significantly decreases when dealing with micro- and nanoparticles. This limitation poses a serious threat, particularly in terms of environmental safety and human health. Therefore, this study enhances the traditional cyclone design by integrating a modern smart filter module. This module enables real-time measurement of dust particle concentration, airflow velocity, and filter resistance, supported by sensor-based control and automatic diagnostics within the system. The efficiency of particle separation is calculated using the following mathematical expression:

$$\eta = \left(\frac{C_{in} - C_{out}}{C_{in}}\right) \times 100\% \quad (1)$$

where:

η – overall purification efficiency (%),

C_{in} – dust concentration at the inlet (mg/m³),

C_{out} – dust concentration at the outlet (mg/m³).

Type of system	C_{in} **, mg/m³**	C_{out} **, mg/m³**	**η, %**
simple cyclone	250	95	62.00
cyclone + smart filter	250	58	76.80

Table 1. Dust Separation Efficiency

The results indicate that the efficiency of the modernized system increased by 14.8%. This improvement can serve as a significant factor in reducing environmental risks and enhancing the working environment in industrial enterprises. The centrifugal force acting on the particles within the airflow is expressed as follows:

$$F_c = \frac{m \cdot v^2}{r} \quad (2)$$

where:

F – centrifugal force (N),

m – mass of the particle (kg),

v – rotational velocity (m/s),

r – radius of rotation (m).

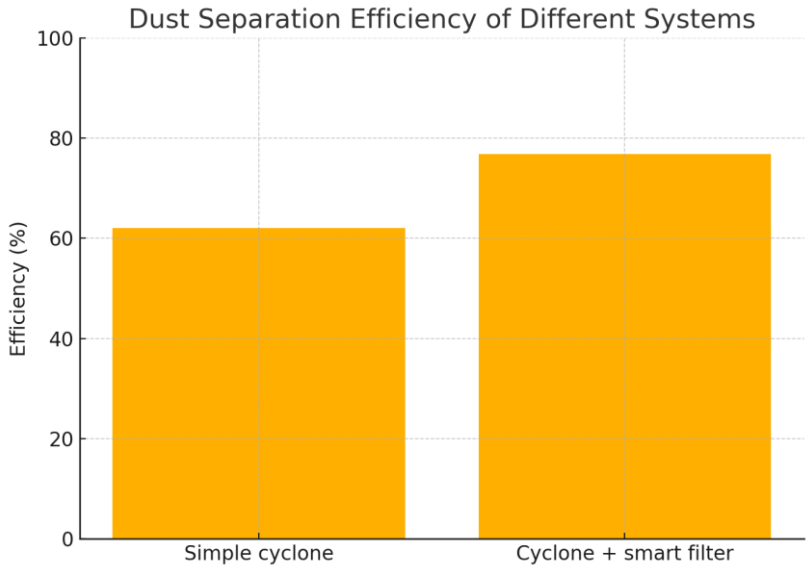

Figure 1. Dust separation efficiency in different system.

The bar chart in Figure 2 compares the dust separation efficiency of two air purification setups used in industrial environments: the conventional cyclone separator and a cyclone separator complemented by a smart filter module. The vertical axis represents the dust removal efficiency, expressed as a percentage, while the horizontal axis lists the two system configurations. The conventional cyclone separator achieves an efficiency of 62.0%. This value reflects the cyclone's ability to remove larger and medium-sized dust particles through centrifugal separation. However, its performance is limited when dealing with fine and ultrafine particles (<10 μm), which constitute a substantial portion of hazardous industrial dust emissions. In contrast, the cyclone + smart filter system demonstrates a significantly higher efficiency of 76.8%. The 14.8% improvement is achieved by adding a multi-layer smart filter at the cyclone's outlet. This filter utilizes advanced materials (such as PVDF with nano-adhesive coatings) and embedded sensors to capture smaller particulates that the cyclone alone cannot remove efficiently. The real-time diagnostic and monitoring capability of the smart filter also enables prompt identification and correction of suboptimal operating conditions, further enhancing overall performance. The marked increase in dust separation efficiency translates to improved workplace air quality and a reduction in harmful particulate emissions to the environment. This can have direct health benefits

for workers and the surrounding community. Enhanced efficiency supports compliance with local and international air quality regulations, which is particularly relevant for Uzbekistan's ongoing efforts to modernize its industrial sector. The integration of smart filtration not only improves particulate removal but also enables automated monitoring and maintenance via the SCADA platform, reducing system downtime and operating costs. The results illustrated by Figure 2 highlight the practical advantage of modernizing conventional dust collection systems. While the cyclone separator remains a reliable and cost-effective first stage, its combination with smart filtration technologies addresses its primary limitation—fine particulate removal. Given the prevalence of dust-related challenges in Uzbekistan's key industries (e.g., textiles, construction materials, chemicals), the adoption of this integrated approach can provide measurable improvements in both environmental protection and industrial process efficiency. Overall, the graph confirms that upgrading existing cyclone separators with smart filter modules is a highly effective method for significantly enhancing dust separation efficiency in industrial settings. This solution is both technically feasible and economically justified, especially in contexts where fine particulate emissions are a major concern. The smart filter material—composed of multi-layered PVDF fabric with nano-adhesive coatings—possesses high porosity, ensuring efficient purification without restricting airflow. In the context of Uzbekistan, dust particles remain one of the major environmental challenges in industrial and manufacturing enterprises. The release of fine particulate matter into the atmosphere poses a direct threat not only to the environment but also to human health. Therefore, it is of great importance to upgrade existing dust separation equipment using modern, energy-efficient, and high-performance technologies. The findings of this study demonstrate that the installation of a smart filter in a cyclone system resulted in a 14–15% increase in dust removal efficiency. This improvement is particularly relevant for many industrial sectors in Uzbekistan, including the chemical, textile, and construction materials industries, where it holds practical significance. Furthermore, the integration of the SCADA automated monitoring platform into the system enables online tracking of pollution levels, diagnostic analysis, and real-time control. This technology represents a significant step toward ensuring environmental safety in accordance with modern standards. As a recommendation, it is proposed to equip existing dust separation systems in Uzbekistan's industrial enterprises with smart filters and to implement automated monitoring tools such as SCADA. This approach will enhance environmental monitoring, improve production efficiency, and—most importantly—contribute to the protection of human health.

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