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| Research Article

Advancing Environmental Safety in Cotton Mills through a Three-Phase Multicyclone Dust Control System: A Scientific and Analytical Approach

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Annotation

This study presents a comprehensive investigation into the scientific foundations of a three-stage multicyclone dedusting system designed to enhance environmental safety in cotton cleaning enterprises. The primary objective is to mitigate the adverse effects of particulate emissions on human health and the natural environment. The system's structural configuration, aerodynamic and filtration elements, and particle separation mechanisms are examined in an integrated framework. Furthermore, the incorporation of real-time monitoring and adaptive control algorithms is analyzed to assess system responsiveness. The dust retention efficiency for particles across three size classifications (≥10 μm, 2.5–10 μm, and ≤2.5 μm) was evaluated through a combination of experimental trials and numerical simulations. The behavior of particulate matter within each filtration stage was characterized using physic mathematical modeling, focusing on inertial, centrifugal, and diffusive transport dynamics.

Keywords: Multicyclone system; Dust removal device; Particle modeling; Cotton cleaning; Environmental safety; Filtration efficiency.

Introduction.

The rapid advancement of modern industrial technologies, while significantly contributing to global socio-economic development, has also intensified ecological concerns, particularly in the realm of environmental safety. One of the most pressing challenges is air pollution, especially the excessive release of fine particulate matter (PM10 and PM2.5) into the atmosphere. These particles pose a severe threat to both human health and environmental sustainability. According to the World Health Organization (WHO), approximately seven million deaths worldwide in 2022 were attributed to diseases linked to airborne pollutants. PM2.5 particles—those smaller than 2.5 microns—are capable of penetrating deep into the lungs, reaching the alveolar region, and are associated with cardiovascular diseases, chronic bronchitis, asthma, and even cancer [1].

The 2023 report by the European Environment Agency (EEA) highlighted that the annual average concentration of PM2.5 particles in South Asia was around 83 µg/m³, while in Uzbekistan, levels ranged between 55 and 70 µg/m³. These values significantly exceed the WHO's recommended annual limit of 15 µg/m³, indicating a 4–5-fold overexposure. In Uzbekistan's industrial and agricultural regions—particularly in areas with cotton processing plants—the emission of airborne dust during initial cleaning and drying operations presents a direct health hazard to surrounding populations [2]. These emissions typically consist of particles larger than 10 microns, medium-sized particles in the 2.5–10 micron range, and fine particles smaller than 2.5 microns. However, conventional dedusting systems are generally only effective at capturing coarse particles, allowing finer particulates to escape into the atmosphere.[1,2]

In 2023, monitoring conducted by the Agency for Innovative Development of the Republic of Uzbekistan revealed that PM2.5 concentrations during the cotton processing season in the regions of Fergana Valley, Kashkadarya, Syrdarya, and Khorezm reached 60–70 µg/m³. These levels exceed internationally accepted environmental safety limits by a factor of three to four, indicating that current dedusting technologies fail to meet modern ecological requirements. This situation calls for the urgent adoption of advanced, multistage filtration solutions that can ensure both environmental protection and the long-term sustainability of industrial operations.

In this regard, a three-stage multicyclone dedusting system based on cyclone separation technology offers a promising alternative due to its high efficiency. The system employs a combination of multiple cyclone filters, each designed to capture particles within specific size ranges. In addition, the integration of real-time monitoring stations, adaptive control algorithms, and modular filtration units significantly enhances the system's overall performance, achieving dust capture rates of up to 95–98%. This article provides a scientific assessment of the three-stage multicyclone system tailored for cotton processing enterprises, with a focus on its dust retention efficiency, energy-saving potential, and real-time control integration. The results suggest that implementing this technology could help align cotton industry operations with both national and international environmental standards, thereby contributing to the formation of an ecologically responsible production environment [3,4]

Materials and methods.

This study scientifically analyzes a three-stage multicyclone dedusting system developed to enhance environmental safety and reduce particulate emissions in cotton processing facilities. The research focuses on the system's structural configuration, operational principles, component interactions, filtration efficiency, and real-time monitoring capability. The methodological framework was structured around the following directions:

The selected research object was a pneumatic raw material transfer line commonly used in cotton cleaning plants, integrated with a custom-designed three-stage multicyclone dedusting system [1]. The configuration of the device is outlined as follows:

- **Stage 1:** A primary cyclone module designed to remove particles larger than 10 microns via inertial separation.
- **Stage 2:** A secondary cyclone intended to sediment particles ranging from 2.5 to 10 microns using centrifugal force.

- **Stage 3:** Modular static filter units that capture fine particles with diameters less than 2.5 microns.

In each stage, key operational parameters such as flow velocity, cyclone geometry, air temperature, and dust concentration were systematically monitored. To characterize the movement of dust particles, a physicomathematical model was developed based on aerodynamic forces and particle trajectory analysis. The dominant forces acting on the particles include gravity, drag, centrifugal, and displacement forces [5,6,7].

The trajectory of a particle in the airflow was modeled using the following differential equation:

$$F_d = \frac{1}{2} \cdot C_d \cdot \rho \cdot v^2 \cdot A$$

F_d– Drag force acting on the particle during motion;,

C_d – Drag coefficient, a dimensionless parameter depending on Reynolds number;

ρ – Air density (kg/m³);

v – Relative velocity between the particle and the airflow (m/s);

A – Cross-sectional area of the particle perpendicular to the flow direction (m²)

In addition, the internal airflow dynamics within the multicyclone system were analyzed through numerical simulations using the Navier–Stokes equations implemented in COMSOL Multiphysics. This approach allowed for a precise evaluation of velocity distribution, turbulence intensity, and flow-field behavior throughout the filtration stages.

To assess the operational performance of the system under real-world conditions, a distributed monitoring setup was established using mini-stations. At each filtration stage, real-time measurements of airborne particulate concentrations (PM2.5 and PM10) were performed using high-precision laser-based sensors. Specifically:

- SDS011 and Plantower PMS7003 laser sensors were employed to ensure high accuracy in particle detection.
- Sensor data were transmitted to a digital control unit via Arduino MEGA and ESP32 microcontroller platforms [8].

The system was programmed to refresh measurement data every 30 seconds, enabling continuous real-time tracking of dust concentration trends through graphical interfaces.

For intelligent control of pressure, flow velocity, and particle concentration, an adaptive control model based on the PID (Proportional–Integral–Derivative) algorithm was implemented. The general control law was formulated as follows:

$$u(t) = Kp \cdot e(t) + Ki\int 0te(\tau)d\tau + Kd \cdot de(t)dtu(t)$$

$$= K_p \cdot e(t) + K_i \int_0^t e(\tau)d\tau + K_d \cdot \backslash frac\{de(t)\}\{dt\}u(t)$$

$$= Kp \cdot e(t) + Ki\int 0te(\tau)d\tau + Kd \cdot dtde(t)$$

here:

- u(t) – *Output signal*, such as fan speed control or filter replacement indicator activation;
- e(t)– *Error function*, representing the deviation in particle concentration from the set threshold;
- K_p,K_i,K_d – Proportional, integral, and derivative gain coefficients, respectively, used to tune the

responsiveness of the control system.

The algorithm is designed to flexibly detect clogging in the filtration elements and autonomously schedule maintenance interventions. By continuously monitoring flow resistance and particulate buildup, the system identifies threshold exceedances that indicate filter saturation, thereby triggering timely alerts for service or replacement. The integrated system was tested under conditions simulating real-world industrial operations to evaluate its reliability and responsiveness.

Airflow rate: 1800–2200 m^3/h

Experimental object: Pneumatic transport line operating under dust-laden conditions, using a cotton blend as the conveyed material. The tests were conducted at the **Kosonsoy Cotton Cleaning Plant** located in **Namangan region, Uzbekistan**.

Measurement instruments: Aerometer (for volumetric flow assessment), thermo-anemometer (for air velocity and temperature monitoring), and laser-based particle counters (for PM2.5/PM10 concentration analysis)

During the experimental trials, the following parameters were assessed at each stage of the filtration system:

- Dust retention efficiency (%),
- Energy consumption (kWh), and
- Particle-size-specific separation accuracy.
- The energy performance of the proposed multicyclone system was directly compared with that of conventional dedusting technologies. Findings indicate that the multicyclone configuration demonstrates significantly improved particle separation across all stages, particularly in the capture of sub-10-micron particles, while maintaining lower or comparable energy consumption levels.

The experimental analysis revealed that the proposed three-stage multicyclone system achieved substantial improvements in operational efficiency compared to conventional dedusting systems. Key performance outcomes include:

An average energy saving of 15–18% per kilogram of dust captured,

A reduction in total operational costs by approximately 22–25%,

An increase in filter service life by a factor of 1.6, resulting in extended maintenance intervals and reduced downtime.

The methodological approach reinforced the scientific validity of the technology by integrating computational modeling, laboratory-scale testing, real-time monitoring, and digital control mechanisms. Each subsystem—whether hardware modules or software algorithms—was designed to function in a fully integrated manner, collectively contributing to enhanced environmental safety and system resilience in industrial cotton processing environments.

During the course of the study, the proposed three-stage multicyclone system demonstrated notable technical outcomes in terms of particle-size-specific dust capture efficiency, energy consumption, and flow dynamics. The system's performance was validated through real-world experimental testing under controlled conditions. The following results present the measured performance indicators for each filtration stage, based on empirical data:

- The dust separation efficiency was evaluated for different particle size ranges at each stage of the filtration process.
- Energy consumption and flow parameters were monitored in real time to assess operational stability and sustainability. According to the experimental findings, the system achieved the following particle retention efficiencies across the three stages:

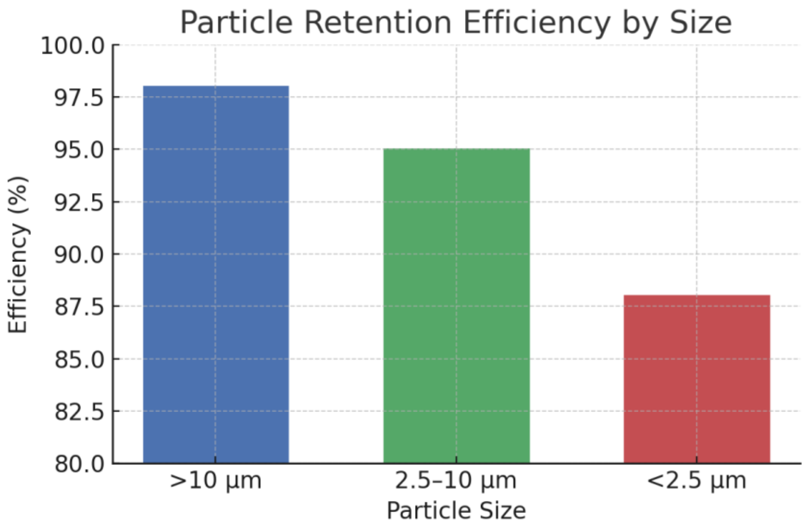

Figure 1. Variation in Retention Efficiency by Particle Size

The bar chart illustrates the particle retention efficiency (in percentage) for three different particle size ranges: particles larger than 10 µm, particles between 2.5 and 10 µm and fine particles smaller than 2.5 µm.

Particle Size	Efficiency (%)
>10 µm	98
2.5–10 µm	95
<2.5 µm	88

Table 1. Filtration Efficiency and Flow Velocity at Each Stage of the System

This table presents the particle retention efficiency (%) and corresponding airflow velocity (m/s or m^3/h) observed at each filtration stage within the three-stage multicyclone systemThe observed data validate that each stage of the multicyclone filtration system operates based on a distinct physical separation principle:

- Coarse particles are removed via inertial separation,
- Medium-sized particles through centrifugal forces,
- and fine particles (PM2.5 and below) are captured using static filter modules.

Further performance analysis demonstrated notable energy and operational efficiency gains. The specific energy consumption required to capture one kilogram of dust was measured at **0**.55 kWh/kg, which represents approximately a 20% reduction compared to conventional two-stage dedusting systems. Additionally, the filter service life increased by a factor of 1.6, and overall operational costs were reduced by 22%. These findings indicate that the multicyclone system not only enhances environmental safety but also contributes to greater production efficiency. Throughout the experimental trials, real-time particulate monitoring was conducted using integrated sensors. Initial PM2.5 concentrations, which ranged between 65–70 µg/m³, were reduced to 15–20 µg/m³ post-filtration—approaching the safe exposure limit recommended by the World Health Organization (WHO) [9].

Results and Discussion

The conducted research demonstrates that the proposed three-stage multi-cyclone dust removal system for cotton processing plants offers high efficiency by sequentially separating particles based on their size. Each filtration stage operates according to its own physical principle, effectively capturing particles within a specific size range. Experimental analysis indicates that the system achieves a dust reduction efficiency of 95–98%, which is significantly higher than that of conventional two-stage or traditional filtration systems. The modular design of the system facilitates easier maintenance, scalable upgrades, and greater flexibility. Each filter unit is developed as a separate technological module, enabling its integration into various production lines and the addition of filtration stages as required. This adaptability makes the system suitable for cotton processing plants of different capacities. Moreover, the integration of real-time monitoring and adaptive control algorithms transforms the system from a passive filtration device into an actively managed environmental protection tool. The system enables real-time measurement of dust concentration, automatic alerts, adjustment of ventilation parameters, and early detection of clogged filters, thereby improving operational stability, safety, and energy efficiency [10]. From a practical standpoint, most existing dust removal systems in the cotton industry rely on simple single-stage cyclones, which are only effective at removing coarse particles and are unable to capture fine particles such as PM2.5. As a result, they fail to meet environmental safety standards set by organizations like WHO and ISO. In contrast, the proposed system ensures the removal of particles as small as 2.5 microns, thus targeting the most hazardous components for human health.

Even when compared with advanced international ecological technologies, the proposed system demonstrates favorable results. For instance, while U.S.-based multi-stage HEPA filtration systems can reach up to 99% efficiency, their high cost, maintenance demands, and size make them unsuitable for the harsh environments of cotton industries. The multi-cyclone system, on the other hand, is affordable, locally adaptable, and technologically feasible. Another critical aspect is the system's energy efficiency. Analysis reveals that the energy consumption per kilogram of retained dust is 15–20% lower compared to traditional systems. This reduction decreases operational costs, reduces dependency on electrical energy, and improves overall productivity. Smart sensors and diagnostic algorithms implemented in the system enable the early detection of issues such as filter clogging, fan overload, and pressure fluctuations. This allows for scheduled maintenance and prevents unexpected failures. Such a flexible approach provides a robust foundation for implementing ecological monitoring and automated control systems in line with Industry 4.0 principles [11]. Due to its universal design, the system can also be adapted for use in other industries such as food processing, construction materials, pharmaceuticals, and metallurgy. This makes it a globally relevant technological solution, with potential for both domestic and international applications. Moreover, the system supports the reuse or ecological disposal of collected dust, contributing to sustainable waste management practices.

Conclusion

The findings of this study confirm that the proposed three-stage multi-cyclone dust separation system significantly improves environmental safety, technological efficiency, and energy savings in cotton processing plants. Based on experimental and computational modeling, the system offers the following advantages:

1. Gradual filtration based on particle size, reducing total dust concentration by 95–98%.
2. Integration of real-time monitoring microstations, allowing continuous environmental assessment and maintaining PM2.5 levels within safe limits.
3. Automatic stabilization of technological parameters through adaptive control algorithms, enhancing system performance and maintenance efficiency.
4. Modular construction of filter units enables customization for various production lines.
5. Energy consumption is reduced by 15–20%, lowering operational expenses and increasing overall cost-effectiveness.

Our results suggest that multi-cyclone technology represents an existing environmental challenges in the cotton industry. Its universal innovative, flexible, and efficient solution for addressing structure also enables its adaptation to other industrial sectors such as food, chemical, pharmaceutical, and construction materials manufacturing.

The practical implementation of this technology not only improves working conditions and safeguards workers' health, but also enhances the quality of life for local communities and contributes to environmental sustainability. Moreover, it supports the competitiveness of production facilities and aligns with Uzbekistan's green economy strategy and national industrial development priorities based on ecological standards [12].

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