

Identification and analysis of factors affecting air flow optimization and particle dispersion in clean rooms of electronic industry

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ABSTRACT

Clean rooms play an important role in electronics industries, specifically for precision manufacturing by strictly regulating pollution control, contaminants, and pressure. Airflow design and particle behavior are key determinants of contamination control performance in clean rooms. Despite technological advances, suboptimal air distribution remains a major contributor to particle dispersion and energy inefficiency. The review systematically examines experimental and modeling studies on airflow management and clean room performance improvement and their real-world application. A search was conducted in Scopus, PubMed, and Web of Science using keywords related to clean rooms, air pollution, and airflow. Following Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines, studies published from 2000 up to November 2025 were screened, and 25 studies were selected. To improve air flow and pollution control, various factors were identified along with their strategies and results. The factors identified were classified into four major classifications and their strategies and results were analyzed. These classifications included architectural and structural factors (e.g., room length, floor height), ventilation and air flow factors (e.g., velocity, air change rate, fan-filter-unit configuration), environmental and operational factors (e.g., activity of personnel, SCARA robot, season), and pollutant characteristics (e.g., particle size, and density). Current evidence indicates that performance improvement of clean rooms requires integrating these factors into a multi-objective framework balancing cleanliness, energy demand, and process stability. We propose a framework connecting different parameters to measurable cleanliness and energy efficiency indices.

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Review

The electronics industry is a highly profitable and rapidly growing sector that plays a major role in national income and export revenues. With the ongoing expansion of semiconductor manufacturing and the growth of the electronics industry, it is crucial to consider the associated health impacts. Research indicates that workers in these sectors are exposed to various air pollution, including white fumes, gasses, and ultrafine particles, posing significant health risks. Furthermore, semiconductor and precision equipment production where even minimal contamination can cause defects and reduce efficiency requires strictly controlled environments [1, 2]. Achieving an optimal balance among product quality, energy consumption, and environmental sustainability remains a persistent and complex challenge.

In this regard, Clean rooms play a central role in achieving these objectives. According to the ISO 14644 standard, clean rooms are classified such as Class 1, 10, 100, 1000, 10,000, and 100,000, where each class denotes the highest allowable concentration of airborne particles in one cubic foot of air. Maintaining this level of cleanliness requires appropriate control measures. Therefore, it is essential to pay attention to air pollution control as much as possible in electronic clean rooms [3, 4].

Several parameters influence air pollution control in clean rooms. Airflow optimization being a key factor in air pollution management [5, 6]. In this regard, reducing the vortex action and non-uniformity is of great importance. Researchers reported that bioaerosols often accumulated in the ceiling-wall junctions as a result of vortex formation, and they controlled the pollutant buildup in these areas by modifying the airflow rate [7]. Other researchers found that airflow discharged from Ultra-Low Penetration Air

(ULPA) filters impinges on cabinet surfaces, generating vortices that promote pollutant buildup. Their simulations further showed that deactivating the ULPA filter diminished vortex formation, thereby markedly lowering particle concentrations [8]. Many researchers showed that both the number and spatial arrangement of Fan Filter Units (FFUs), together with equipment positioning, exert substantial effects on pollutant particle distribution and accumulation, as well as on the overall particle removal rate [9].

Obstructions introduced by personnel and equipment within a clean room can markedly alter the airflow patterns. In a study, it was compared numerical and experimental findings for different ventilation systems and found that indoor heat source has a significant effect on the indoor airflow pattern and pollutant spread [10]. A study noted that the upward thermal plumes produced by human bodies could disturb the unidirectional airflow [11]. In addition to supplying air, equipment, and personnel, factors such as geometry, room length, environmental factors such as solar radiation, and pollutant characteristics affect airflow management, vortex reduction, and pollution control. This study systematically reviews existing research findings and evaluates the effectiveness of different airflow management strategies. The respective advantages and real-world applications of these approaches are critically analyzed. Furthermore, future research directions and potential technological innovations for improving airflow uniformity, air pollution control, and occupational air quality in clean rooms are proposed. The goal of this review is to provide a scientific foundation and practical reference for the design and operational optimization of clean room airflow systems, supporting cleaner, safer, and more sustainable industrial environments.

Search strategy

A search was conducted in the Scopus, PubMed, and Web of Science (ISI) databases. Published studies from the year 2000 to November 2025, were reviewed. Following keywords were used to find relevant articles according to:

("Cleanroom" OR "Cleanrooms" OR "Clean room" OR "Clean rooms" OR "Critical Environment" OR "Sterile Room" OR "CleanZone" OR "ISO 14644") AND (Pollution* OR Particle* OR Particulate* OR "Contaminant removal" OR Aerosol OR Bioaerosol OR Contamination* OR Contaminate OR Nanoparticle OR "Gas contaminate") AND (Airflow OR "Air flow" OR "Laminar Flow" OR "Turbulent Flow" OR "Air Filtration" OR "Air Circulation" OR "Air rate" OR "Air distribution" OR "Ventilation" OR "Air Exchange Rate")

Inclusion and exclusion criteria

Original studies focusing on the optimization of various parameters to enhance airflow and air pollution control in electronic clean rooms were

reviewed. To ensure clarity and avoid translation issues, only English-language studies with full-text availability were included.

Study selection

The studies retrieved from the databases were imported into EndNote (version 21). Titles and abstracts were screened based on the inclusion criteria, followed by a full-text review of the selected studies. To enhance accuracy, two authors independently conducted this process. Fig. 1 presents the study selection process according to the PRISMA framework.

Data extraction

The included studies were carefully reviewed, and the necessary information was extracted. The extracted data from the studies included the first author's name, year of publication, country, room class, process product, optimization method, parameters investigated, evaluation criteria, and key findings.

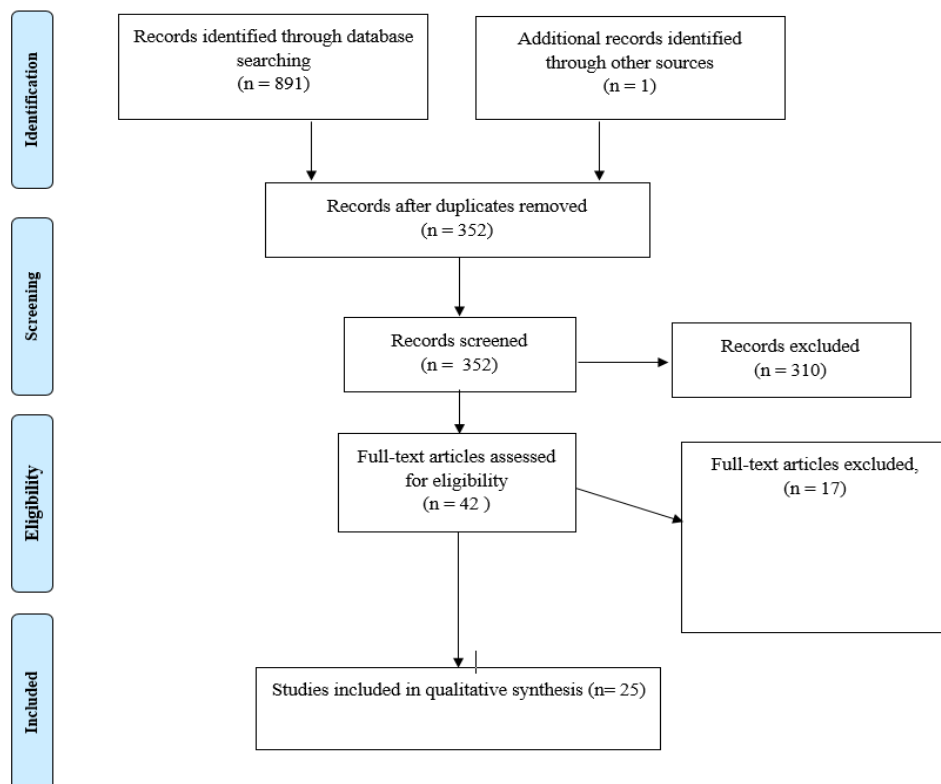


Fig. 1. Studies selection process

Results

Studies characteristics

After screening the papers, 25 papers were included in the study. The main characteristics of the papers, including method, year of publication, country, etc., was extracted. The characteristics

of the selected papers are summarized in Table 1. Also, the frequency of methods used to investigate factor optimization is presented in Fig. 2.

The review of the studies showed that the highest number of studies were related to Taiwan (n=10, 40%) (Table 1).

Table 1. Characteristics of selected studies

Study	Year	Country	Product (s)	Class	Method
[12]	2005	Korea	Semiconductor, Flat Panel Display (FPD)	ISO 5 (Class 100)	Computational Fluid Dynamics (CFD)
[13]	2021	China	Different electronic production	ISO 5	Experimental
[14]	2010	Taiwan	Wafer	-	CFD
[15]	2003	Taiwan	Wafer	Class 1	CFD
[16]	2017	Thailand	Hard disk drive (HDD), Head stack assembly (HSA)	Class 1000	CFD, SST
[17]	2005	Republic of Korea	Semiconductor	Class 1	CFD
[18]	2006	Taiwan	Semiconductors	Class 1	CFD
[19]	2010	Korea	LCD	Class 3	Experimental, CFD
[20]	2011	Taiwan	-	Class 6	Experimental
[8]	2018	Thailand	HDD reader heads	Class 6	CFD
[21]	2022	Taiwan	Semiconductors (Wafers)	-	CFD
[22]	2022	China	Semiconductors (Wafers)	-	Numerical simulations, Experimental
[23]	2024	Taiwan	Optical product	Class 10,000	Experimental, CFD
[24]	2025	Taiwan	Semiconductors	Class 1	Experimental, CFD
[25]	2002	Taiwan	Semiconductors	Class 1	Experimental, CFD
[26]	2010	South Korea	Wafers, photomasks	-	Gaussian Diffusion Sphere Model (GDSM)
[27]	2014	Taiwan	Integrated Circuit Testing	Class 6-8	Experimental
[28]	2023	China	-	Class 6	CFD
[29]	2025	South Korea	Semiconductors	ISO 6	CFD
[30]	2013	China	Semiconductors	-	Numerical simulation
[31]	2021	China	Semiconductors	Class 5	CFD
[32]	2009	Taiwan	MEMS (Micro-Electro-Mechanical Systems Laboratory)	ISO Class 6, ISO Class 7	CFD
[33]	2012	Republic of Korea	Photomask, Wafer	-	Statistical Particle Tracking (SLPT) model
[34]	2022	China	-	-	Experimental
[35]	2025	USA	Semiconductor	-	CFD, Discrete Phase Model (DPM)

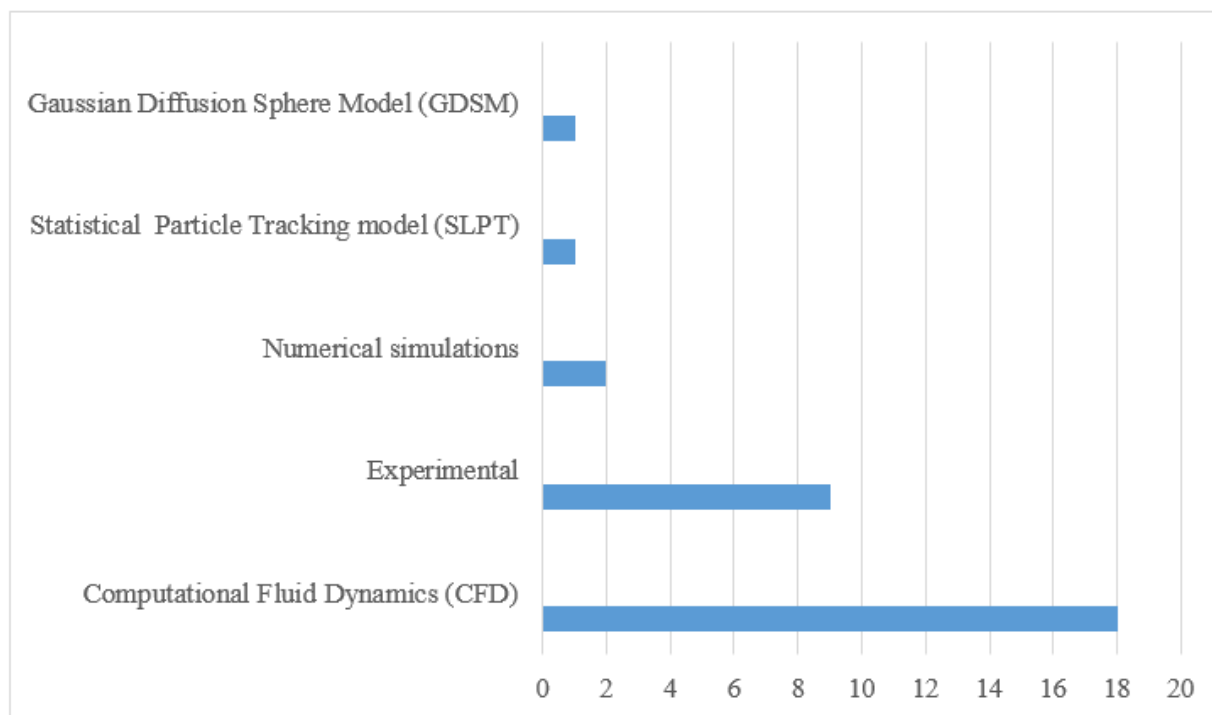


Fig. 2. Frequency of methods for factor optimization in selected studies

Fig. 1 indicates that Computational Fluid Dynamics (CFD) represents the most frequently utilized approach for optimizing airflow and contamination control in clean rooms. The high prevalence of CFD-based studies reflects its unique ability to simulate complex flow patterns, turbulence behavior, and particle transport with a high degree of spatial and temporal resolution. This dominance also highlights the growing reliance on virtual prototyping in contamination control research, where CFD enables researchers to evaluate multiple design scenarios, ventilation strategies, and operational conditions in a cost-effective and non-intrusive manner. Overall, the widespread adoption of CFD underscores its critical role as the primary methodological framework for advancing knowledge and guiding evidence-based design in clean room airflow optimization.

Identified factors

Given that studies have reported heterogeneous

findings regarding airflow management, the results of the present study were organized into four classifications. These classifications included architectural and structural factors (room length, floor height, etc.), ventilation and air flow factors (velocity, air change rate, fan-filter-unit configuration, etc.), environmental and operational factors (activity of personnel, SCARA robot, season etc.), and pollutant characteristics (particle size, and density, etc.).

Architectural and structural factors

Various parameters were identified to control flow and pollution in the architectural and structural factors. The parameters along with their strategies and results are presented in Table 2. A review of the results of studies in the field of architectural and structural factors shows that increasing the perforated floor porosity beyond 25% will increase the deflection and turbulence in the flow. Also, increasing the slot area can reduce vorticity and improve the flow (Table 2).

Table 2. Research on optimization of architectural and structural factors

Parameters	Class	Origin parameter	Strategy	Result	Ref.
Clean room Length	Class 1	6 m	About 116% increase in length	Non uniformity decreased from 13% at 6 m to 5% at 13 m	[17]
Perforated floor porosity	Class 1	25%	32% reducing	Decrease deflection angle about 1.9%	[24]
	ISO 5 (Class 100)	-	100% increase with maximum airflow inclination	Increase deflection angle about 3% Decrease possibility of particle deposition on the product	[12]
Slot areas	Class 1	2374 mm ²	About 141% increase About 270% increase	Smaller circulation zones Smaller circulation zones	[18]
Floor height	Class 1	600 mm	50% increase 33% reduction	Reduction deflection angle (3.5 %) Higher turbulent intensity	[24]
Design of SMIF (Standard Mechanical Interface) enclosures	Class 1	-	Contamination Isolation	Isolate the product from personnel (the primary pollution source)	[15]

Ventilation and air flow factors

Several parameters were identified as critical for regulating airflow patterns and controlling contamination under ventilation and air-flow-related factors. The parameters along with their strategies and results are presented in

Table 3. As presented in Table 3, the results of the studies show that the use of Fan Dry Coil Units (FDCUs), FFU Coverage rate 25%, and centrally positioned fan filter units are effective in improving airflow and controlling pollution.

Table 3. Research on optimization of ventilation and air flow factors

Parameters	Class	Origin parameter	Strategy	Result	Ref.
Flow rate	Class 3	1.5 m ³ /s	40% Reduction	75% reduction in mean air-age	[19]
				Airflow parallelism was improved	
				50% reduction in particle concentration	
Air Exchange Rate (ACH)	Class 6	-	Comparison of increase in ACH in FDCU system and wall-return system	ACH has a more pronounced effect on particle removal in the FDCU system than it does in a wall-return system	[20]
Return air vent design	Class 6-8	Wall return schemes	Fan dry coil units (FDCUs)	About 60% increase in particles elimination	[27]
	Class 6	Wall return schemes	Fan dry coil units (FDCUs)	50% increase in particles elimination	[20]
Number of Fan filter units (FFU)	-	-	Switching off in zone without a particle source	40.6% reduction in air supply volume	[34]
	-	-	Adding two FFUs	Removal time is reduced by 2 to 7 minutes for different velocity	[35]
	ISO Class 6, ISO Class 7	-	Adding six FFUs to both sides of the process area	Eliminated most vortices and resulted in the lowest contaminant concentration contours	[32]
Air velocity	Class 1	0.42 m/s	28% reduction in velocity	Reduction in Turbulent kinetic energy (TKE)	[24]
	-	0.22 and 0.2 m/s	Stable	The final residual count of particles emitted from different surfaces was zero	[35]
	-	0.22, 0.2, 0.18, 0.16, and 0.14 m/s	Stable for each velocity	Residual count of particles released by the worker are completely expelled within the first minute	[35]

Table 3. Continued

Parameters	Class	Origin parameter	Strategy	Result	Ref.
Air velocity	-	0.12	Stable	Takes an additional minute for completely expulsion	[35]
	-	0.22 m/s	36% reduction in velocity	21% increase in stable time (time when the count of resident particles remain unchanged)	[35]
	-	0.22 m/s	45% reduction in velocity	About 64% increase in stable time	[35]
FFU arrangement	Class 10,000	Dispersed fan filter units	Centrally positioned fan filter units	15% reduction in particle concentration	[23]
	ISO 6	-	Horizontal FFU arrangement with 30% coverage	61.52% removal efficiency	[29]
FFU Coverage rate	ISO 5	25%	100% increase	Most subzones remained well protected (with dimensionless concentrations far below 0.2)	[13]
	Class 6	25%	ranging from 25% to 100%	Pollutant removal was optimal at 25%.	[28]
FFUs air speed	Class 1000	0.50 to 0.70 m/s	Reduction (0.35 to 0.65 m/s)	Reduce the particle counts down below the threshold level of class 100 clean room	[16]
Inlet layout and type	-	-	(12 vertically-oriented entrainer air streams (EAS))	73.3% reduction in pollutant during winter	[21]

Environmental and operational factors

The environmental and operational parameters extracted from the studies are presented in

Table 4. Reducing the presence and activity of humans and the activity of robots is one of the most important aspects of control in this field.

Table 4. Research on optimization of environmental and operational factors

Parameters	Strategy	Result	Ref.
Human or personnel	Presence of operator	Creates turbulent flow and increases the number of particles	[25]
SCARA robot velocity	Reduction velocity of robot, Robot's velocity is less than or equal to the supplied air velocity	Increase cleaning performance	[22]
Automatic guided vehicle	Increase velocity	Create recirculation zones and accumulation of pollution	[30]
Season	Solar radiation	During the winter is more marked due to the difference between the surfaces (temperature difference between the building surfaces and the atmosphere). Depending on the pollutant	[21]
Equipment Layout	Far from zone with high airflow inclination	Decrease possibility of particle deposition on the product	[12]
Filtration configuration	Closing the specific ULPA filter interacting with equipment	Elimination of vortex levels dropped to approximately half of their original concentration	[8]

Pollutant characteristics

Particle characteristics is very important in airflow optimization and control, because the outcome of most strategies and different

conditions can depend on this factor. Table 5 presents the most important known parameters along with their strategies and outcomes.

Table 5. Research on optimization of pollutant characteristics

Parameters	Class	Strategy	Result	Ref.
Location of pollutant source	Class 5	Near the clean zone	ACR should increase about 20% (for same velocity of FFUs)	[31]
Particle size of pollutant	-	Particle size ranging from 0.003 to 1.5 μm	Reduces deposition velocity onto an inverted flat surface	[26]
	Class 6-8	FDCU-return ventilation system	Efficient for 1 to 5 μm particles but weak for 0.1 to 1 μm	[27]
Particle size	-	Increase air flow velocity	Increase particle deposition velocity for d_p smaller than about 0.5 μm	[33]
			Independent of the airflow velocity for d_p larger than about 0.5 μm	
Particle density	-	Increase particle density	Increase particle deposition velocity (size larger than 0.1 μm)	[33]
			Particle density was negligible for the particle sizes smaller than about 0.1 μm	
Moving velocity of product	-	About 233% increase in Dimensionless moving velocity of product	About 82% increase in particle deposition velocity of particles (0.1 μm)	[14]

As presented in Table 5, the effect of factors such as return air vent design, and air velocity depends somewhat on the size and density of the particles. It is worth noting, some parameters are completely condition dependent and exact optimal values cannot be determined for them. These parameters and the related conditions will

be discussed.

Discussion

In this systematic review, an attempt has been made to identify and categorize the factors and parameters related to airflow and contamination control in clean rooms of the electronics industry.

Human or personal presence

Human presence and activity significantly influence cleanliness standards, as even minimal movements can disrupt airflow patterns and affect airborne particle concentrations. Yang et al. reported that in biopharmaceutical clean rooms, a single individual can release up to 2,000 particles per cubic meter, emphasizing the need to consider human presence when identifying contamination sources [36]. Both experimental and computational studies demonstrate that human motion destabilizes airflow, as moving individuals generate wake flows that carry and disperse pollution [37, 38].

Fan filter units (FFUs)

The FFU area ratio is a critical determinant of air distribution efficiency and particle control in clean rooms. A comparative study examining FFU coverage ratios of 50% and 25% demonstrated that a 50% ratio maintains stronger airflow isolation, ensuring low contamination levels across most subzones even with reduced air supply. Conversely, at a 25% ratio, lateral particle dispersion increases, leading to higher contamination in adjacent areas. This issue becomes more severe when the contamination source is not located directly beneath the FFU airflow, as a 25% coverage significantly reduces ventilation effectiveness [13]. Increasing FFU coverage minimizes gaps between clean airflow streams, thereby improving contaminant removal efficiency. However, it also raises installation costs and energy consumption. Optimization analyses suggest that a balance can be achieved between safety and cost-effectiveness. One study identified a 30% coverage rate as the optimal value, offering adequate gas leakage control and operator safety. Such multi-criteria optimization approaches can be applied to

various clean room design scenarios [29].

The arrangement of FFUs has a direct impact on airflow patterns within clean rooms. A horizontal FFU layout promotes uniform airflow and the formation of stable clean air curtains, thereby preventing contamination dispersion and improving control efficiency. In contrast, a cross arrangement can cause airflow interference and generate weak or vortical regions that facilitate contaminant spread. Yao et al. reported that, in most cases, a horizontal FFU configuration provides superior performance in maintaining contamination control [29].

FFUs are essential components of clean room ventilation systems, and their operational strategies and airspeed settings play a crucial role in contamination control. Deactivating FFUs in subzones distant from active particle sources is an effective approach to reducing unnecessary airflow. Studies indicate that selectively turning off FFUs in non-contaminant-generating areas can decrease total air supply by up to 40.6%, resulting in significant energy savings without substantially increasing contamination risk [34].

Research suggests that maintaining FFU airflow velocities within the optimal range of 0.35–0.65 m/s effectively minimizes particle concentration [16]. Velocities below this range may fail to sustain adequate unidirectional flow for suppressing particle resuspension, whereas excessive speeds can disrupt laminar flow, generate turbulence, and promote particle dispersion. Moreover, operating above the recommended range increases contamination risk and energy consumption, thereby reducing overall system efficiency.

Clean room dimensions and structure

Recent research indicates that variations in

clean room dimensions significantly influence a key metric of deflection angle from the ideal unidirectional path. The dimensions of the cleanroom process zone—including its length, width, and height—significantly influence the stability of the airflow pattern. Additionally, comparative analyses showed that longer clean rooms ($y = 13$ m) achieved greater flow uniformity (non-uniformity = 5%) than shorter ones ($y = 6$ m, non-uniformity = 13%) [17].

Grid porosity of clean room floors is one of the most influential parameters in this context. Research indicates that increasing the perforation rate from a baseline of 25% to 50% slightly increased the deflection angle (by approximately 3%) and Turbulent Kinetic Energy (TKE), indicating enhanced lateral mixing. Conversely, reducing porosity to 17% led to a decrease in the deflection angle (to about 1.9%) [24]. These findings showed that higher porosity enhances overall airflow evacuation and reduces non-uniformity, but it may also introduce localized turbulence. Another critical floor-related factor is the height of the raised floor, which determines the available space beneath the perforated panels for airflow distribution. Increasing the floor height from 600 mm to 900 mm resulted in a noticeable decrease in deflection angle (by about 3.5%) and a significant reduction in maximum turbulent intensity. On the other hand, reducing the plenum height to 400 mm had adverse effects. It increased the level of turbulence [24].

Airflow specifications

The balance between adequately sweeping particles away and preventing turbulence-driven resuspension is complex and highly velocity-dependent. Decreasing the velocity from a baseline of 0.42 m/s reduced deflection

angles in the primary flow. The results show that reducing air velocity from the baseline of 0.42 m/s to 0.30 m/s decreases the deflection angle by 11%, while increasing velocity to 0.50 m/s raises the deflection angle by 18%. These findings suggest that excessive velocity can introduce unnecessary turbulence, altering the expected downward and unidirectional flow patterns that are paramount for contamination removal [24]. Practical guidelines for clean room velocity optimization also reflect the need for nuanced control. Airspeeds ranging from 0.134 to 0.274 m/s have been investigated for uniform room-wide distribution. In comparison, localized velocities of approximately 0.344 m/s have been recommended directly above pollutant sources to restrict contaminant migration into adjacent clean areas. A velocity of 0.475 m/s is often cited as optimal in highly sensitive environments where contamination control is paramount, balancing cleanliness and energy efficiency. Some specific setups may employ velocities as high as 0.52 m/s, but this entails a substantial increase in energy consumption without proportional contamination control benefits. Crucially, customizing airspeed according to the spatial layout and pollutant source proximity can yield significant resource savings. Studies have shown that spatially differentiated velocities can reduce overall required air volume by 51% to 72% without compromising cleanliness [31]. Modeling outcomes indicate that supplying airflow velocities between 0.2 and 0.6 m/s provide a stable and efficient velocity for contaminant removal, aligning with the findings of Guldana et al., who similarly emphasized the effectiveness of moderate velocities in limiting particle dispersion. The velocity of 0.3 m/s offered the most favorable balance between maintaining cleanliness and

reducing energy use, particularly in facilities where recirculation is restricted for chemical or biological safety. These results reinforce the conclusion that optimized, mid-range velocities can enhance contaminant control without incurring unnecessary operational costs [39]. Airflow rate is among the most influential parameters in determining clean room performance. In a comparative assessment of airflow rates ranging from 1.5 m³/s to 0.9 m³/s, it was found that lower airflow rate led to improved flow parallelism, contributing to a more laminar and predictable airflow pattern. Interestingly, this adjustment also yielded a dramatic decrease in mean air age—from 25 seconds to just 6 seconds, amounting to a 75% reduction. This sharp decline in air age directly translates to faster contaminant removal and improved environmental turnover, both of which are essential in maintaining stringent cleanliness standards. Moreover, particle concentrations under these optimized airflow conditions declined by approximately 50%, with a corresponding 50% reduction in defect rates [19].

System design

Studies have shown that adjusting ACH based on the proximity to pollution sources and critical area can reduce clean air demand by 51% to 72%. This not only improves energy efficiency but also enables more precise airflow control, minimizing turbulence and promoting stable laminar flow. Thus, a well-calibrated ACH system contributes simultaneously to contamination control and the broader objective of airflow optimization in clean room environments [27, 31].

Fan Dry Coil Unit (FDCU)-based return systems have demonstrated markedly better performance than conventional wall-return

setups, eliminating up to 60% more airborne particles and over 50% more submicron particles. This superior performance is linked to the FDCU's capacity to support more controlled and directed return airflow, which mitigates recirculation zones and suppresses undesirable turbulence. Furthermore, FDCU systems help contain thermal plumes, as evidenced by smaller local air temperature index (q) values, thereby stabilizing airflow patterns. These features are central to airflow optimization strategies, as they enhance directional consistency and reduce interference with clean air delivery. By improving both contaminant removal and flow uniformity, FDCU-return systems offer a powerful tool for achieving optimized and resilient airflow dynamics in high-sensitivity clean rooms [20, 27].

Equipment

The motion of robotic systems and automated equipment within clean rooms, such as SCARA robots and Automated Guided Vehicles (AGVs), plays a pivotal role in shaping airflow dynamics and influencing particulate dispersion. Research indicates that reducing the operating velocity of SCARA robots (Robot's velocity is less than or equal to the supplied air velocity) can significantly improve airflow uniformity and enhance surface cleaning performance [22].

Similarly, the movement of AGVs has been shown to create local recirculation zones, especially near the floor, which can trap airborne particles and promote their accumulation [30]. These recirculation zones act as stagnant pockets that disrupt the intended unidirectional airflow, leading to uneven contaminant removal and higher particle residence times. As AGVs move through clean room spaces, the air currents generated in their wake may entrain

particles and carry them beyond controlled areas, undermining the effectiveness of HEPA-filtered ventilation systems.

Also, the findings indicate that the presence and arrangement of interior equipment play a significant role in particle behavior within clean rooms. In particular, the under-table zones and other geometric obstructions were shown to create localized recirculation regions that trap airborne particles and hinder their removal. Such stagnant zones disrupt the intended unidirectional airflow and can become persistent sources of contamination, especially in environments requiring stringent cleanliness levels. These results highlight the importance of carefully designing and positioning equipment to minimize airflow obstruction and prevent the formation of particle-retention areas [39].

Environmental conditions

Solar radiation creates temperature gradients on building surfaces, generating buoyancy-driven convection that destabilizes nearby airflow. These effects intensify in winter due to stronger thermal contrasts, producing vertical currents that disrupt laminar flow near air intakes such as Make-Up Air Units (MAUs). Computational studies on semiconductor facilities show that winter solar radiation induces recirculating vortices around inlets, increasing pollutant residence time and infiltration risk [21].

Pollutant feature

The location and height of the pollution source are critical parameters in determining the trajectory of particle movement within the airflow. A study showed that particles released from a height of 1.5 m (close to equipment surfaces or human activity) have a greater impact on particle concentration at the working level. Moreover, when the particle source is

located directly beneath an FFU, particles are removed more effectively, whereas positioning the source outside the direct airflow zone of the FFU leads to wider contamination spread in adjacent subzones. Therefore, the placement of equipment, potential particle sources, and even staff behavior (such as standing under an FFU or at the edge of the ventilated zone) should be considered in both the design and operation of clean environments to minimize particle dispersion effects [13].

Airflow management is significantly impacted by the spatial relationship between particle sources and the designated clean zones. Findings indicate that when contamination sources are located farther from critical clean zones, maintaining the required cleanliness level becomes less demanding in terms of clean air volume [31]. This outcome is primarily due to the enhanced opportunity for particles to settle or be removed before reaching sensitive areas.

The deposition behavior of airborne particles is intricately tied to their size, particularly when interacting with inverted surfaces. Larger particles (0.003 to 1.5 μm) exhibit a reduced deposition velocity onto inverted flat surfaces. As particle size increases, gravitational pull accelerates downward motion, pulling particles away from inverted surfaces rather than toward them. Moreover, larger particles are less influenced by Brownian motion, further decreasing the likelihood of deposition onto upward-facing areas [26]. This dynamic emphasizes the importance of particle size in contamination modeling and highlights the necessity of targeted airflow strategies to prevent particle accumulation in overhead zones.

Ventilation strategies must be carefully matched to the size range of targeted particles.

Studies reveal that Fan-Driven Ceiling Units (FDCUs) with return air systems show limited effectiveness in controlling fine particles (0.1–1 μm), while demonstrating greater efficacy for larger particles (1–5 μm) (27). The diminished performance for ultrafine particles likely stems from their strong susceptibility to air turbulence and Brownian motion, allowing them to bypass controlled airflow paths and remain suspended for extended periods. In contrast, larger particles, which follow more predictable inertial trajectories, are more readily captured or redirected by ventilation currents. These findings underline the need for multi-modal filtration strategies in clean room environments, particularly in industries like electronics manufacturing, where particle size sensitivity is high. Ventilation systems should be supplemented by localized filtration and directional flow controls to manage diverse particle populations adequately.

Product feature

Surface temperature gradients play a pivotal role in influencing particle deposition dynamics within clean room environments, particularly in high-precision electronic manufacturing processes. The velocity at which airborne particles settle onto surfaces commonly referred to as deposition velocity is highly sensitive to both the temperature of the surface and the surrounding airflow characteristics. Experimental studies have demonstrated that upward movement of substrates such as wafers induces airflow disturbances that intensify particle concentration gradients [14]. This condition significantly increases the deposition velocity, thereby raising the likelihood of contamination on the product surface. In high-sensitivity clean room settings, such as semiconductor fabrication, even minor changes

in vertical airflow can shift particle trajectories and accelerate their deposition on critical surfaces.

Despite extensive research on cleanroom airflow and particle dispersion, a key challenge remains. The interactions among architectural, ventilation, operational, and pollutant-related factors are complex and highly nonlinear, making it difficult to predict contamination outcomes or optimize system performance. To address these challenges, Artificial Intelligence (AI) may be a suitable solution that requires feasibility studies. AI is capable of learning complex relationships from data without prior knowledge [40]. This can be used to classify cleanroom performance levels by combining design and operational factors into cleanliness indices or particle concentration thresholds.

Strengths

This study employed a rigorous and transparent systematic review methodology in accordance with PRISMA principles, which enhanced the reproducibility and credibility of the findings. The current review offers a broad understanding of the complexities involved in clean room air pollution management. A key strength of the research is the development of an integrated classification framework that systematically categorizes influencing factors into architectural–structural, ventilation–airflow, operational–environmental, and pollutant-specific parameters. This multidimensional perspective provides a comprehensive understanding of airflow optimization in electronic-industry cleanrooms, bridging the gap between engineering design variables and contamination control outcomes. Furthermore, the study synthesizes both experimental investigations and computational modeling approaches, including CFD-based analyses,

enabling a balanced evaluation of theoretical predictions and practical performance. The study offers practical approaches to improve cleanroom performance, and achieve more stringent contamination control under real operational conditions. The emphasis on electronic manufacturing environments enhances the practical relevance of the results, particularly for precision fabrication processes where particle control is critical. Finally, the proposed multi-objective framework linking airflow parameters to cleanliness and energy efficiency indicators contributes to sustainable cleanroom design and operation.

Limitations

Our search strategy was developed based on the study objective and recognized guidelines to retrieve the most relevant studies. Only English-language articles were included, which may limit the comprehensiveness of the evidence. The diversity of cleanroom configurations, performance indicators, airflow strategies, and particle measurement techniques across studies also introduced methodological heterogeneity, preventing quantitative meta-analysis and limiting direct comparison of results. The review focused primarily on electronic-industry cleanrooms. While this specialization improves contextual relevance, it restricts the generalizability of findings to other sectors such as pharmaceutical or biomedical cleanrooms, which may exhibit different contamination sources and airflow requirements. Many reviewed studies relied on numerical models or small-scale experimental setups, which may not fully capture real-world operational variability, such as fluctuating production loads or human activity. Finally, potential publication bias cannot be excluded, as only peer-reviewed articles indexed in

selected databases were included, possibly omitting relevant industrial reports.

Future work

Filtration and biofiltration technologies are among the most widely employed methods for pollution control. However, studies in this field are limited for clean rooms in the electronics industry. Therefore, research directions in this field seem necessary. Future studies should further investigate the effects of human movement, occupancy density, surface temperature, and filtration type and layouts under real operating conditions, as well as assess the long-term relationships between airflow behavior and exposure levels. Moreover, similar investigations in clean rooms of other industries such as pharmaceutical, biotechnological, and precision manufacturing sectors, can provide broader insights and support the development of universal guidelines for air pollution control and air quality management. Also, Future investigations should prioritize the evaluation and comparison of energy consumption across a range of cleanroom operating conditions. Machine learning and optimization algorithms can be used to identify optimal configurations of fan-filter units, airflow velocity, and cleanroom geometry based on real-time monitoring data.

Conclusion

This systematic review identified and analyzed the key factors influencing airflow optimization and particle dispersion in electronic-industry cleanrooms. The findings demonstrate that cleanroom performance is governed by the complex interaction of architectural–structural parameters, ventilation design, operational conditions, and pollutant characteristics. Variables such as room geometry, airflow

velocity, air change rate, fan-filter-unit configuration, personnel and robotic activity, and particle size distribution collectively determine airflow stability, contaminant transport, and energy consumption.

The evidence indicates that improving cleanroom performance cannot rely on a single parameter or isolated engineering modification. Instead, effective contamination control requires an integrated, multi-objective approach that simultaneously considers cleanliness level, energy efficiency, and process reliability. Optimization strategies should therefore combine appropriate cleanroom dimensions, optimized airflow distribution, advanced filtration systems, and controlled operational practices to achieve stable airflow patterns and reduced particle dispersion.

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Competing interests

The authors declare that they have no competing interests.

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Ethical considerations

Ethical issues (Including plagiarism, Informed Consent, misconduct, data fabrication and/

or falsification, double publication and/ or submission, redundancy, etc.) have been completely observed by the authors.

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