# Real-Time LEV Sensor Monitoring for Fume Hood Safety and Performance: A Case Study at the Department of Chemistry, Malaysia Headquarters

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## ABSTRACT

Fume hoods are primary engineering controls for reducing laboratory personnel exposure to hazardous airborne chemicals; however, their effectiveness can be compromised by delayed, manual, and inconsistent airflow monitoring that allows abnormal operating conditions to persist. This study reports the deployment and evaluation of an automated Local Exhaust Ventilation (LEV) monitoring system across 43 chemical fume hoods at the Department of Chemistry, Malaysia Headquarters. The system provided continuous, real-time monitoring of ventilation parameters and incorporated chemometric analysis using Principal Component Analysis (PCA) and Linear Discriminant Analysis (LDA) to detect and classify operational anomalies. Performance was validated against handheld anemometer measurements ($n = 215$), showing strong agreement ($R^2 = 0.98$) and low mean error (0.012 m/s). Following implementation, anomaly detection lag decreased from an average of 14.5 hours to less than two minutes, and operational uptime increased to 99.5%. Optimized airflow control was associated with a 35% reduction in energy consumption. Cost–benefit analysis estimated a payback period of 2.2 years with projected annual savings of RM 274,250. User surveys indicated increased confidence in laboratory safety, system transparency, and compliance documentation. Overall, these findings support automated LEV monitoring as a practical approach to strengthening laboratory safety management, operational efficiency, and sustainability, with potential applicability to broader laboratory settings in Malaysia.

**Keywords**: Automation, Chemical Laboratory, Fume Hood, Local Exhaust Ventilation, Safety Monitoring

## INTRODUCTION

Fume hoods are vital engineering controls in chemical laboratories, designed to minimize occupational exposure to toxic vapors, gases, and aerosols. Their effectiveness depends on maintaining consistent face velocity and exhaust airflow, traditionally verified through periodic manual monitoring using handheld anemometers. In Malaysia, reliance on manual spot checks can present operational challenges, including inconsistent measurements, delayed identification of ventilation failures, and incomplete compliance documentation. Such limitations conflict with risk-based and preventive occupational safety and health management principles emphasized in ISO 45001:2018 (International Organization for Standardization [ISO], 2018) and with regulatory expectations enforced by the Department of Occupational Safety and Health (DOSH), Malaysia.

At the Department of Chemistry, Malaysia Headquarters, limitations in monitoring resources and inspection frequency constrained routine verification of fume hood performance. To address these gaps and support systematic performance monitoring, an automated Local Exhaust Ventilation (LEV) monitoring system was implemented to enable continuous data acquisition and real-time assessment of ventilation conditions. Automated LEV monitoring supports early anomaly detection, preventive maintenance, and auditable documentation aligned with occupational safety management and regulatory oversight.

This study reports a case study on the deployment of an automated LEV monitoring system across chemical fume hoods at the Department of Chemistry, Malaysia Headquarters. The objectives were to: (1) evaluate the accuracy of automated sensors against manual anemometer readings, (2) apply chemometric tools for anomaly detection and classification, (3) assess operational improvements in detection time, uptime, and energy use, (4) conduct a cost–benefit analysis of automated versus manual monitoring, and (5) evaluate user perceptions and implications for laboratory safety management and national policy.

The use of Principal Component Analysis (PCA) and Linear Discriminant Analysis (LDA) for multivariate pattern recognition and classification has been previously demonstrated by the authors in related analytical contexts. In forensic chemistry, these techniques were applied to discriminate gasoline residue matrices with up to 98% correct classification using chromatographic data combined with chemometrics (Mahat et al., 2023). Similarly, application of PCA and LDA to multi-element profiles of Malaysian stingless bee honeys achieved high classification accuracy and established geographical provenance (Shadan et al., 2018; Dzolin et al., 2023). These studies provide an analytical foundation for extending chemometric methods to real-time ventilation monitoring in laboratory safety systems.

## METHOD

### System Implementation

The project involved retrofitting 43 chemical fume hoods and 67 associated ducting systems with multiparameter sensors distributed across three building levels. Each installed unit continuously measured total pressure, static pressure, duct velocity, and face velocity at one-minute intervals. Sensor outputs were transmitted to a centralized server for secure storage, real-time visualization, and compliance reporting. The system architecture was designed to integrate with the existing laboratory information technology infrastructure and to support authenticated access to dashboards, automated alarm notifications, and historical trend review.

### Validation Study

To assess measurement accuracy, 215 paired observations were obtained by collecting readings from the automated sensors and a handheld anemometer across the monitored fume hoods. Agreement between methods was evaluated using correlation analysis, mean absolute error (MAE), and Bland–Altman analysis. This validation approach was used to determine whether the automated measurements were comparable to conventional manual readings and remained within acceptable accuracy expectations for ventilation performance monitoring.

### Chemometric Analysis

The chemometric workflow applied in this study follows established Principal Component Analysis (PCA) and Linear Discriminant Analysis (LDA) methodologies previously used by the authors for multivariate classification of complex analytical datasets (Shadan et al., 2018; Mahat et al., 2023; Dzolin et al., 2023). In those applications, PCA was used to reduce dimensionality and reveal dominant patterns, while LDA enabled supervised classification into predefined categories with high predictive performance. In the present work, the same framework was adapted to multivariate ventilation sensor data to support anomaly detection and operational state classification.

PCA was performed to reduce dimensionality and to identify multivariate patterns associated with deviations in ventilation performance, with the first two principal components accounting for more than 78% of the total variance. LDA was subsequently used to classify abnormal operating conditions into predefined categories, including filter clogging, fan failure, sash misuse, and sensor drift. Statistical significance was evaluated using chi-square testing with $\alpha = 0.01$. Chemometric methods were selected because ventilation performance is inherently multivariate and may exhibit subtle, correlated shifts that are not readily captured by univariate threshold approaches.

### Operational and Economic Assessment

Operational performance was monitored over a four-month period to quantify changes in anomaly detection time, downtime, operational uptime, and energy consumption following implementation. A cost–benefit analysis was conducted to compare automated and manual monitoring approaches, incorporating capital costs, operating and maintenance costs, labor requirements, downtime impacts, and energy-related savings. These inputs were used to estimate the return on investment (ROI) and the payback period.

**User Feedback**

User perceptions were assessed through a survey of laboratory personnel (n = 87) following system deployment. participants included chemists, technical staff, and laboratory assistants. the questionnaire combined likert-scale items with open-ended questions to capture both quantitative ratings and qualitative feedback related to perceived safety, confidence in ventilation performance, and operational convenience.

# RESULTS

**Accuracy of Automated Sensors**

Automated sensor measurements showed strong agreement with handheld anemometer readings ($R^2 = 0.98$; MAE = 0.012 m/s). Agreement was consistent across the observed airflow range, indicating stable measurement performance under typical operating conditions. These findings support the suitability of the automated monitoring system as an alternative to periodic manual measurements for routine fume hood airflow verification.

**Anomaly Detection with Chemometrics**

Over the four-month monitoring period, 103 ventilation anomalies were identified. PCA indicated distinct clustering patterns associated with abnormal operating conditions. As shown in Figure 1, anomaly classes formed separated groupings in the PC1–PC2 score space, suggesting that the multivariate sensor signals captured differentiable anomaly signatures. LDA further classified anomalies with an overall accuracy of 99% ($p < 0.01$), with clear class separation observed in the discriminant space (Figure 2).

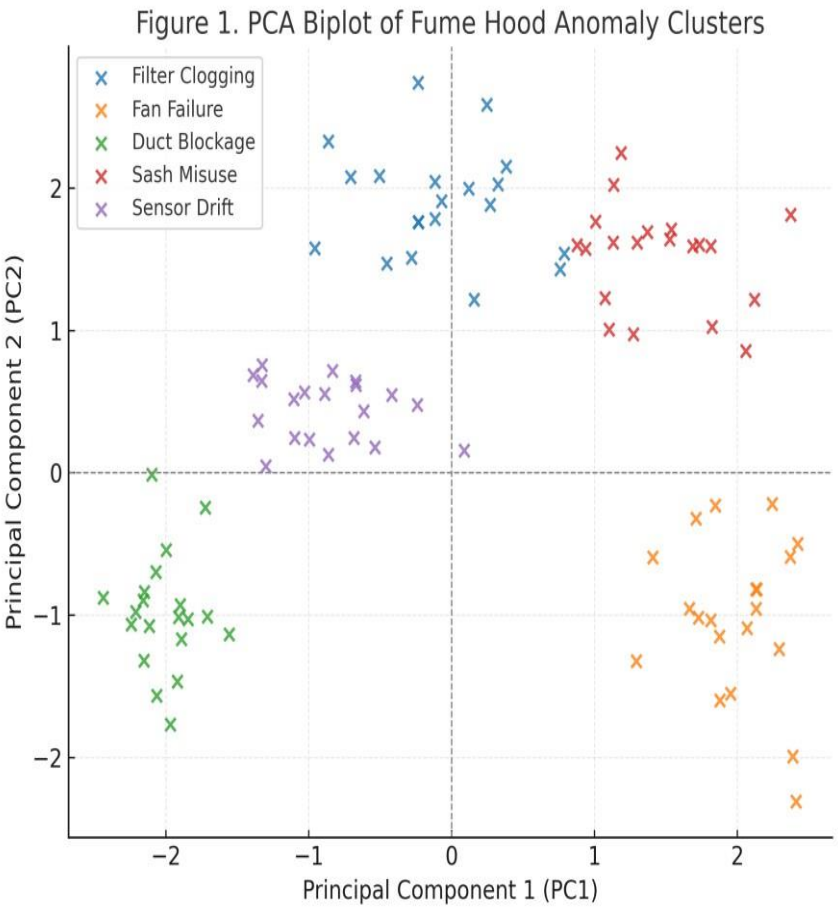


Figure 1: PCA biplot showing clustering of airflow anomaly types (PC1 vs PC2).

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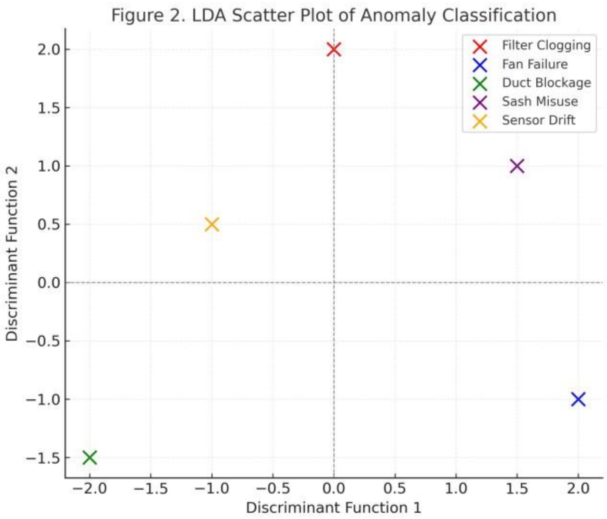


Figure 2: LDA scatter plot demonstrating clear separation of anomaly classes.

## Operational Performance

Detection lag decreased from an average of 14.5 hours under manual monitoring to less than 2 minutes with automated monitoring. Operational uptime increased from 92% to 99.5% over the observation period. In addition, optimized sash monitoring was associated with a 35% reduction in energy use relative to the baseline. Collectively, these improvements indicate enhanced responsiveness to ventilation faults and more stable ventilation availability for routine laboratory operations.

Table 1 Performance comparison of manual and automated fume hood monitoring.

| Parameter | Manual Monitoring | Automated Monitoring |
|---|---|---|
| Measurement Frequency | Monthly checks | Every 60 seconds |
| Detection Lag | 14.5 hours | <2 minutes |
| Uptime | 92% | 99.5% |
| Anomaly Detection | Reactive | Predictive (PCA/LDA) |
| Data Recording | Paper logs | Digital database |
| Energy Consumption | Baseline | -35% |
| Payback Period | - | 2.2 years |

## Economic Outcomes

The automated monitoring system required an initial capital investment of RM 602,930 and an estimated annual maintenance cost of RM 18,500. Based on the cost–benefit model applied in this study, the payback period was estimated at 2.2 years, with projected annual savings of RM 274,250 thereafter. These findings indicate that automated ventilation monitoring can provide measurable operational value in addition to safety and compliance benefits.

## User Perceptions

Survey responses indicated increased user confidence in laboratory safety following system deployment, including perceived reassurance during handling of hazardous chemicals. participants also highlighted the practical value of real-time alerts for improving situational awareness and facilitating timely responses to ventilation anomalies. Qualitative comments emphasized improved transparency of hood performance status and greater trust in laboratory safety infrastructure.

# DISCUSSION

This study indicates that automated lev monitoring can improve ventilation management relative to periodic manual checks by providing continuous measurement, faster identification of abnormal conditions, and comprehensive digital records. These functions are consistent with riskbased and preventive occupational safety and health management principles emphasized in iso 45001:2018 (international organization for standardization [iso], 2018). In the malaysian context, where laboratory safety practice gaps have been reported in survey-based assessments of laboratory staff, strengthening monitoring approaches may contribute to more consistent implementation of safe work systems (che hassan et al., 2017).

Beyond basic threshold alarms, the integration of pca and lda provided multivariate diagnostic capability for distinguishing anomaly patterns and classifying ventilation states. similar to prior research showing that fume hood monitoring interventions (e.g., motion and sash height alarms) can improve response and user behavior, the present study extends ventilation monitoring by applying chemometric analytics to support anomaly categorization and targeted response actions (kongoletos et al., 2021). The strong classification performance observed here is also consistent with the authors' previous applications of pca and lda to chemically complex datasets, including chromatographic gasoline residue profiles and multielement honey provenance classification (shadan et al., 2018; mahat et al., 2023; dzolin et al., 2023).

From a compliance perspective, automated, time-stamped datasets strengthen audit readiness by enabling traceable evidence of performance checks, alarm events, and corrective actions. this aligns with regulatory oversight expectations associated with lev system design, inspection, testing, and examination in malaysia, as reflected in dosh guidance for lev systems. Compared with manual recordkeeping, digital monitoring can reduce documentation gaps and improve consistency in compliance reporting, particularly in facilities managing many hoods with limited inspection resources.

Operationally, the observed reductions in detection lag and the increase in uptime suggest improved responsiveness and continuity of ventilation availability. in settings where laboratory throughput supports timesensitive forensic, environmental, and regulatory activities, improved ventilation reliability may reduce workflow disruption and support safer routine operations. in addition, the associated reduction in energy use is consistent with the broader understanding that laboratory ventilation is a major contributor to facility energy demand, and that improved sash management and airflow control can materially affect energy consumption (kongoletos et al., 2021).

Economic results further support adoption considerations. while capital expenditure can be substantial, the modeled payback period and projected savings suggest that automated monitoring may offer operational value beyond compliance, particularly when labor, downtime, and energy impacts are included in the cost basis. However, the transferability of economic outcomes depends on site-specific factors such as hood inventory, hvac design, energy tariffs, staffing models, and maintenance capacity.

Several limitations should be acknowledged. first, the study was conducted at a single facility, and ventilation configurations, usage patterns, and maintenance practices may differ across laboratories. second, sensor drift may become more significant over longer durations and should be managed through calibration and verification planning. third, the chemometric models were developed using four months of data; longer deployments are needed to evaluate model stability across seasonal variation, operational changes, and evolving failure modes. Future work could evaluate additional modeling approaches (e.g., machine learning classifiers) and compare performance, interpretability, and maintenance requirements under extended real-world operation.

In summary, the findings support the practical value of automated lev monitoring for improving ventilation performance visibility, supporting riskbased safety management aligned with iso 45001:2018, and strengthening auditable documentation relevant to dosh expectations for lev systems.

# CONCLUSION

Automated LEV monitoring improved fume hood performance management by enabling accurate, real-time airflow measurement and multivariate anomaly classification. In this case study, implementation of continuous monitoring was associated with higher operational uptime, substantially reduced detection delays, and improved availability of time-stamped records to support safety management and regulatory oversight. Economic evaluation further indicated favorable cost recovery under the assumptions applied. Overall, the findings support broader consideration of automated LEV monitoring for laboratories seeking to strengthen occupational safety and health controls in alignment with DOSH oversight and ISO 45001:2018 principles.

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