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Smart Fume Detection, Extraction, and Filtration System for CNC Laser Machines

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ABSTRACT

This study developed and evaluated a Smart Fume Detection, Extraction, and Filtration System for CNC Laser Machines at Cebu Technological University–Argao Campus to improve airborne contaminant management during laser cutting and engraving. Anchored in the Cyber-Physical Machine Tool framework, sensor-based monitoring, airflow and filtration principles, Sustainable Manufacturing, and Garvin's Eight Dimensions of Quality, the study employed a developmental research design. The prototype integrated MQ-4 and MQ-135 sensors, microcontroller-based control, automated ventilation, warning mechanisms, digital monitoring, and multistage filtration. Data were collected through 20 controlled operational trials involving plywood and acrylic specimens, technical measurement instruments, observation logs, and questionnaire evaluations from 100 purposively selected respondents. Descriptive statistics and inferential tests assessed technical performance, material-based differences, and contaminant reduction. Results demonstrated 91.7% detection accuracy, 91.2% sensor reliability, a 4.28-second response time, 53.9 CFM extraction airflow, and 77.4% filtration efficiency, meeting all established benchmarks. Mean measured fume concentration decreased significantly from 393.29 ppm to 88.97 ppm, representing a 77.38% reduction ($p < 0.0001$). Significant differences between plywood and acrylic were observed in detection accuracy, response time, airflow, and fume concentrations, but not in sensor reliability or filtration efficiency. The prototype obtained an overall quality rating of 3.82, interpreted as Reliable. Further sensor calibration, extended testing, and contaminant-specific occupational safety validation are recommended. The study supports Sustainable Development Goals 3, 4, 8, 9, and 12 through occupational health, technical education, safer working conditions, industrial innovation, and responsible production. Its sustainability contribution includes improved fume management, adaptable automation, and institutional operating and maintenance guidance, subject to further validation before broader implementation.

Keywords: *Air Filtration, CNC Laser Machines, Fume Detection, Occupational Safety, Sensor Reliability, Smart Monitoring, Sustainable Manufacturing, Ventilation System*

1. INTRODUCTION

The advancement of Industry 4.0 has accelerated the adoption of automation, intelligent sensing, and digitally controlled manufacturing technologies. Computer Numerical Control (CNC) laser machines support precise and efficient material processing; however, laser cutting and engraving generate airborne contaminants that require appropriate environmental and occupational safety controls. Soori et al. (2024) emphasized the importance of integrating technological efficiency with personnel safety and environmental responsibility, while Ahmed et al. (2025) highlighted the accuracy and operational reliability of CNC laser systems. Despite these technological developments, conventional CNC laser exhaust systems primarily remove contaminated air without necessarily providing real-time fume monitoring, automated extraction control, and integrated filtration. This limitation establishes the need for an intelligent auxiliary system that can detect changes in fume concentration, activate appropriate ventilation responses, and reduce airborne contaminants. This study focuses on the development and evaluation of a Smart Fume Detection, Extraction, and Filtration System for CNC Laser Machines at Cebu Technological University Argao Campus. The system integrates sensors, microcontroller-based control, automated extraction, warning mechanisms, digital monitoring, and filtration into an aftermarket prototype designed to complement existing CNC laser equipment. Its technical performance and overall quality are evaluated to establish a basis for safer, more controlled, and environmentally responsible laser-processing operations.

Research Problem

CNC laser cutting and engraving produce smoke, particulate matter, vapors, and gaseous contaminants through the thermal decomposition of processed materials. The composition and concentration of these emissions depend on material properties, laser power, cutting speed, and operating conditions. Research on CNC laser technologies has largely emphasized machining accuracy, processing efficiency, and material quality. Anrinal et al. (2022) demonstrated the integration of mechanical and electronic systems in automated CNC laser fabrication, while Anrinal et al. (2023) and Hadi Nurwahyudin et al. (2025) examined laser-processing performance and material characteristics. These developments highlight the need for complementary research addressing airborne emissions during CNC operations. Although conventional exhaust mechanisms provide ventilation, they may lack continuous fume detection, automatic threshold-based activation, and filtration performance monitoring. Advanced commercial systems may also involve substantial acquisition and maintenance costs, creating a need for accessible auxiliary solutions. Sneineh et al. (2025) emphasized the growing relevance of cost-conscious CNC technologies, supporting the development of practical and adaptable engineering systems. The central research problem concerns the design, integration, and technical evaluation of a smart fume-control system capable of supplementing existing CNC laser ventilation. Specifically, the study addresses the technical requirements for fume detection, automatic ventilation, filtration, warning, and digital monitoring; the prototype's detection accuracy, sensor reliability, response time, extraction airflow, and filtration efficiency; differences in measured operating safety conditions before and after system integration; and the prototype's overall quality based on Garvin's Dimensions of Quality. The study also addresses the need for an Operation, Safety, and Maintenance Standards Manual to guide system operation, inspection, maintenance, and safe integration. The developed prototype is intended as a supplementary engineering control rather than a replacement for established occupational safety procedures or manufacturer-prescribed ventilation systems.

Assumptions of the Study

The study is guided by the assumption that airborne emissions generated during CNC laser cutting and engraving can be monitored through appropriate gas or air-quality sensors and that

changes in sensor measurements can initiate automated extraction and warning responses. It further assumes that integrating detection, extraction, and filtration into a coordinated system can improve fume management compared with relying solely on conventional exhaust arrangements. The proposed system operates on the principle that microcontroller-based monitoring can translate sensor measurements into predetermined control actions. Sensor readings exceeding programmed thresholds are expected to activate the extraction mechanism and warning functions, while the filtration assembly is intended to reduce measured airborne contaminants before discharge. The application of accessible electronic components and automated control is supported by related developments in sensor-based systems (Subagyo & Prasetyaningrum, 2024), computerized control applications (Katduang et al., 2024), and prototype integration (Das et al., 2024). The study also assumes that measurable indicators, including detection accuracy, sensor reliability, response time, extraction airflow, filtration efficiency, and changes in fume concentration, provide an objective basis for evaluating prototype performance. Operational testing using plywood and acrylic specimens allows the system to be assessed under selected laser-processing conditions. These assumptions are limited to the technical functions and conditions investigated. Sensor readings alone cannot establish compliance with contaminant-specific occupational exposure limits, and the prototype does not replace comprehensive workplace safety measures.

Objectives of the Study

The primary objective of this study is to design, construct, integrate, and technically evaluate a Smart Fume Detection, Extraction, and Filtration System for CNC Laser Machines at the FabLab of Cebu Technological University Argao Campus during 2026. Specifically, the study aims to determine the technical design requirements for fume detection, automatic ventilation, filtration, warning, and digital monitoring; develop and integrate an aftermarket auxiliary prototype with an existing CNC laser machine; and evaluate its detection accuracy, sensor reliability, detection response time, extraction airflow, and filtration efficiency. The study further aims to determine whether statistically significant differences exist in measured fume concentration, airborne contaminant reduction, and operating safety conditions before and after system integration. It also evaluates prototype quality in terms of performance, features, reliability, conformance, durability, serviceability, aesthetics, and perceived quality, consistent with Garvin (1987). Finally, the study seeks to develop an Operation, Safety, and Maintenance Standards Manual based on its findings to guide proper operation, inspection, maintenance, troubleshooting, and technical use of the system.

Conceptual and Theoretical Framework

The study is anchored in the Cyber-Physical Machine Tool (CPMT) framework, sensor-based monitoring and detection principles, airflow and filtration principles, Sustainable Manufacturing, and Garvin's Dimensions of Quality. These foundations explain the integration of intelligent sensing, automated control, mechanical extraction, filtration, and technical quality evaluation within an auxiliary CNC laser safety system. The CPMT framework emphasizes the integration of physical machinery with computational technologies, sensors, and automated feedback mechanisms. Kaarlela and Outeiro (2025) explained that cyber-physical systems support real-time monitoring and adaptive machine control, while Ameer and Fatahi Valilai (2025) highlighted the importance of converting operational data into actionable information. In this study, sensors monitor fume conditions, a microcontroller interprets measurements, and connected actuators initiate extraction and warning responses. Sensor-based monitoring and detection principles support the conversion of environmental conditions into measurable electrical signals. Çekik and Turan (2025) demonstrated the application of sensor-based analysis in identifying abnormal CNC operating conditions. The present study applies continuous monitoring and threshold-based control rather than predictive machine-learning techniques. Airflow and filtration

principles explain the movement and treatment of contaminated air. Extraction performance depends on fan capacity, pressure differences, duct configuration, and filtration resistance, while filtration effectiveness depends on contaminant characteristics, filter media, and airflow conditions. These principles establish the basis for evaluating extraction airflow, response time, and contaminant reduction. Sustainable Manufacturing principles support the integration of environmental protection, operational efficiency, and workplace safety. Soori et al. (2024) emphasized the need to consider environmental and economic factors alongside manufacturing performance. The proposed system applies these principles through automated fume management and the potential reduction of unnecessary continuous ventilation. Prototype quality is evaluated using Garvin's Dimensions of Quality. Garvin (1987) identified performance, features, reliability, conformance, durability, serviceability, aesthetics, and perceived quality as complementary dimensions of product quality. These dimensions provide a comprehensive basis for assessing the prototype beyond its measured technical performance. Conceptually, the study follows an input-process-output framework. Inputs include sensors, microcontrollers, extraction hardware, filtration media, technical requirements, and CNC laser operating conditions. The process involves system design, construction, integration, fume detection, automated extraction, filtration, and technical evaluation. The expected outputs comprise a functional prototype, verified performance measurements, quality assessments, and operational safety and maintenance guidelines. The study is also guided by Philippine environmental, occupational safety, and fire-protection legislation. The Philippine Clean Air Act provides the regulatory basis for controlling air pollution (Republic Act No. 8749, 1999), while occupational safety requirements support the identification and control of workplace hazards (Republic Act No. 11058, 2018). The revised implementing regulations strengthen occupational safety implementation (Department of Labor and Employment, 2025). Workplace environmental measurement principles further emphasize the need for contaminant-specific assessments (Occupational Safety and Health Center, 2026), while fire-safety requirements guide the safe integration of electrical, mechanical, and filtration components (Republic Act No. 9514, 2008). Collectively, these theoretical, conceptual, and regulatory foundations support the development of a measurable, responsive, and technically assessable auxiliary fume-control system for CNC laser operations.

Sustainable Development Goal and Multidisciplinary Sustainability Relevance

The study aligns with selected United Nations Sustainable Development Goals (SDGs) through its emphasis on occupational health, quality education, technological innovation, environmental protection, and responsible manufacturing practices. In relation to SDG 3 (Good Health and Well-Being), the study supports the development of an engineering control intended to reduce airborne contaminants generated during CNC laser operations through real-time fume detection, automated extraction, and filtration, thereby contributing to improved environmental conditions for machine operators, laboratory personnel, and students while complementing existing occupational safety measures without independently establishing compliance with occupational exposure limits. For SDG 4 (Quality Education), the study contributes to safer technical education and practical training environments by introducing an auxiliary fume-management system within the university Fabrication Laboratory (FabLab) and demonstrating the application of sensors, microcontroller programming, automated control, and filtration technologies in industrial technology education. In support of SDG 8 (Decent Work and Economic Growth), the proposed system promotes safer working conditions by addressing airborne hazards associated with laser cutting and engraving, while its auxiliary configuration may serve as a practical technical reference for small-scale fabrication shops and local artisans seeking to improve workplace fume management. Regarding SDG 9 (Industry, Innovation and Infrastructure), the study advances industrial innovation by integrating intelligent sensing, automated ventilation, digital monitoring, and filtration into an aftermarket system compatible

with existing CNC laser infrastructure, demonstrating how accessible and adaptable technologies can enhance manufacturing equipment without fundamentally modifying its primary functions. Furthermore, SDG 12 (Responsible Consumption and Production) is supported through the controlled extraction and filtration of process-generated emissions and the potential reduction of unnecessary continuous ventilation through threshold-based operation, although actual energy savings require separate measurement. These contributions reflect Sustainable Manufacturing principles that emphasize environmental responsibility, operational efficiency, and workplace safety. From a multidisciplinary perspective, the study addresses environmental sustainability through localized contaminant management and filtration; public health and occupational sustainability through improved fume detection and control; technological sustainability through adaptable, microcontroller-based engineering solutions; and educational and institutional sustainability through safer laboratory operations and the development of technical operating and maintenance guidelines. Overall, the study demonstrates how intelligent environmental-control technologies can contribute to safer, more efficient, and environmentally responsible CNC laser operations by providing a technically evaluated auxiliary fume-management system and practical operational guidance, while recognizing the need for further technical validation, contaminant-specific assessment, and long-term performance evaluation before broader workplace implementation.

2. METHODOLOGY

Research Design

The study utilized a developmental research design involving the systematic creation, testing, refinement, and evaluation of a functional engineering prototype. This design was appropriate because the research required translating technical specifications into an operational system through iterative development and empirical testing. The research followed an input-process-output framework. Inputs included technical specifications, fume sensors, microcontrollers, extraction hardware, filtration materials, monitoring components, and applicable safety requirements. The development process involved system design, assembly, integration, calibration, operational testing, and refinement. The resulting prototype incorporated real-time fume detection, automatic ventilation, filtration, warning, and digital monitoring functions. Its technical performance and quality were evaluated to determine its suitability as an auxiliary fume-control system for existing CNC laser equipment.

Research Locale or Study Setting

The study was conducted at the Fabrication Laboratory (FabLab) of Cebu Technological University–Argao Campus, located at Ed Kintanar Street, Lamacan, Argao, Cebu, Philippines. The laboratory provided the CNC laser equipment, electrical infrastructure, and technical environment necessary for prototype assembly, integration, and evaluation. Ahmed et al. (2025) emphasized the growing relevance of compact and affordable digital manufacturing systems for educational applications, while Katduang et al. (2024) highlighted the accessibility of low-cost CNC technologies in vocational training. The laboratory environment accommodated controlled laser cutting and engraving trials using 3-mm-thick plywood and acrylic specimens to generate representative airborne emissions. Subagyo and Prasetyaningrum (2024) explained that thermal material removal during laser processing can produce burning and undesirable emissions. The testing environment therefore allowed observation of the prototype's detection, extraction, and filtration functions under simulated fabrication conditions. The facility also provided a controlled setting for evaluator assessments of prototype functionality, quality, and operational reliability. Das et al. (2024) emphasized the importance of effective component integration in translating digital instructions into physical responses, while Soori et al. (2024) underscored the importance of personnel safety in sustainable manufacturing.

Participants or Data Sources

The study involved 100 purposively selected respondents affiliated with Cebu Technological University Argao Campus. The proposed respondent distribution comprised 10 FabLab personnel and CNC operators, 10 technical or IT personnel, 30 faculty and staff, and 50 students. Participants were selected based on their knowledge, technical expertise, or direct experience with FabLab operations, CNC laser equipment, electronic systems, automation, or related laboratory activities. Purposive sampling was employed to obtain informed assessments of the prototype's functionality, usability, and quality. Wang et al. (2025) highlighted systematic expert assessment in identifying machine-tool performance characteristics. The sampling discussion also identified healthcare personnel and university administrators as relevant evaluator categories, particularly for health precautions and institutional implementation. Soori et al. (2024) emphasized personnel health in sustainable machining, while Katduang et al. (2024) discussed the importance of technical and institutional support for accessible CNC technologies. Eligible participants were required to have relevant institutional affiliation, technical or operational familiarity, and voluntary consent. Individuals lacking relevant experience, declining participation, directly involved in prototype development where conflicts of interest could arise, or submitting substantially incomplete evaluations were subject to exclusion. Technical data were obtained through repeated CNC laser trials using plywood and acrylic specimens under controlled operating conditions. The sampling approach considered systematic variation in testing parameters, consistent with the Latin Hypercube Sampling approach discussed by Schmitt et al. (2024). Li and Liu (2024) emphasized the importance of consistent detection accuracy in evaluating manufacturing technologies.

Research Instruments or Materials

The study utilized technical measurement instruments and a researcher-developed evaluation questionnaire. The technical instruments included MQ-series gas and fume sensors, an external reference air-quality measuring device, an airflow measuring instrument such as an anemometer, a stopwatch or digital timer, and a structured technical observation log. These instruments measured detection accuracy, sensor reliability, response time, extraction airflow in cubic feet per minute (CFM), and filtration efficiency. The prototype incorporated a microcontroller-based control system, extraction fan or blower, ducting, filtration media, warning mechanism, digital display, and supporting electronic components. It was designed as an aftermarket auxiliary device connected to the existing CNC laser machine through its designated exhaust interface. The system operated through three interconnected stages: sensor-based fume detection, automated extraction, and filtration before air discharge. The microcontroller processed sensor signals and activated the appropriate ventilation and warning functions when predetermined thresholds were reached. The technical observation log recorded operating conditions, material specimens, sensor and reference readings, detection status, response time, alarm activation, airflow, contaminant measurements, and repeated-trial observations. Sensor accuracy was established through comparison with reference measurements, while reliability was assessed through repeated detection trials, including correct detections, false positives, and false negatives. A researcher-made questionnaire assessed functionality, usability, and prototype quality using a five-point Likert scale. Its quality indicators were based on Garvin (1987), covering performance, features, reliability, conformance, durability, serviceability, aesthetics, and perceived quality. The questionnaire distinguished subjective evaluations from objective technical measurements, with additional quality indicators grounded in Garvin's framework (Garvin, 1987). The research instruments were subjected to expert content validation to establish clarity, relevance, and technical appropriateness. The questionnaire was also intended for pilot testing with comparable respondents outside the final sample, with internal consistency assessed through an appropriate reliability measure such as Cronbach's alpha.

Data Gathering Procedure

Data collection involved preliminary preparation and calibration, controlled operational testing, evaluator assessment, and post-testing data consolidation. Before testing, the researchers secured institutional authorization, inspected the prototype, and verified the operation of its sensors, microcontroller, extraction mechanism, filtration assembly, warning system, and digital monitoring components. Initial calibration established baseline air-quality measurements under normal laboratory conditions. MQ-series sensor readings were compared with an external reference instrument to determine detection thresholds and evaluate measurement consistency. Repeated trials assessed correct detections, missed detections, false activations, and response time. Signal-filtering procedures, including moving-average filtering, persistence requirements, and hysteresis where applicable, were considered to minimize fluctuations and unnecessary activation. Calibration settings were adjusted before formal testing and documented for consistent application. Operational testing involved controlled CNC laser cutting and engraving using plywood and acrylic specimens. Fume measurements were first obtained under baseline and no-filtration conditions, followed by comparable trials with the developed system activated. Sensor readings and reference measurements were recorded before, during, and after filtration. The researchers also measured extraction airflow, detection response time, warning activation, and system operation using standardized technical observation procedures. Filtration efficiency was determined by comparing contaminant measurements obtained without filtration and under corresponding filtration conditions. Repeated trials were conducted to evaluate consistency across materials and operating conditions. Sensor reliability was further examined through true-positive, true-negative, false-positive, and false-negative classifications, with possible variations caused by sensor drift, environmental interference, or threshold settings documented. Following technical testing, qualified respondents observed the operating prototype and completed the researcher-developed evaluation questionnaire. Their assessments covered functionality, usability, and the applicable dimensions of prototype quality. Completed questionnaires and technical observation records were checked, coded, organized, and consolidated for statistical analysis. The resulting evidence supported the evaluation of the developed system and preparation of its proposed Operation, Safety, and Maintenance Standards Manual.

Data Analysis

The collected data were analyzed using descriptive and inferential statistical methods. Technical performance measurements were summarized to determine detection accuracy, sensor reliability, response time, extraction airflow, filtration efficiency, and contaminant reduction. Detection accuracy was determined from the proportion of correct classifications, while false-positive and false-negative rates were examined to assess sensor dependability. Filtration efficiency was calculated from the percentage reduction in measured contaminant concentration between comparable no-filtration and filtration conditions. Weighted mean and standard deviation were used to analyze respondents' evaluations of prototype functionality, usability, and quality. The weighted mean determined the overall rating for each indicator and quality dimension, while standard deviation described variation in evaluator responses. A five-point Likert scale, with numerical ratings ranging from 1 to 5, was used to interpret the assessments. Grand mean scores provided an overall measure of evaluated prototype quality. A paired-samples t-test was specified to determine significant differences in contaminant concentrations before and after filtration under comparable conditions. The analysis considered the paired structure of observations, independence between pairs, quantitative measurements, and approximate normality of differences. Where assumptions were not satisfied, an appropriate nonparametric alternative could be considered. For comparisons involving three or more material groups, one-way analysis of variance (ANOVA) was specified to examine differences in

technical performance measurements. The analysis considered independence, normality, and homogeneity of variances, with post-hoc testing where significant differences were identified. All inferential tests used a 0.05 significance level. The results were interpreted against the study's technical requirements and evaluation criteria to determine prototype performance and guide operational improvements.

Ethical Considerations

The study incorporated ethical safeguards to protect participant rights, confidentiality, and physical safety. Administrative clearance and ethical approval were to be obtained from Cebu Technological University before data collection. All 100 respondents were to receive information regarding the study's objectives, participation requirements, confidentiality measures, and right to withdraw without penalty. Participation was voluntary and required informed consent. Safety precautions were established for prototype demonstrations and operational testing. CNC laser activities were to be conducted under controlled laboratory conditions using existing ventilation and the developed filtration system to minimize exposure to generated fumes. Applicable laboratory safety procedures and equipment-operating requirements were observed throughout testing. Participant responses were to be anonymized and treated confidentially. Technical records, digital logs, and questionnaire results were to be stored in password-protected files accessible only to authorized researchers. Research integrity was maintained through transparent reporting of technical measurements, evaluator assessments, and identified system limitations. Methodological trustworthiness was supported through sensor calibration against reference instruments, expert validation of the research questionnaire, repeated operational trials, and consistent measurement procedures. Three qualified experts in engineering and technology management were designated to review the evaluation instrument. These measures supported the reliability, accuracy, and ethical conduct of the prototype's technical and quality evaluation.

3. RESULTS AND DISCUSSION

3.1 Technical Design Requirements and Subsystem Performance

3.1.1 Fume Detection Subsystem

The fume detection subsystem achieved an overall detection accuracy of 91.7% ± 2.1% and sensor reliability of 91.2% ± 1.8%, exceeding the established 85.0% benchmarks. Its mean response time was 4.28 ± 0.31 seconds, satisfying the requirement of less than 6.0 seconds. Plywood trials recorded higher detection accuracy (92.8%) and reliability (91.8%) than acrylic trials (90.6% for both indicators). Response time was also shorter for plywood at 4.07 seconds than for acrylic at 4.48 seconds. Mean baseline fume concentrations were 339.2 ppm for plywood and 447.4 ppm for acrylic. Respondents rated user understanding at 3.85 ± 0.81 and response clarity at 3.79 ± 0.90, both interpreted as Reliable. These findings indicate that the subsystem provided satisfactory detection accuracy, consistency, and responsiveness under the tested conditions. Differences between plywood and acrylic demonstrate the importance of evaluating sensor performance across materials with varying emission characteristics, consistent with CNC processing studies (Açık, 2023; Ameer & Fatahi Valilai, 2025) and (Anrinal et al., 2023; Elvaris Manalu et al., 2023). Favorable user assessments also support the integration of understandable monitoring information into automated CNC systems (Gyasi et al., 2022; Katduang et al., 2024). However, sensor measurements require further contaminant-specific calibration and reference validation before they can establish occupational exposure compliance (Department of Labor and Employment, 2025).

3.1.2 Automatic Ventilation Subsystem

The automatic ventilation subsystem recorded extraction airflow above the minimum benchmark of 45.0 CFM. The consolidated operational results showed an average airflow of 53.9 ± 2.0 CFM, with material-specific measurements of approximately 55.2 CFM for plywood and 52.5 CFM for acrylic. Mean fan activation latency was 4.28 ± 0.31 seconds, meeting the required response time of less than 6.0 seconds. Respondents rated automatic activation utility at 3.82 ± 0.94 and component integration at 3.83 ± 0.84, both classified as Reliable. The results demonstrate that the ventilation subsystem achieved the prescribed airflow and activation-time requirements. Its automated operation reflects the integration of mechanical extraction and electronic control in CNC manufacturing systems (Ahmed et al., 2025; Das et al., 2024; Gyasi et al., 2022). Nevertheless, measured airflow does not independently establish effective contaminant capture because actual performance depends on duct configuration, inlet placement, enclosure sealing, and filtration resistance. Further validation of complete system response and workplace ventilation performance remains necessary (Department of Labor and Employment, 2025; Occupational Safety and Health Center, 2026).

3.1.3 Filtration Subsystem

The filtration subsystem reduced mean fume concentration from 339.2 ppm to 75.4 ppm during plywood processing and from 447.4 ppm to 102.6 ppm during acrylic processing. Filtration efficiency reached 77.7% ± 1.8% for plywood and 77.0% ± 1.3% for acrylic, producing an overall efficiency of 77.4% ± 1.6%. This exceeded the 70.0% benchmark by 7.4 percentage points. Respondents rated filter serviceability at 3.74 ± 0.82 and design conformance at 3.83 ± 0.84, both interpreted as Reliable. The findings indicate substantial reductions in monitored fume concentrations across both materials, despite differences in their initial emission levels. These results are relevant to material-specific CNC laser processing (Anrinal et al., 2023; Elvaris Manalu et al., 2023). Systematic performance measurement supports consistent engineering evaluation (Ameer & Fatahi Valilai, 2025). However, the reported efficiency represents a reduction in measured sensor responses and does not independently verify the removal of every hazardous chemical or particulate component. Additional contaminant-specific measurements and extended filtration testing are therefore required.

3.1.4 Warning Subsystem

The warning subsystem achieved a mean alarm activation latency of 4.28 ± 0.31 seconds, remaining 1.72 seconds below the maximum response-time requirement. Alarm indication clarity received a mean rating of 3.79 ± 0.80, while practical support utility obtained 3.81 ± 0.86. Both indicators exceeded the reference benchmark of 3.41 and were classified as Reliable. These findings indicate that the warning mechanism activated within the prescribed period and provided indications considered understandable and useful by respondents. Automated warning functions complement intelligent CNC monitoring and manufacturing technologies (Gyasi et al., 2022). The importance of measurable operational responses is consistent with data-driven manufacturing principles (Ameer & Fatahi Valilai, 2025). Clear warning information also supports operator awareness and technical training (Ibarra Kwick et al., 2024), while effective integration contributes to equipment functionality (Ahmed et al., 2025). However, favorable ratings do not independently establish correct operator responses during actual hazardous conditions, emphasizing the need for further functional and safety validation (Department of Labor and Employment, 2025).

3.1.5 Digital Display and Monitoring Subsystem

The digital monitoring subsystem obtained an overall weighted mean of 3.83 with a standard deviation of 0.39, interpreted as Reliable. Automated monitoring features received the highest rating of 3.95, followed by display clarity at 3.86, automatic activation utility at 3.82, alarm clarity at 3.79, and practical control assistance at 3.72. All indicators exceeded the reference benchmark of 3.41. The findings demonstrate favorable evaluator perceptions of the display's usefulness, clarity, and contribution to system operation. The integration of digital monitoring with automated manufacturing functions is consistent with developments in CNC technology (Das et al., 2024; Gyasi et al., 2022; Katduang et al., 2024). Nevertheless, perceived display quality does not independently confirm measurement accuracy. Verification of displayed sensor readings, operating states, and warning indications remains essential for reliable monitoring.

3.2 Prototype Design, Construction, and Integration

3.2.1 System Architecture and Hardware Components

The developed prototype integrated five functional layers: fume detection, electronic control and display, automatic extraction, filtration, and machine interface. Its principal components included MQ-4 and MQ-135 sensors, an Arduino UNO or ESP32 microcontroller, a 16 × 2 I^2C LCD, an audible and visual warning system, a centrifugal DC blower, and a three-stage filtration assembly. The filtration components consisted of a mesh pre-filter, activated-carbon media, and an H13 HEPA element. The prototype also incorporated a 6-mm acrylic enclosure, rubber seals, and a 100-mm flexible aluminum duct connected to the existing CNC laser exhaust interface. The integrated architecture enabled the coordination of sensing, automated control, airflow movement, contaminant treatment, and operational monitoring. This approach is consistent with the integration of electronic and mechanical components in automated CNC equipment discussed by Das et al. (2024) and Gyasi et al. (2022). Material-processing studies also support the importance of considering operating conditions during laser cutting and engraving (Anrinal et al., 2023; Elvaris Manalu et al., 2023). However, component compatibility, sensor calibration, electrical safety, filtration resistance, and enclosure suitability require verification before extended operation (Das et al., 2024; Ahmed et al., 2025).

3.2.2 Automated Control and Operational Modes

The prototype's control firmware incorporated four operating states: standby, pre-alarm, active extraction, and purge. During standby, sensor readings below 150 maintained monitoring without activating the blower or alarm. Readings between 150 and 300 initiated a pre-alarm warning, while readings above 300 triggered full extraction and continuous alarm activation after the specified persistence interval. The purge state maintained ventilation as readings decreased, allowing additional fume removal before returning to standby. The LCD communicated the corresponding operating conditions and warning status. The programmed control sequence established a coordinated response between fume detection, ventilation, warning, and monitoring. This functionality reflects developments in automated CNC monitoring and control (Das et al., 2024; Katduang et al., 2024). Nevertheless, programmed thresholds represent system-defined operating conditions rather than independently validated occupational exposure limits. Sensor calibration and verification of activation thresholds are necessary to establish dependable operation.

3.2.3 Evaluation of Prototype Integration

The prototype obtained an overall design and integration rating of 3.82 ± 0.39, interpreted as Reliable. Automated monitoring features received the highest indicator rating of 3.95, followed

by display clarity at 3.86, suitability for the FabLab environment at 3.84, and component integration at 3.83. Consistent operation during repeated use received the lowest rating of 3.65, although it remained within the reliable category. All twelve assessed indicators met the established quality benchmark. The results indicate favorable evaluator assessments of the prototype's functional coordination, monitoring features, physical construction, and compatibility with its intended operating environment (Das et al., 2024; Ahmed et al., 2025). The positive ratings for monitoring and display functions are consistent with intelligent manufacturing principles (Gyasi et al., 2022; Kaarlela & Outeiro, 2025). Wu et al. (2024) further demonstrated the application of deep-learning-based fault prediction in CNC machine tools, highlighting the broader importance of intelligent monitoring technologies for identifying potential equipment faults and supporting operational reliability. However, the relatively lower repeated-use reliability rating identifies a need for further operational testing and component refinement. These considerations are supported by research on CNC measurement, equipment quality, and maintenance (Anrinal et al., 2023; Li & Liu, 2024; Kumar, 2024; Oleksiak et al., 2023).

3.2.4 Evaluation Across Respondent Categories

The 100 respondents gave the prototype an overall integration rating of 3.82, interpreted as Reliable. Student fabricators recorded the highest overall mean of 3.92, followed by faculty and staff at 3.80, technical and IT personnel at 3.71, and FabLab personnel and CNC operators at 3.53. Among FabLab personnel and CNC operators, reliability received a comparatively low mean of 3.24, while features and conformance obtained 3.50 and 3.42, respectively. The findings indicate generally favorable assessments across respondent categories, although perceptions differed according to their operational roles and experience. These variations reinforce the importance of evaluating CNC technologies within their intended working environments (Das et al., 2024; Ahmed et al., 2025). The favorable student assessments relate to the educational application of monitoring technologies (Ibarra Kwick et al., 2024; Kaarlela & Outeiro, 2025), while the lower operator ratings suggest areas requiring closer technical examination. Relevant considerations include operational workload, system responsiveness, maintenance, and anomaly detection (Muhammad Ilham Romadoni & Rr. Rochmoeljati, 2024; Ameer & Fatahi Valilai, 2025; Çekik & Turan, 2025). The differences are descriptive and were not established as statistically significant.

3.3 Technical Performance and Material-Based Comparison

3.3.1 Overall Technical Performance

Across twenty operational trials, the prototype achieved detection accuracy of 91.7% ± 2.1%, sensor reliability of 91.2% ± 1.8%, response time of 4.28 ± 0.31 seconds, extraction airflow of 53.9 ± 2.0 CFM, and filtration efficiency of 77.4% ± 1.6%. All five indicators exceeded their respective benchmarks of 85.0% detection accuracy, 85.0% reliability, less than 6.0 seconds response time, 45.0 CFM airflow, and 70.0% filtration efficiency. Mean monitored fume concentration decreased from approximately 393.3 ppm to 89.0 ppm after filtration. These results demonstrate that the prototype met its established technical performance requirements under the tested conditions. The integration of sensing, control, extraction, and filtration is consistent with developments in intelligent CNC manufacturing and automated monitoring (Ameer & Fatahi Valilai, 2025; Çekik & Turan, 2025; Gyasi et al., 2022; Das et al., 2024). However, achievement of prototype benchmarks does not independently establish long-term reliability, complete contaminant removal, or compliance with occupational exposure standards.

3.3.2 Performance Differences Between Plywood and Acrylic

The material-based trials showed that plywood achieved higher detection accuracy (92.8%) than acrylic (90.6%), with a statistically significant difference ($t = 2.305$, $p = 0.0333$). Response time was significantly shorter for plywood (4.07 seconds) than acrylic (4.48 seconds), with $t = -4.105$ and $p = 0.0007$. Extraction airflow was also significantly higher for plywood (55.21 CFM) than acrylic (52.54 CFM), with $t = 3.804$ and $p = 0.0013$. Pre-filtration concentrations were significantly higher for acrylic (447.37 ppm) than plywood (339.21 ppm), with $p < 0.0001$. Post-filtration concentrations likewise differed significantly, at 102.57 ppm for acrylic and 75.36 ppm for plywood ($p < 0.0001$). However, sensor reliability ($p = 0.1589$) and filtration efficiency ($p = 0.3207$) did not differ significantly between materials. These findings indicate that several technical performance indicators varied between plywood and acrylic, while sensor reliability and proportional filtration efficiency remained statistically comparable. Material-specific variations are relevant to CNC laser processing because different substrates and operating conditions may influence emission characteristics and equipment performance (Anrinal et al., 2023; Elvaris Manalu et al., 2023; Das et al., 2024; Gyasi et al., 2022; Çekik & Turan, 2025). Nevertheless, the observed differences cannot be attributed exclusively to material type without controlling other operating variables.

3.4 Changes in Measured Environmental Safety Conditions

3.4.1 Fume Concentration Before and After System Integration

The combined results from twenty trials showed that mean monitored fume concentration decreased from 393.29 ± 58.21 ppm before filtration to 88.97 ± 14.61 ppm afterward. This represented an absolute reduction of 304.32 ppm, equivalent to approximately 77.38%. The paired-samples t-test confirmed a statistically significant difference, $t(19) = 30.016$, $p < 0.0001$, with a reported Cohen's d of 6.71. The post-filtration concentration represented 22.62% of the original measured level. The findings demonstrate that the system substantially reduced monitored fume concentrations during the experimental trials. This supports the application of automated environmental controls in CNC operations (Das et al., 2024) and the importance of quantitative manufacturing performance assessment (Ameer & Fatahi Valilai, 2025). However, the reduction does not independently establish that the remaining concentration is safe for occupational exposure. Such a determination requires contaminant identification, calibrated measurements, and comparison with applicable exposure limits (Department of Labor and Employment, 2025; Occupational Safety and Health Center, 2026).

3.4.2 Material-Specific Contaminant Reduction

During plywood processing, mean fume concentration decreased from 339.21 ± 15.91 ppm to 75.36 ± 4.73 ppm, representing a reduction of 263.85 ppm or approximately 77.79%. The difference was statistically significant, $t(9) = 49.497$, $p < 0.0001$, with a reported Cohen's d of 15.65. During acrylic processing, concentration decreased from 447.37 ± 20.05 ppm to 102.57 ± 4.09 ppm, corresponding to a reduction of 344.80 ppm or approximately 77.04%. This difference was also significant, $t(9) = 53.484$, $p < 0.0001$, with a reported Cohen's d of 16.91. The findings demonstrate substantial reductions in measured fumes for both materials, although acrylic retained a higher post-filtration concentration. The comparable percentage reductions indicate relatively consistent filtration performance despite different initial concentrations. These findings reinforce the relevance of material-specific evaluation in CNC laser processing (Anrinal et al., 2023; Elvaris Manalu et al., 2023; Ngadiyono et al., 2025). Nevertheless, the statistical results establish reductions within each material group rather than a significant difference in

reduction between groups. The reported effect sizes also require verification, and occupational safety conclusions remain dependent on contaminant-specific assessment (Department of Labor and Employment, 2025; Occupational Safety and Health Center, 2026).

3.5 Quality Evaluation Based on Garvin's Eight Dimensions of Quality

3.5.1 Overall Prototype Quality

The prototype obtained a grand overall quality mean of 3.82 ± 0.39, interpreted as Reliable. All eight quality dimensions met the established benchmark. Perceived quality received the highest mean of 3.86, followed by serviceability at 3.85, aesthetics at 3.84, features and durability at 3.83 each, performance at 3.82, reliability at 3.79, and conformance at 3.77. The dimension means ranged from 3.77 to 3.86, indicating consistently favorable assessments across the evaluated characteristics. The results demonstrate that respondents assessed the prototype positively in terms of functionality, automated features, physical construction, maintainability, and overall design quality. This multidimensional approach is consistent with the importance of evaluating engineering systems beyond their primary operating functions (Kumar, 2024). Favorable ratings across the eight dimensions indicate that the prototype satisfied the study's quality criteria, although evaluator perceptions do not independently establish long-term operational reliability or safety compliance.

3.5.2 Strengths and Areas for Improvement

Perceived quality, serviceability, and aesthetics obtained the highest ratings, indicating favorable assessments of the prototype's overall workmanship, maintenance accessibility, and physical arrangement. Performance and durability both received means of 3.82, while features obtained 3.83. Reliability and conformance received the lowest means of 3.79 and 3.77, respectively, although both remained within the Reliable classification. The findings identify maintenance accessibility, physical organization, and perceived workmanship as relative strengths, while repeated-use reliability and design conformance warrant further refinement. These considerations are consistent with research emphasizing automation, equipment monitoring, maintenance, and user-oriented CNC system development (Das et al., 2024; Çekik and Turan, 2025; Oleksiak et al., 2023; Ibarra Kwick et al., 2024). Consistent with Kumar (2024), comprehensive engineering quality assessment requires consideration of multiple operational and physical characteristics. The differences among quality ratings should not be interpreted as statistically significant without additional testing.

3.6 Development of the Operation, Safety, and Maintenance Standards Manual

3.6.1 Technical and Operational Specifications

The study's technical findings provided the basis for developing the proposed Operation, Safety, and Maintenance Standards Manual. Detection accuracy of 91.7% ± 2.1%, sensor reliability of 91.2% ± 1.8%, response time of 4.28 ± 0.31 seconds, and extraction airflow of 53.9 ± 2.0 CFM informed the recommended operating specifications. These included a calibrated dual-sensor arrangement, a 10-sample moving-average filter, maximum trigger latency below 6.0 seconds, and minimum operational airflow of 45.0 CFM. The derived specifications connect measured prototype performance with procedures for preparation, operation, monitoring, and maintenance. This approach is consistent with the integration of automated control and performance monitoring in CNC technologies (Ahmed et al., 2025; Ameer & Fatahi Valilai, 2025; Das et al., 2024). However, these values represent study-derived operating requirements rather than independently established regulatory standards.

3.6.2 Safety, Filtration, and Maintenance Requirements

The measured contaminant reduction of 77.38% ± 1.58% supported the proposed three-stage filtration assembly consisting of a mesh pre-filter, activated-carbon pad, and H13 HEPA element. The manual also incorporated a proposed exhaust-monitoring criterion below 100.0 ppm, a quick-access filter drawer, and LCD monitoring of gas concentration, operating mode, and warning status. Filter accessibility received a mean rating of 3.95 ± 0.81, while display clarity obtained 3.86 ± 0.83. The overall quality rating of 3.82 ± 0.39 further supported the development of standardized procedures covering pre-operation, system control, safety, maintenance, inspection, and troubleshooting. These provisions translate the experimental findings into practical guidance for managing the developed system. Their emphasis on filtration, monitoring, and maintenance is consistent with engineering research concerning material processing, equipment servicing, and measurement reliability (Anrinal et al., 2023; Oleksiak et al., 2023; Li and Liu, 2024). However, the proposed exhaust criterion requires contaminant-specific validation and must not be interpreted as an occupational exposure limit. The manual remains subject to further technical verification and applicable workplace safety requirements (Department of Labor and Employment, 2025; Occupational Safety and Health Center, 2026).

4. CONCLUSIONS AND RECOMMENDATIONS

The study concludes that the developed Smart Fume Detection, Extraction, and Filtration System for CNC Laser Machines demonstrated satisfactory technical performance under the tested conditions. The prototype achieved a detection accuracy of 91.7%, sensor reliability of 91.2%, average response time of 4.28 seconds, extraction airflow of 53.9 CFM, and filtration efficiency of 77.4%, meeting or exceeding all established benchmarks. Mean measured fume concentration decreased significantly from 393.29 ppm to 88.97 ppm, representing a 77.38% reduction. Significant differences between plywood and acrylic trials were observed in detection accuracy, response time, airflow, and fume concentrations, while sensor reliability and filtration efficiency remained statistically comparable. The prototype obtained an overall quality rating of 3.82, interpreted as “Reliable,” based on Garvin's Eight Dimensions of Quality. These findings establish the prototype's potential as an auxiliary fume-control system for CNC laser operations and provide the technical basis for the proposed CTU FabLab Standards Manual. However, further validation is necessary to establish long-term reliability, contaminant-specific filtration effectiveness, and compliance with occupational safety requirements.

It is recommended that the developed system undergo further technical refinement, calibration, and extended operational testing before routine implementation in academic fabrication laboratories and industrial workshops. Future improvements should prioritize sensor accuracy and reliability, material-specific contaminant detection, extraction airflow optimization, filtration effectiveness, and maintenance accessibility. Additional trials involving suitable laser-processing materials and varying operating conditions should be conducted to verify system consistency and durability. Independent contaminant-specific testing by qualified occupational safety professionals is necessary to determine compliance with applicable exposure limits. The proposed CTU FabLab Standards Manual should undergo technical review and pilot implementation to validate operating procedures, alarm thresholds, calibration requirements, filter replacement intervals, maintenance schedules, and safety precautions. Feedback from CNC operators, technical personnel, and other relevant users should guide continued improvement to ensure dependable and practical system operation.

The study was limited to controlled CNC laser trials involving plywood and acrylic specimens, with performance assessed through selected technical indicators and evaluator ratings. The MQ-4 and MQ-135 sensors were subject to calibration requirements, environmental influences, and limitations in identifying specific airborne contaminants. Although the prototype demonstrated significant reductions in measured fume concentrations, these results did not independently establish the removal of all hazardous substances or compliance with occupational exposure limits. Furthermore, the evaluation did not conclusively establish long-term durability, performance under prolonged industrial operation, or suitability across other materials and fabrication environments. These limitations indicate that the prototype's demonstrated effectiveness applies primarily to the experimental conditions investigated and requires further technical and occupational safety validation before broader implementation.

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