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ABSTRACT :

The aim of this thesis is to discuss data-driven risk management for improving laboratory safety culture in metal powder laboratories. This has necessitated the adoption of a mixed-method methodology for in-depth analysis of both the environmental conditions and safety practices. Quantitative information on the laboratory's every vital parameter was collected on a real-time basis using highly accurate sensors for temperature, humidity, and level of particulate matter PM10, PM2.5, PM 100. Qualitative information was gathered from semi-structured interviews from laboratory assistants, pointing at perceived risks, safety practices, and necessary improvements.

The results show that though the temperature remains constant in the lab, the high level of humidity may affect the nature of the metal powders and even laboratory safety. The extreme fluctuation and multi-peak of PM concentration shows that some operations are possible safety hazards. The correlation analysis performed indicates a complicated interaction of environmental variables and particulate matter concentration, thus requiring an integrated approach in managing risks.

The theme analysis of the responses of laboratory assistants underlines the importance of keeping the same level in safety, especially the use of PPE. At the same time, it points out some points that require improvement, such as fire safety and deeper training in safety issues. Merging sensor data with qualitative data underlines the capability of data-driven approaches to enhance safety and foster an active safety culture.

This study furthers the field by demonstrating how quantitative data analysis, in conjunction with qualitative insights, can be used to enhance laboratory safety. The paper provides a framework for using real-time monitoring and data analytics to identify and mitigate risks, with a novel approach to promoting safety culture in metal powder laboratories. Proposed interventions include the installation of real-time monitoring systems, the development of improved safety training programs, and routine maintenance of safety equipment. Future research should focus on advanced data analytics and the assessment of long-term effects of improved safety protocols on laboratory safety culture.

KEYWORDS: Laboratory Safety Culture, Risk Management, Metal Powders, Data-Driven Safety Analysis Additive Manufacturing, Laser Powder Bed Fusion.

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1 Introduction

Laboratory safety is the most important part of scientific research, especially when dangerous substances like metal powders are handled. A good safety culture can be achieved only from a combination of these types of work environments, protection of workers' health and well-being, research integrity, and compliance with strict regulatory requirements. Failures in laboratory safety may lead to serious consequences, such as minor injuries, catastrophic accidents, loss of life, major property damage, and long-term environmental contamination.

The hazards are very high, especially in metal powder laboratories. Most of the metal powders are highly reactive and show serious risks of fire, explosion, and health hazards. Particles in fine form are easily inhalable and therefore can give rise to serious respiratory problems, while some metal powders reacting in nature may react explosively if not handled appropriately. Thus, protocols with a very strict sense of safety are required for effective hazard controls.

Historically, laboratory safety standards have prioritized reactive measures, concentrating on addressing problems post-occurrence rather than avoiding them. These measures often encompass regular safety inspections, employee training programs, and personal protective equipment (PPE). Although these measures are essential elements of any safety strategy, they may prove inadequate in mitigating all potential dangers, especially those that are not readily observable or that develop because of alterations in processes, materials, or environmental circumstances.

In this context, the incorporation of data-driven methodologies into laboratory safety protocols markedly improves conventional safety management. Data-driven safety techniques utilize advanced technology, including real-time environmental monitoring, predictive analytics, and machine learning, to identify and manage risks prior to their manifestation as incidents. These technologies provide the ongoing surveillance of essential parameters such as temperature, humidity, and particulate matter concentrations, delivering instantaneous feedback and enabling swift corrective measures.

For example, high-precision sensors, placed at strategic positions in the laboratory, can detect oscillations of ambient conditions that may characterize increases in hazards, such as particulate matter indicating poor ventilation or continuous hazardous operations. Predictive analytics studies historical data to forecast future safety incidents so that laboratories can adopt preventive measures. Moreover, machine learning algorithms can identify patterns and correlations in data that may be missed by human analysts, giving more profound insights into the root causes of safety issues and helping to improve the safety standard.

A data-driven methodology enhances a proactive safety culture by promoting continuous improvement and vigilance. It enables laboratory personnel to actively participate in the safety protocol, utilizing data to inform them of their actions and decisions. The essential shift is from a reactive to a proactive mindset transformation vital for fostering a safety culture that complies with regulations and anticipates and mitigates hazards before they inflict harm.

Implementing data-driven safety solutions is in line with the current trends of industrial safety and risk management, which stress the adoption of technology to enhance operational safety. The use of data analytics in safety management has been an area of growing interest within the realm of industrial system analytics, on which this research is based. By using data, labs can enhance safety results and improve operational efficiency and productivity.

This study, rooted in pursuing a master's degree in technology focusing on industrial system analytics, aims to demonstrate the necessity and effectiveness of integrating advanced data analytics into safety management practices, particularly in metal powder laboratories. By combining sensor data with sophisticated analytical methods, this research seeks to optimize safety protocols and develop robust solutions for mitigating the unique risks associated with these specialized settings.

1.1 Problem Statement

Despite significant technological and safety advancements, metal powder laboratories face numerous hazards compromising worker safety, research integrity, and operational efficiency. These risks' dynamic and ever-changing nature necessitate more than traditional risk management techniques. Traditional safety measures often fall short in anticipating and mitigating these hazards effectively. Moreover, the lack of comprehensive, data-driven approaches hampers efforts to foresee and prevent potential dangers before they manifest. Consequently, there is a pressing need to employ cutting-edge data analytics, innovative risk management techniques, and direct input from machine operators to enhance safety culture and operational workflows in metal powder laboratories.

One of the primary challenges in metal powder laboratories is the dynamic and evolving nature of risks. Unlike static hazards, these risks change with variations in processes, materials, and environmental conditions. Conventional safety protocols, typically dependent on rigid procedures and checklists, may lack the adaptability required to confront these evolving threats. This constraint necessitates the creation of more flexible and proactive safety solutions that can address the dynamic nature of threats in these environments while integrating machine operators' feedback to enhance real-time safety measures and operational efficiency.

Alongside the evolving nature of risks, there exists an imperative to enhance the anticipation of potential dangers. Many laboratories currently employ risk management approaches that are primarily reactive, concentrating on addressing problems post-occurrence. This reactive methodology may result in considerable safety oversights and incidents, underscoring the imperative for anticipatory instruments and methodologies. Predictive analytics, using historical data to project future events, can be very instrumental in transitioning from a reactive to a proactive risk management framework. Again, engaging the machine operators, particularly in such processes as additive manufacturing and laser powder bed fusion, can provide vital insight into risk identification and management at the operational level.

Furthermore, the lack of comprehensive data integration poses a significant challenge in effectively managing laboratory safety. Many laboratories do not have systems to collect and analyze safety-related data from multiple sources cohesively. This fragmentation hinders the ability to accurately identify patterns, correlations, and potential hazards. Integrating advanced data analytics and practical insights from machine operators can provide a holistic view of the laboratory environment, facilitating more informed decision-making and risk management.

Real-time monitoring of critical parameters such as particulate matter levels, temperature, and humidity is another area that requires improvement. Without real-time data, laboratories cannot promptly detect and respond to emerging risks, potentially compromising safety and research outcomes. Implementing high-precision sensors and continuous monitoring systems can enhance the ability to maintain safe working conditions by providing immediate feedback and enabling quick corrective actions. Machine operators play a crucial role in interacting with these systems, and their experiences can highlight areas where monitoring systems can be optimized for both safety and operational performance.

Moreover, the application of predictive analytics in laboratory safety is still limited. Machine learning algorithms and statistical models have shown great potential in various industries but are not widely adopted in laboratory settings. These tools can predict potential safety incidents, allowing for implementing preventive measures before an incident occurs. Exploring and integrating these advanced analytical techniques can significantly bolster the effectiveness of safety protocols. By incorporating machine operator feedback, laboratories can identify practical challenges in the workflow and tailor predictive systems to real-world needs.

Cultivating a proactive safety culture is essential for long-term safety improvements in metal powder laboratories. Many laboratories, however, struggle with ingrained reactive safety practices. Shifting this mindset requires innovative risk management strategies emphasizing continuous improvement and vigilance. Promoting active engagement with safety practices, using data to inform actions, and integrating machine operators' insights can foster a proactive safety culture, leading to better safety and operational outcomes.

Finally, there is often a disconnect between established industrial best practices and the latest technological advancements. Bridging this gap is crucial to ensure laboratories benefit from tried-and-tested safety measures and cutting-edge innovations. Integrating these elements and machine operators' practical experiences can create a more robust, comprehensive safety management and operational framework.

Research Question: How can data-driven risk identification and innovative solution implementation enhance the safety culture in metal powder laboratories?

How can machine operators' experiences and feedback be leveraged to improve safety protocols and operational efficiency in metal powder laboratories, particularly in additive manufacturing processes?

Addressing these problems through integrating advanced data analytics, innovative risk management techniques and insights from machine operators aims to develop robust solutions that improve current safety protocols and anticipate and mitigate future risks. This approach will foster a proactive safety culture, ensuring a safer working environment, improving operational workflows, and preserving research integrity in metal powder laboratories.

1.2 Scope and Objectives of Thesis

This thesis examines and discusses the difficulties related to risk management and safety culture in metal powder laboratories. The study will use data-driven strategies to improve safety procedures, reduce hazards, and promote a continuous improvement culture. Essential topics covered in this thesis include analyzing today's safety culture, methodically identifying risks based on lab assistants' input and sensor data, determining the efficacy of current risk mitigation techniques, and formulating suggestions for cutting-edge risk management procedures. Although metal powder laboratories are the main focus of this project, the knowledge acquired from it may have broader implications for improving safety in other hazardous material handling situations.

1.3 Objectives

1. Evaluate the current safety culture in metal powder laboratories across various settings, emphasizing how risks are identified, monitored, and mitigated.
2. Systematically identify and document risks using lab sensor data and laboratory assistant feedback, pinpointing deficiencies in current risk management practices.
3. Investigate and assess the effectiveness of existing risk mitigation strategies and identify innovative practices that could be implemented in metal powder environments.
4. Develop recommendations for advanced risk management strategies based on sensor data analysis and personnel feedback, aiming to enhance safety protocols in metal powder laboratories.

2 Introduction to the Literature Review

The literature review aims to provide a comprehensive background on industrial safety, risk management, and integrating data-driven approaches in metal powder laboratories. Powder characterization for additive manufacturing is crucial in determining the quality and attributes of the final products. Research indicates that the use of nanoparticles in metal and polymer powder feedstocks can boost processability, refine grain size, and improve material characteristics. (Kusoglu et al., 2021). This underscores the need to comprehend and regulate powder characteristics to enhance additive manufacturing techniques.

Monitoring metal exposure is crucial for safeguarding the health and safety of personnel in metal powder laboratories. Assessing and applying methods for measuring occupational exposure, such as laser diffraction analysis, is essential for maintaining metal powder quality and providing a safe workplace.(Graff et al., 2017a). Monitoring and analyzing metal exposure levels enables the implementation of appropriate safety measures to limit risks associated with metal handling and processing.

Conducting process safety analysis for hazardous materials is essential for industrial safety in metal powder laboratories. Comprehending the impact of water atomisation on metal particles is crucial for guaranteeing safe handling and processing. Water atomisation, a conventional technique employed in powder metallurgy and metal additive manufacturing, significantly influences the quality of the resultant powders. (Asgarian et al., 2020). Examining the impacts of water atomization mitigates hazards linked to the management of hazardous substances, hence enhancing workplace safety.

The generation of metal powders from machining chips represents a sustainable method that minimizes waste and enhances resource efficiency. Research on the impact of temperature and time variables on the spraying of metallic powders, mostly utilizing plasma atomization techniques, underscores the potential for creating efficient ways for generating metal powders from machining chips (Ermakov et al., 2020). This improves sustainability practices and diminishes environmental effects.

The Laser Metal Deposition process needs monitoring and control to ensure quality and consistency in the additive manufacturing processes. The in-situ optical signals during laser metal deposition can be analyzed for a better understanding and manipulation of the deposition process. (Li et al., 2021). By monitoring and analyzing process signals in real time, laboratories can optimize process parameters, improve part quality, and enhance overall efficiency in laser metal deposition.

Additional topics include the recovery of metals from industrial wastewater. (Luchcińska et al., 2023), the importance of high-quality metallic powders in manufacturing processes, safety risks in civil engineering laboratories (Y. Zhang et al., 2020), workplace exposure measurements in industrial 3D printing (Kangas et al., 2023a), and the development of metal powder hot embossing for micromanufacturing (Sequeiros et al., 2020). It also covers the preparation and characterization of feedstocks for metal powder shaping, and the compaction behavior of powder bed fusion feedstock. (Sillani et al., 2021), the influence of reputation information on safety trust formation targeted the safety issues in lithium-metal batteries (Heine et al., 2014a), industrial applications of monolithic metal-organic frameworks, laboratory-scale gas atomizers for metallic powder manufacturing (del Rio et al., 2022), water atomization of metal powders, and particle safety assessment in additive manufacturing processes (Alijagic et al., 2022).

Overall, industrial safety, risk management, and integrating data-driven approaches in metal powder laboratories are multifaceted areas that require a comprehensive understanding of powder characterization, biomonitoring of metal exposure, process safety analysis, sustainable powder production methods, and process monitoring and control in additive manufacturing processes. By incorporating insights from research studies in these areas, laboratories can enhance safety protocols, optimize processes, and improve overall operational efficiency.

2.1 Industrial Safety and Risk Management

Industrial safety and risk management have evolved significantly, focusing on implementing fundamental principles and methodologies to enhance safety practices in various industries. One approach involves applying High-Reliability Organizations (HRO) and resilience engineering principles to fields like construction to address the perception that risk is inherent in work processes. (Harvey et al., 2019). This challenges the notion that safety management hinders productivity, emphasizing the importance of reframing cognitive perspectives to prioritize safety.

Dynamic risk assessment frameworks utilizing Bayesian networks have been developed to improve risk management in process industries. (Kanes et al., 2017). While traditional risk assessment methods have been static, these dynamic approaches consider the evolving nature of risks and aid in making informed risk-based decisions. Moreover, the oil and gas sector has concentrated on establishing process safety key performance indicators (KPIs) to perpetually assess safety management systems and diminish the probability of major incidents.

The integration of modern technology such as computer vision and deep learning has facilitated the prediction and prevention of safety dangers for construction workers and equipment. (M. Wang et al., 2019). By monitoring interactions and identifying danger zones through these techniques, proactive safety measures can be implemented to mitigate risks effectively. Furthermore, applying process safety management principles in university laboratories presents unique challenges but offers a proven approach to enhancing safety within academic research environments. (Olewski & Snakard, 2017).

A multidisciplinary engineering perspective on system safety principles emphasizes fail-safe measures, safety margins, un-graduated response strategies, defense-in-depth approaches, and observability-in-depth principles (Saleh et al., 2014). These principles underscore the importance of designing safety mechanisms that are robust, proactive, and observable to prevent and mitigate risks effectively across various engineering disciplines.

The integration of modern methodology, technical advancements, and established safety principles has greatly enhanced industrial safety and risk management processes. By adopting dynamic risk assessment frameworks, utilizing advanced technologies, and implementing established safety management principles, industries can improve safety protocols, reduce risks, and promote a culture of ongoing enhancement in safety practices.

2.1.1 Core Principles of Industrial Safety

The key areas of consideration in industrial safety are very critical and required of any workplace where working involves dangers and risks. Basic principles will include risk assessment and hazard identification, together with preventive measures. Risk assessment includes the identification of those hazards that can arise, the establishment of their likelihood, and the estimation of their effects upon workers, the environment, and operations as a whole. Hazard identification points to any probable sources of danger, from an ill-maintained machine to harmful chemicals. Prevention strategies mitigate risks through safety protocols, employee training, and appropriate safety equipment. (Baratchi et al., 2018).

2.1.2 Hazard Identification

Risk management in industrial settings has evolved from traditional methods to modern, technology-driven approaches. Initially, it focused on static assessments, often overlooking dynamic changes in processes and environments. Modern approaches, such as dynamic risk assessment, allow real-time monitoring and adjustment of strategies, ensuring a proactive and responsive safety approach. (Kalantarnia et al., 2009).

(Ismail Iqbal et al., 2020) Illustrates a typical risk management process in Figure 1, high-lighting key steps that align with this evolution. Hazards are first detected and analyzed, then risks are ranked according to severity or probability. The decision-making phase presents several alternatives, including the elimination, mitigation, or acceptance of risks, with actions executed according to these selections. The process includes ongoing monitoring of performance and change, which reflects the modern approach's emphasis on adaptability and responsiveness to real-time conditions.

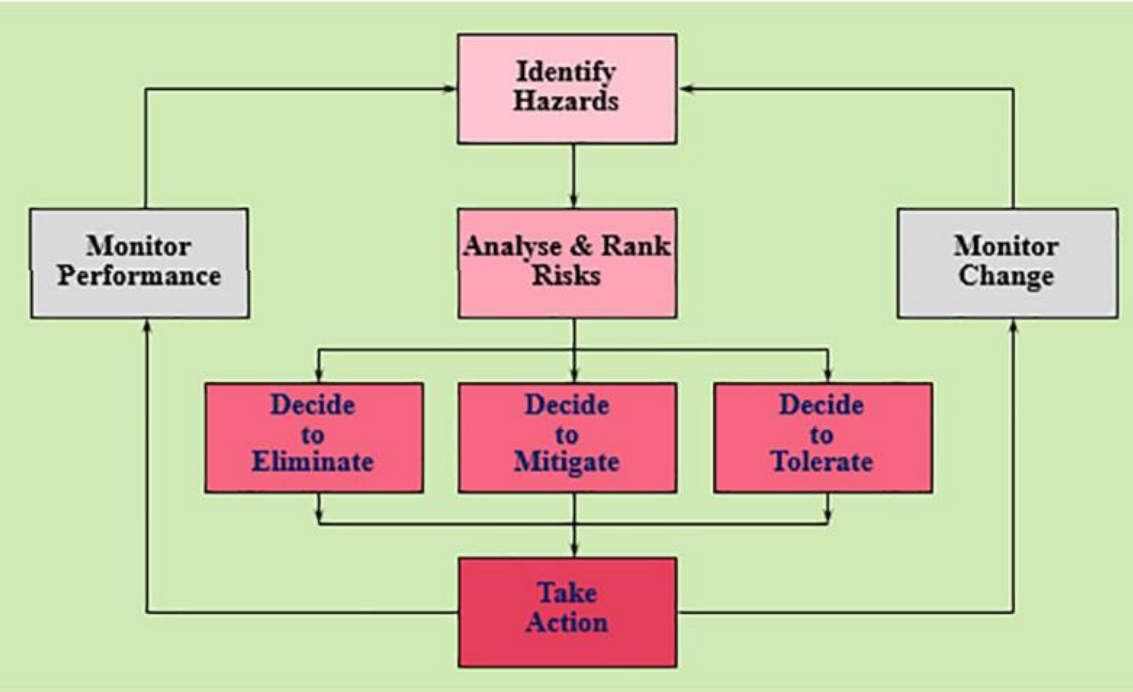

Figure 1 Risk management proposed plan

2.1.3 Technological Advancements:

Technological breakthroughs, such as Building Information Modelling (BIM), have transformed fall hazard detection and prevention in building safety planning by offer-ing detailed digital models of structures, hence enhancing hazard identification and prevention tactics. (S. Zhang et al., 2015).

In summary, industrial safety principles are based on comprehensive risk assessment, precise hazard identification, and efficient prevention techniques. The historical evolution of risk management indicates a transition towards dynamic and technology-oriented methodologies to maintain continuous safety.

2.2 Safety Culture in Laboratories

Safety culture in laboratory environments encompasses behavioral elements that encourage individuals to prioritize and assume responsibility for safety protocols. It entails establishing a collaborative environment characterized by collective accountability for safety, encouraging transparent communication, and nurturing a supportive climate. (Leggett, 2012). This joint dedication to safety not only improves the laboratory's overall safety performance but also fosters a positive work atmosphere where safety is esteemed and prioritized.

Essential components of safety culture include fostering collective responsibility for safety among all personnel, facilitating transparent communication on safety issues, advocating for ongoing enhancement of safety protocols, and embedding safety considerations into every facet of laboratory operations. (Huston et al., 2018). Safety culture is dynamic and requires continuous efforts to foster and sustain a culture in which safety is a fundamental value and an essential component of daily operations. Improving the safety culture in laboratory environments is essential for minimizing injuries, preserving lives, and increasing productivity and results. (McGarry et al., 2013). Engaging students in initiatives to enhance safety culture, such as through student-led safety teams or collaborative safety programs, can provide novel insights, heightened involvement, and a collective dedication to laboratory safety procedures. (Espinasse et al., 2021). Incorporating green chemistry and safety considerations into laboratory culture further emphasizes the importance of holistic safety practices and sustainability in laboratory operations. (O’Neil et al., 2021a).

2.2.1 Key Determinants of Safety Culture

Safety culture in the laboratory environment is the shared attitudes, values, goals, and practices concerning safety. In order to prevent all kinds of accidents, a strong safety culture has to be built. A strong safety culture promotes shared responsibility, creates a positive environment, and increases safety performance. Key factors influencing safety culture encompass leadership, communication, and employee engagement. Effective leadership that prioritizes safety and sets a positive example significantly impacts safety culture. Open communication channels and involving employees in safety initiatives empower them to take ownership of safety practices, leading to a proactive and safety-conscious environment. (Cooper, n.d.).

2.2.2 Case Studies and Best Practices

Case studies of laboratories with exemplary safety cultures provide valuable insights. For example, a chemical laboratory with a collaborative safety culture showed improved safety performance and a supportive work environment. (Czornyj et al., 2018). An academic research laboratory in Argentina successfully fostered a safety culture by prioritizing safety from the ground up, leading to feasible safety investments. (Fracaroli & Caminos, 2021). Incorporating green chemistry practices has enhanced safety while promoting environmentally friendly research approaches. (O'Neil et al., 2021b). Implementing identity safety, which entails prioritizing the well-being of each person, fosters a more inclusive and supportive safety culture. (Kimble-Hill, 2021).

In summary, the safety culture inside laboratories depends on leadership, communication, and employee participation to establish a secure and supportive work environment. Studying case studies and applying best practices can assist institutions in fostering a culture that prioritizes safety and promotes well-being.

2.3 Hazards in Metal Powder Laboratories

Hazards in metal powder laboratories encompass concerns connected with heavy metal exposure, toxicity, and occupational emissions. Heavy metals in metal powders can be a health hazard. Exposure to elements such as nickel, chromium, and molybdenum has been reported to cause different kinds of ill health. (Ljunggren et al., 2019). The toxicity of heavy metals is a big concern, putting possible risks to human health due to exposure to these elements. (Jaishankar et al., 2014) Exposure to emissions from industrial processes, such as 3D printing, can cause concerns in the workplace, where materials including epoxy resins and metal powders serve as potential skin irritants and cause occupational health hazards. (Kangas et al., 2023). Moreover, nano- and submicron-sized particles in metal powders pose dangers related to their handling and processing, underscoring the necessity of appropriate safety protocols in metal powder laboratories. (Matveev et al., 2024a). By comprehending and alleviating these threats, laboratories can guarantee the safety and welfare of personnel while sustaining a secure working environment.

2.3.1 Specific Hazards and Risks

Besides these general hazards, metal powder laboratories present their special group of hazards: fire, explosion, and toxic exposure brought about by the intrinsic properties of the metal powders. First, the metal powders are combustible themselves and tend to ignite rather easily, thus giving very difficult-to-control fires. They may form explosive combinations in the atmosphere, posing considerable explosion hazards. Fine metal powder particles may present health hazards by inhalation, ingestion, or dermal exposure. (Reding & Shiflett, 2018). Titanium powder, prevalent in multiple industries, enhances the explosive potential of explosives owing to its elevated density and melting point. Comprehending the hazards linked to metal powders, including titanium, is crucial for secure management in laboratory environments. (Chiumenti et al., 2017). Similarly, boron powder can enhance explosion power but requires careful handling due to its reactivity and explosive nature. (Yao et al., 2021).

2.3.2 Regulatory Standards and Safety Protocols

The regulatory regulations and safety guidelines of such organizations as OSHA and NFPA must be followed to ensure the safe handling, storage, and disposal of metal powders. Those standards define the requirements for ventilation, personal protective equipment, storage conditions, and emergency response actions that reduce the risks. (Reding & Shiflett, 2018). Industry-specific standards provide guidance tailored to the unique hazards of different metal powders, such as handling protocols for aluminum powder in the aerospace and automotive industries. Safe management in laboratory environments requires an understanding of the hazards associated with metal particles and a commitment to the requirements of regulatory standards.

2.4 Data-Driven Approaches to Risk Management

Data-driven methodologies for risk management employ sophisticated analytics and extensive data to improve decision-making and successfully reduce risks. These techniques utilize analytical tools to analyze extensive data sets and derive significant insights for operational risk management. Araz et al., (2020). Organizations can leverage big data to enhance their comprehension of potential hazards, discern patterns and trends, and proactively mitigate vulnerabilities in their operations.

Data mining frameworks are essential in supply chain risk management (SCRM) for assessing risk exposure levels, technology improvements, and information overload in supply chain networks. (Er Kara et al., 2020). The development of a better capability in the assessment, monitoring, and response of risks in real-time through data-driven methodologies would increase the resilience and effectiveness of supply chain operations for these organizations.

The integration of Internet of Things (IoT) technologies with big data analytics has transformed the disaster risk management processes for businesses to better anticipate, prepare for, and respond to potential threats (Shah et al., 2019). By using data-driven methodologies, organizations can improve their level of disaster preparedness, optimize resource allocation, and minimize the impact of unexpected events on their operations.

The application of big data analytics within risk management frameworks in policing has shown promise in enhancing crisis management capabilities. (Qadir et al., 2016). The use of data-driven methods enables law enforcement agencies to scale up their anticipation and response to security crises and thus resolve the crisis more effectively and efficiently.

Additionally, a data-driven methodology has been crucial in assessing epidemiological susceptibility risk globally. (Akter & Wamba, 2019). Principal component analysis is just one of the advanced analytical techniques that can considerably help researchers draw a conclusion on determinants of the risk and develop measures targeting the reduction of disease transmission.

The key benefits of data-driven methodologies in risk management involve better risk assessment, enhancements in decision-making, proactive mitigation of risks, and increased operational resilience. Big data and advanced analytics could be used to help organizations enhance their processes related to risk management and, subsequently, improve protections around their assets, reputation, and various stakeholders.

2.4.1 Data Analytics and Real-Time Monitoring

Data analytics improves safety measures across multiple industries, including laboratory environments. Organizations can identify patterns, trends, and anomalies that indicate the possibility of safety issues through data collection and analysis coming from sensors, equipment, and processes. It is easier to promptly detect anomalies from normal conditions with real-time monitoring, allowing an immediate response to prevent accidents. Predictive analytics can anticipate prospective safety concerns using previous data, enabling proactive risk management techniques. (Barker, 2021).

2.4.1.1 Sensor Technology

Sensor technology is essential for monitoring ambient conditions and identifying laboratory dangers. Diverse sensors, including those for air quality, temperature, humidity, and mobility, safeguard laboratory personnel and maintain experimental integrity. For example, air quality sensors detect hazardous gases, while temperature and humidity sensors maintain optimal experimental conditions. Integrating sensor technology into safety protocols allows continuous monitoring and prompt response to safety concerns. (Al-Okby et al., 2021, 2022).

2.4.2 Machine Learning and Predictive Analytics

Machine learning algorithms analyze complex datasets to identify patterns and predict risks. Training machine learning models on historical safety data helps develop predictive models to anticipate hazards, prioritize safety measures, allocate resources effectively, and prevent accidents. Machine learning can also optimize safety protocols, personalize training programs, and improve overall safety performance. (Barker, 2021). Data-driven approaches, including data analytics, sensor technology, and machine learning, enhance safety protocols in laboratory settings. Leveraging these technologies for real-time monitoring, predictive insights, and risk prediction helps proactively identify and mitigate safety risks, creating safer laboratory environments.

2.5 Current Practices in Metal Powder Laboratories

Current practices in metal powder laboratories involve a range of methodologies and considerations to ensure safety, efficiency, and quality in operations. These practices include evaluating hazardous chemicals in metal powders to assess potential risks and ensure compliance with safety standards (Lakhe et al., 2019). Additionally, measuring techniques for occupational exposure during metal additive manufacturing are being evaluated to enhance worker safety and minimize health risks associated with metal processing (Graff et al., 2017a). Deformation processes, such as warm extrusion and swaging, produce composite materials with specific properties like low density, high strength, and high conductivity (Tian et al., 2017). Process safety analysis identifies and mitigates risks associated with metal synthesis and processing, mainly focusing on highly combustible metals like aluminum and titanium powders (Lakhe et al., 2019). Furthermore, producing metal matrix composites involves the generation of nano- and submicron-sized particles through specialized synthesis conditions, contributing to developing advanced materials with tailored properties (Matveev et al., 2024b). By integrating these practices, metal powder laboratories can optimize their processes, enhance safety measures, and advance the production of high-quality metal powders and composites.

2.5.1 Existing Safety Protocols and Practices

The metal powder laboratory contains safety protocols that reduce risks in handling, storing, and processing metal powders. Standard operating procedures provide the user with information on the proper handling, storage, transportation, and disposal of metal powders, to ensure that personal protective equipment can be used effectively to minimize exposure to hazardous substances (Moylan et al., 2013).

2.5.2 Occupational Risk and Safety Procedures

Investigations of occupational exposure during additive manufacturing with metal powders underline the need for tight safety measures to prevent inhalation of fine particles and reduce health risks. Evaluation of safety measures in chemical laboratories shows that further improvement and compliance with best practices are necessary to provide a safe workplace. (Dugheri et al., 2022a).

Occupational exposure during additive manufacturing processes involving metal powders poses significant health risks due to inhaling fine particles. Studies have shown that AM operators have increased exposure to metals like cobalt compared to workers like welders (Ljunggren et al., 2019b). Nanosized particles in the additive manufacturing environment contribute to this exposure, particularly when handling metal powders (Graff et al., 2017b). To address these risks, it is crucial to understand exposures' sources, magnitudes, and health effects to develop effective risk assessment and management processes in occupational settings (Leso et al., 2021). Chemical laboratory safety precautions make one look not at being good enough but at striving for continuous improvement and following best practices to have a safer place to work. Safety assessment in such an environment holds a prime significance in ensuring the protection of workers against hazardous conditions arising due to chemicals (Chen et al., 2020). Only rigorous safety policies implemented, and continuous improvement of procedures can reduce the workplace hazards associated with occupational chemical exposure, hence making the work environment safer for all those involved.

In conclusion, studies on occupational exposure in additive manufacturing underscore the necessity for rigorous safety protocols to mitigate health hazards linked to metal powder inhalation. Evaluations of safety standards in chemical laboratories underscore the necessity of ongoing enhancement and compliance with best practices to ensure a secure working environment. Enhancing workplace safety in these contexts can be significantly achieved by comprehending the origins and health implications of exposures, as well as by executing effective risk assessment and management protocols.

2.6 Historical Context and Evolution of Metal Powder Laboratories

To augment safety protocols in metal powder laboratories, suggested enhancements encompass the implementation of comprehensive training programs, the upgrading of ventilation systems, the development of detailed emergency response plans, the advancement of environmental monitoring practices, the conduct of regular safety audits, and the promotion of collaboration and knowledge sharing among personnel.

Thorough training programs are crucial to guarantee that all individuals are proficient in safety regulations and procedures. These programs must encompass subjects such as the management of hazardous materials, the utilization of personal protective equipment (PPE), and emergency response protocols Ali et al., (2022). Furthermore, enhanced ventilation systems are essential for regulating exposure to airborne pollutants and preserving air quality in laboratory settings, hence mitigating health concerns linked to metal powders (Sivan et al., 2024).

Comprehensive emergency response plans are essential for efficiently addressing unexpected events. These plans must delineate specific evacuation methods, spill containment measures, and communication protocols during emergencies. (Heine et al., 2014b). Moreover, the equipment for advanced environmental monitoring will guarantee the real-time assessment of air quality, the detection of potential risks, and a safe place for laboratory staff to work in (Escobar-Hernandez et al., 2021).

Regular safety audits will help determine the effectiveness of the safety policies and identify areas that need improvement. Audits are supposed to be carried out periodically to evaluate the adherence to safety standards, identify potential risks, and execute necessary remedial measures. (Ayi, n.d.). Moreover, cultivating teamwork and knowledge exchange among personnel can improve safety culture, advance best practices, and stimulate a proactive safety strategy in metal powder laboratories.

Implementing these suggested enhancements will enable metal powder laboratories to fortify their safety measures, reduce hazards, and establish a secure working environment for all people managing metal powders.

2.6.1 Early Developments and Technological Milestones

Metal powder laboratories have a rich historical development that has marked critical technological advancements and milestones. The evolution of these laboratories can be traced back to the early experiments aimed at developing novel materials and understanding the properties of metal powders. One significant milestone in this evolution is the development of composite materials, such as the work by (Goroch et al., 2020), where they aimed to create a composite consisting of tungsten powder and other metal powders to achieve a density close to that of lead under laboratory conditions. This early research laid the foundation for exploring the potential applications of metal powders in various fields.

2.6.2 Particle-Level Understanding and Additive Manufacturing

As research advanced, the emphasis transitioned to comprehending the interactions and dynamics of metal powders at the particle level. Research such as that conducted by (Escano et al., 2018), which analyzed the dispersion dynamics of metal powders in additive manufacturing by high-speed X-ray imaging, yielded significant insights into the microstructural behavior of metal powders. These investigations were essential in enhancing the comprehension of metal particle behavior in various processing conditions, resulting in advancements in manufacturing processes.

2.6.3 Advancements in Methodologies and Applications

The advancement of metal powders using revolutionary procedures such as electrolysis has significantly enhanced the functionalities of metal powder laboratories. (Nikolić et al., 2021) Investigated the relation of the morphology and crystal structure of metal powders produced by electrolysis, with emphasis on the role played by crystallographic influences in dendritic growth. This paper explains the mechanism that underlies the production of metal powders through electrolysis; hence, contributing to the optimization of powder synthesis methods.

2.6.4 Progression of Imaging Technologies and Apparatus

Innovations in imaging technologies, such as X-ray computed microtomography, have transformed the characterization of metal powders. Studies such as that by (Muchavi et al., 2016), which considered X-ray computed microtomography of MIM and DPR components, have provided valuable insights into the microstructural features of sintered metal components. Researchers enhanced the quality and performance of metal powder products by analyzing the density and porosity of sintered components.

2.6.4 Specialized Equipment for Metal Powder Production

The advancement of specialized equipment for metal powder manufacture has significantly contributed to the growth of metal powder laboratories. Del Rio et al. (2022) Designed a laboratory-scale gas atomizer to manufacture metallic powders intended for use in the techniques of metal additive manufacturing. The device thus prepared tailor-made metal powders for specific uses, enabling their processing and treatment in a differentiated manner to improve their characteristics.

2.6.5 Optimization of Spraying Techniques and Additive Fabrication

On the other hand, efforts have been directed toward enhancing the spraying process to create spherical-shaped metal powders. Ermakovet al., (2020) Studied temperature and time parameters for the plasma atomizer spraying of metallic powders. The particle size and morphology have been controlled in developing technologies and methods to obtain spherical metal powders, which improves the quality and performance of the powder.

2.6.6 Additive Manufacturing Procedures

Advancements in additive manufacturing processes have driven the establishment of metal powder laboratories. Research such as that conducted by (Wei et al., 2023), which concentrated on forecasting the process-microstructure-property link in fusion-based metal additive manufacturing, has been essential in elucidating the influence of printing circumstances on the final microstructure and properties of printed components. Researchers have enhanced additive manufacturing techniques for metal powders through the integration of computational modeling and experimental validation.

2.6.7 Novel Applications in Energy Storage and Conversion

Furthermore, developing novel catalysts and electrochemical processes using metal powders has opened new avenues for energy storage and conversion applications. For instance, (Crockett et al., n.d.) explored the preparation of highly reactive lithium metal dendrites for synthesizing organolithium reagents, showcasing the versatility of metal powders in chemical synthesis. These advancements highlight the diverse range of applications that metal powder laboratories have explored.

The historical evolution of metal powder laboratories has been marked by an ongoing pursuit to comprehend the characteristics and behaviors of metal powders across different scales. Researchers have made substantial progress in using the potential of metal powders, from the early creation of composite materials to advanced additive manufacturing techniques and electrochemical applications. Through the integration of multidisciplinary approaches such as materials science, chemistry, and physics, metal powder laboratories have transformed into centers of innovation, propelling progress across various sectors.

2.7 Case Studies of Incidents and Lessons Learned

Examining case studies of occurrences and the insights gained in metal powder laboratories is essential for improving safety standards and averting similar accidents. Comprehending the fundamental causes of occurrences yields significant insights into the elements contributing to accidents, enabling laboratories to tackle underlying problems and execute specific preventative strategies. (Papadopoli et al., 2020). By assessing response techniques utilized in previous mishaps, laboratories might discern effective methods and enhance emergency response plans to guarantee a prompt and coordinated reply in analogous circumstances. (Stuart, 2023). Applying insights from case studies allows laboratories to strengthen their safety culture, refine risk management methods, and cultivate a proactive safety approach. By implementing this role-based strategy, laboratories can markedly improve their safety practices, mitigate hazards, and foster a proactive safety culture.

2.7.1 Analysis of Incidents and Root Causes

It is essential to draw insights from relevant references to analyze specific case studies of incidents in metal powder laboratories and understand the root causes, response strategies, and lessons learned. Hugelius et al. (2020) Note the issues encountered in managing mass casualty or disaster scenarios, highlighting the significance of case studies and lessons learned reports. Analyzing occurrences in metal powder laboratories reveals that comprehending the fundamental causes of accidents, formulating efficient reaction tactics, and applying lessons learned are essential for improving safety standards.

In metal powder laboratories, mishaps may include chemical exposures and equipment problems. According to Melmer et al., (2019), which emphasizes insights gained from mass casualty incidents, it is essential to ensure laboratory safety and establish emergency response protocols to effectively limit hazards. In the event of a chemical spill involving metal particles, immediate containment procedures and appropriate decontamination processes must be executed to safeguard laboratory personnel and avert further escalation of the situation.

2.7.2 Structured Investigation and Analysis

Furthermore, Drupsteen and Guldenmund (2014) Emphasize learning from incidents through structured investigation and analysis. Implementing this idea in metal powder laboratory mishaps necessitates comprehensive root cause analysis to uncover systematic failures or deficiencies in safety protocols. By comprehending the fundamental elements leading to mishaps, laboratories can execute specific corrective measures to avert analogous occurrences in the future.

2.7.3 Response Strategies and Lessons Learned

Savoia et al. (2012) discuss using action reports (AARs) to promote organizational learning in emergency preparedness. Documenting accidents via comprehensive reports and performing post-incident evaluations in metal powder laboratories can enhance organizational learning. By recording response techniques, outcomes, and lessons learned, laboratories may perpetually enhance their safety protocols and emergency preparation.

2.7.4 Anticipatory Risk Management

Drupsteen et al. (2013) Highlight the critical steps in learning from incidents to prevent future occupational safety and risk management accidents. This methodology could be very well applied in metal powder laboratories by analyzing organizational weaknesses causing safety accidents and improving those areas. It enables a laboratory to improve its safety culture through the early detection of weak points and other hazards, thereby preventing incidents well in advance.

2.7.5 Identification of Hazards and Evaluation of Risks

Moreover, the reference by Park and Vanderwal (2023) The lessons learned from an asphyxiation incident involving dry ice underscore the importance of understanding hazards associated with laboratory materials in metal powder laboratories, where reactive materials are routinely managed, it is imperative to prioritize hazard identification, risk evaluation, and the implementation of suitable safety protocols to avert accidents and safeguard staff.

In conclusion, by utilizing insights from case studies of incidents in metal powder laboratories and correlating them with lessons from diverse fields, such as emergency preparedness and occupational safety, laboratories can fortify their safety protocols, improve emergency response capabilities, and cultivate a culture of continuous improvement. Root cause analysis, incident reporting, organizational learning, and proactive risk management are essential components in safeguarding the safety and welfare of staff in metal powder laboratories.

2.8 Comparative Analysis of Safety Protocols

A comparative review of safety protocols in metal powder laboratories and additive manufacturing environments is crucial for finding best practices, common difficulties, and opportunities for standardization. By assessing safety protocols across multiple contexts, organizations can utilize insights to augment safety measures, reduce risks, and enhance operational efficiency. Comprehending the technical challenges and requirements for characterizing metal additive manufacturing powders, along with initiatives to standardize characterization methods, can guide the formulation of standardized safety protocols that mitigate specific risks linked to metal powders utilized in additive manufacturing processes. Slotwinski & Garboczi (2015). Evaluating occupational exposure risk assessments in powder-bed fusion processes within metal-additive production can aid in identifying potential dangers and formulating guidelines to reduce exposure to hazardous compounds in laboratory environments. (Dugheri et al., 2022b).

Furthermore, investigating the side effects of the laser-metal powder interaction in laser powder bed fusion processes can provide valuable insights into safety considerations related to material reuse and the efficient interaction between lasers and metal powders. (Santecchia et al., 2020). By investigating corrosion problems in metallic materials created by selective laser melting, organizations may formulate preventive strategies to mitigate material degradation and guarantee the durability and integrity of components manufactured through additive techniques. (Kong et al., 2019). By conducting a comparative analysis of safety protocols in metal powder laboratories and additive manufacturing environments, organizations can improve safety practices, tackle prevalent challenges, and strive for the standardization of protocols to foster a culture of safety and risk mitigation in these settings.

2.8.1 Handling Metal Powders in Additive Manufacturing

A comparative review of safety protocols across several laboratories or businesses is essential for identifying best practices, common difficulties, and opportunities for standardization. Analyzing many references about additive manufacturing, materials science, and powder metallurgy might yield significant insights to improve safety protocols in these domains.

One key aspect to consider is handling metal powders in additive manufacturing processes. References such as (Han et al., 2019; Rane & Strano, 2019) Shed light on preventing cracking in high-strength superalloys and the rapid production of metallic parts. Safety protocols in these laboratories should focus on minimizing exposure to fine metal powders, implementing proper ventilation systems, and ensuring the use of personal protective equipment to mitigate health risks associated with metal powder handling.

As discussed by Chiumenti et al. (2017), safety protocols should address the potential hazards of working with high-energy lasers and molten metal powders in the context of thermal analysis and numerical simulations in additive manufacturing. Protective barriers, safety interlocks, and regular equipment maintenance are essential for safety protocols to prevent laboratory accidents using blown powder technology.

2.8.2 Material-Specific Protocols

Furthermore, Ladani and Sadeghilaridjani (2021) Cite that, though there is progress in the fabrication of highly conductive metals such as copper and aluminum, their specific safety requirements need to be covered by the protocols. A lab working with the use of such material should have protocols regarding its safe handling, storage, and disposal to avoid accidents and protection of personnel.

As discussed in metallography and 3D printing of metal components (Murr, 2018), the safety protocols should adequately deal with metal powders, equipment maintenance, and personnel training on how to operate these complex additive manufacturing systems safely. Regular inspections, risk assessments, and emergency response drills are some of the main compositions of the safety protocols in laboratories involved in metal additive manufacturing.

Moreover, A. Jiménez et al.'s (2021) review of powder-based laser hybrid additive manufacturing emphasizes the importance of post-process technologies for producing metal parts with the required accuracy and material properties. Laboratory safety in using hybrid additive manufacturing solutions should concern any possible danger during post-processing, including heat treatment and surface finishing, so that not only people can be safe but also the integrity of the manufactured parts.

2.9 Psychological and Behavioural Considerations in Laboratory Safety

Psychological and human factors are crucial in laboratory safety, influencing safety practices and decision-making processes. Stress, fatigue, and cognitive biases can impact individuals' perception of safety, adherence to safety protocols, and decision-making under challenging circumstances. Studies have shown that workload, mental stress, job satisfaction, and organizational relationships significantly affect workers' safety in various settings, including laboratories. Idrees et al., (2017). Psychological safety, which allows individuals to voice concerns and take risks, is vital in fostering a safety culture and positively influencing safety practices in teams. (Diabes et al., 2021; Greene et al., 2020).

Moreover, decision fatigue, where decision quality decreases after prolonged decision-making sessions, can affect the ability to make sound judgments regarding safety protocols and risk management in laboratory settings (Hirshleifer Paul et al., 2018). Addressing these psychological and human factors is essential to enhance laboratory safety. Strategies to alleviate these issues may encompass the implementation of stress management programs, the promotion of open communication and psychological safety, the provision of sufficient rest periods to counteract fatigue, and the integration of decision-making assistance technologies to diminish cognitive biases (Liu et al., 2022). By acknowledging and mitigating these psychological and human aspects, laboratories may establish a safer work environment, refine decision-making processes, and elevate overall safety measures to avert accidents and foster a culture of safety.

2.9.1 Impact of Psychological Factors

Psychological and human factors significantly influence laboratory safety, impacting safety practices, decision-making, and overall safety culture. Stress, weariness, and cognitive biases are critical elements influencing humans in laboratory environments and may result in safety issues. (X. Wang et al., 2019) Underscore the significance of psychological safety within organizational contexts, noting that elevated stress levels might hinder decision-making and jeopardize safety. Training programs focusing on stress management, mindfulness, and open communication channels can help individuals cope with stress and maintain focus on safety protocols.

Fatigue is a significant factor influencing laboratory safety, as discussed by (Sallinen & Hublin, 2015). Fatigue leads to breakdowns in concentration, reduced vigilance, and accidents. Organizations can reduce the occurrence of fatigue through scheduling practices that allow rest breaks and support a work/life balance.

Cognitive biases, as discussed by Ménard and Trant (2020), Besides, the influences of confirmation bias and over-confidence biases may cause the person to show less care about the risks. The awareness of critical thinking training programs, including cognitive biases, reduces biases in decision-making when it comes to safety.

2.9.2 Strategies for Improving Laboratory Safety

O'Neil et al. (2021), underscore the importance of training in mitigating psychological and human aspects of laboratory safety. Integrating safety concepts and risk assessment into the educational curriculum helps foster a safety culture from the initial phases of laboratory work. Ongoing training and refresher courses can bolster safety protocols.

Organizational culture significantly influences safety procedures, as articulated by Abdallah et al. (2019). Organizations that emphasize safety, cultivate open communication, and promote the reporting of near misses establish an environment conducive to psychological safety. Commitment from leadership, explicit safety policies, and a culture of accountability are vital for establishing a robust safety culture in laboratories. Addressing stress, exhaustion, and cognitive biases through specialized training programs can enable staff to make educated safety decisions and successfully limit risks. Encouraging a constructive safety culture, facilitating transparent communication, and emphasizing safety across all organizational tiers are essential measures to improve laboratory safety and safeguard staff welfare.

2.10 Progress in Safety Equipment and Technologies

Recent development in the field of safety equipment and technology for the metal powder laboratory introduces new ideas for personal protective equipment, enhanced ventilation, and sophisticated fire suppression systems. Some of the polymer 3D printing technologies also applied to fabricate specific personal protective equipment for metal powder laboratory applications can provide better protection and comfort in handling metallic powders. (Arefin et al., 2021). Furthermore, innovations in ventilation systems have concentrated on enhancing air quality and minimizing exposure to airborne pollutants in laboratories, guaranteeing a safer working environment for staff. (Cho et al., 2022). Moreover, the advancement of sophisticated fire suppression systems, including novel gas hydrate technology, has improved fire safety protocols in metal powder laboratories, offering effective methods for addressing fires involving flammable metals. (Gaidukova et al., 2023). Safety procedure improvements can be achieved with many improvements in safety procedures in metallic powder laboratories by integrating advanced safety equipment and technologies, and there is also a reduction of risks when one is exposed to metallic powders.

2.10.1 Advancements in Personal Protective Equipment (PPE)

These modern developments in the field of safety equipment and technologies used in handling metal powder-based lab work have improved the safety scenario and reduced hazards while handling metal powder considerably. All PPEs, ventilation facilities, fire suppression facilities, and monitoring facilities have rapidly developed to enhance the standard of safety in the laboratory.

Special personal protective equipment developed in the metal powder laboratory was a milestone development in this field. (Albertus et al., 2021; Tu et al., 2015) Conducted studies related to personal protective devices with improvements that could keep factory workers away from hazardous chemical exposure, especially from metallic elements. High-performance gloves, goggles, and respiratory protection are some high-tech personal protective equipment fabricated by advanced material technologies in order to enhance safety and comfort for professionals around the laboratory.

2.10.2 Improved Ventilation and Fire Suppression Systems

Ventilation systems have experienced substantial enhancements to regulate airborne pollutants in metal powder facilities. Nanostructured electrolytes, as examined by Tu et al. (2015), have improved the stability of lithium electrodeposition in secondary batteries, therefore diminishing the risk of exposure to toxic fumes. Advanced ventilation systems featuring HEPA filters and air quality monitoring have been implemented to maintain a secure working environment and reduce the inhalation of metal powder particles.

Fire suppression systems specifically designed for metal laboratories have been created to mitigate the distinct fire risks posed by flammable metal powders. References such as Zhu et al. (2018) emphasize the necessity of employing fire suppression systems that comply with NFPA regulations to prevent and control fires in laboratories managing flammable metals. Advanced fire suppression technologies like inert gas systems and automatic sprinklers have been integrated to extinguish fires and safeguard laboratory assets promptly. Recent advancements in safety equipment and technologies tailored for metal powder laboratories have transformed safety practices and significantly enhanced safety outcomes. Improvements in personal protective equipment, ventilation, fire suppression systems, and monitoring technologies have better protected workers, reduced the risks of working with metal powders, and inculcated a safety culture in the laboratory. With the use of this technology and knowledge of what is yet to come, laboratories processing metal powders can keep focusing on safety, reduce possible risks, and protect employees.

3 Research Design

This study employs a mixed-methods approach, integrating quantitative and qualitative data to examine laboratory safety culture in metal powder laboratories thoroughly. The research design centers on the dual collection of environmental data through high-precision sensors and qualitative insights from laboratory personnel interviews. This model gives insight into technical and human factors influential in laboratory safety and thus allows for the elaboration of effective management of risks. A mixed-methods design offers the advantage of balancing quantitative measurements against depth from the qualitative perspective, important for the comprehensive capture of how environmental conditions and human behavior interactively influence safety in the laboratory.

3.1 Methodology

The methodology will integrate both quantitative sensor data and qualitative insights into analyzing prevailing practices for safety and the identification of areas for improvement. Such quantitative data to be measured in real-time includes temperature, humidity, and particulate matter levels, using sensors installed in the laboratory. Qualitative data will be obtained through semi-structured interviews with the laboratory assistants regarding perceived risks, current safety practices, and possible improvements. This work combines standardized safety culture assessment tools, adapted to include sensor data analytics, and extends the holistic view of safety management of metal powder laboratories by covering environmental risks and human aspects.

Quantitative analysis involves descriptive statistics, correlation analysis, and regression to identify patterns and predictors of safety incidents. In contrast, qualitative thematic analysis uncovers recurring themes related to human perceptions of safety, attitudes toward safety protocols, and communication barriers. This dual approach enables a deeper understanding of the dynamic factors that shape laboratory safety culture, with quantitative data highlighting objective risk factors and qualitative data providing insights into subjective perceptions and behaviors.

3.2 Data Collection

Quantitative data were recorded in real time from sensors installed within the laboratory environment. Sensors in continuous operation monitored ongoing processes and captured the essential parameters of temperature, humidity, and particulate matter levels of PM10, PM2.5, and PM100. Real-time data collection has therefore been crucial in the identification of possible risk factors and the dynamical conditions in metal powder laboratories.

Apart from the quantitative data, qualitative information was retrieved through semi-structured interviews with laboratory assistants in the metal powder laboratory. These interviews were meant for in-depth responses with regard to perceived risks, safety practices, and suggested improvements. The semi-structured nature of these interviews allowed the participants to explain in detail both experiences and perspectives; hence, there would be a deeper understanding of the human factors that involve laboratory safety.

Standardized tools to assess safety culture in the laboratories were adopted and adapted to integrate sensor data analytics. The tool allowed for an all-round assessment of the then-present state of the safety culture, such as in the identification, monitoring, and mitigation of risks. This proposal integrates quantitative sensor data with in-depth qualitative interview responses to holistically investigate safety practices and perceptions, taking into consideration both environmental and human factors.

3.3 Quantitative Data Analysis

In this respect, quantitative data analysis encompasses several necessary statistical techniques for sensor data interpretation: the so-called descriptive statistics, that is, arithmetic mean, median, standard deviation, and calculation of the range for summarizing the central tendency, dispersion, and distribution of the environment variables. These metrics will be important in observing patterns, outliers, and trends of laboratory conditions and hence give a base understanding of factors that influence safety. For example, the average particulate matter concentration indicates the level of exposure while the standard deviation denotes the variability in the level of exposure.

Correlation analysis follows the descriptive one in order to show the relations existing between the different environmental parameters. In this context, the Pearson correlation coefficient will be used to estimate the linear relationship between the temperature, humidity, and particulate matter levels (PM10, PM25, and PM100) expressed by a number ranging from -1 to +1. The number -1 means a perfect negative correlation, the number +1 means a perfect positive correlation, and the number 0 indicates no relationship. This analysis seeks to check whether variations in temperature and humidity result in changes in the concentration of particulate matter, with the possible aim of discovering risk factors that may correlate with safety incidents.

Multiple linear regression analysis is then performed to explore these relationships further. This technique models the relationship between independent variables (temperature, humidity) and the dependent variable (particulate matter levels). The following equation represents the regression model:

$$PM = \beta 0 + \beta 1 \times Temperature + \beta 2 \times Humidity,$$

Where PM represents particulate matter levels, β0 is the intercept, and β1 and β2 are the coefficients for temperature and humidity, respectively. The coefficients indicate the estimated change in particulate matter levels for a one-unit change in temperature or humidity, assuming other factors are constant. The significance of these relationships is evaluated using p-values, with values below 0.05 typically indicating statistical significance. This regression analysis helps identify critical predictors of particulate matter levels and understand the extent of their impact.

3.4 Qualitative Data Analysis

Such quantitative findings may be complemented by qualitative data analysis, which could provide more insight into those human factors influencing laboratory safety culture. Thematic analysis will be the primary method for systematic identification, analysis, and reporting of patterns within interview data.

Interviews are first transcribed verbatim to ensure the transcription is as accurate as possible. After transcription, the coding of data begins, by which segments are labeled regarding critical themes about safety culture, risk perception, and safety practices. The codes have been organized into bigger themes capturing repeated ideas and insights from interview responses, including, among others, safety concerns, perception of risks, and improvement suggestions.

Once themes are identified, they are interpreted within the broader context of laboratory safety. This involves exploring the relationships between themes and other aspects of the safety culture, such as communication barriers or attitudes toward safety protocols. The insights from thematic analysis highlight how human factors—such as communication, compliance, and perception of safety measures—affect overall safety behavior.

By integrating qualitative and quantitative insights, this study provides a comprehensive view of the factors affecting safety in metal powder laboratories. This combined approach ensures that both technical and human dimensions of safety are thoroughly examined, leading to more informed and practical recommendations for improving safety culture and risk management practices.

3.5 Summary of Methodology

This chapter outlines the detailed mixed-methods approach adopted to examine and enhance safety culture and risk management in metal powder laboratories. By integrating quantitative environmental sensor data and qualitative interviews, the study aims to provide a comprehensive understanding of the various factors influencing laboratory safety.

The quantitative methods focus on monitoring and analyzing environmental conditions that contribute to immediate safety risks, while qualitative interviews offer deeper insights into the human and cultural aspects of safety. By combining these methods, the research ensures a holistic analysis that accounts for both technical and behavioral dimensions.

This methodological framework provides a solid foundation for the subsequent analysis and interpretation of data, leading to practical recommendations for improving safety practices and management strategies in metal powder laboratories:

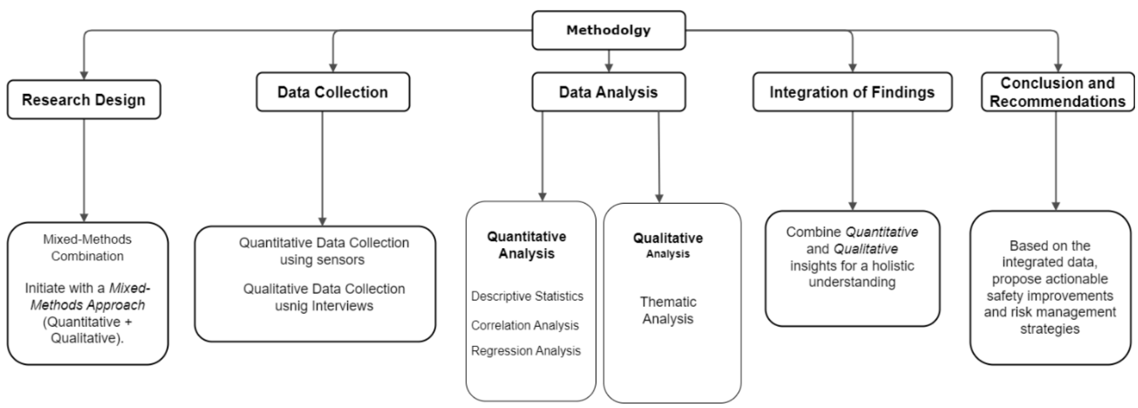

Figure 2: Methodology Framework

4 Data Collection

The paper provides a detailed description of data collected from the environmental sensors in the metal powder laboratory on particulate matter levels-PM10, PM25, and PM100-as well as temperature and humidity over two different periods, which are the last seven and the last 14 days. The patterns, correlations, and eventual causes for fluctuation in the particulate matter level are to be determined with a view to enhancing laboratory safety and working conditions.

Data was collected using two high-precision environmental sensors, C61EA3 and C69841, which continuously recorded PM10, PM25, PM100, temperature, and humidity over the specified periods. These sensors were strategically placed to ensure comprehensive coverage of different laboratory areas, capturing various environmental and process data. Collected data were stored in a central database. Data were then analyzed for trends and correlations amongst the environmental variables of temperature, noise, and light. These are all determinant parameters given the safety improvement and operational efficiency in the laboratory. Analysis will help enhance our understanding of environmental factors that affect the safety of laboratories besides mitigation strategies for the known potential risks.

4.1 Temperature, Humidity, and Particulate Matter Analysis

Figure 1 shows the trends of particulate matter (PM10, PM2.5, PM100) along with temperature and humidity variations recorded over an approximate period of nine days. The data analysis presents several findings related to the conditions in the environment and the laboratory’s risks.

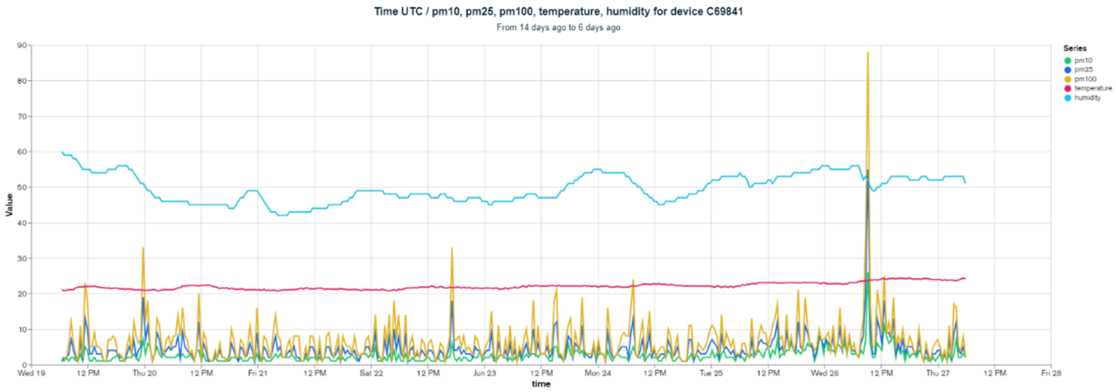

Figure 3. An overview of Time UTC vs.-/ pm 10, pm25, pm100, Temperature, and Humidity for Device C69841

The analyzed temperature and humidity over the period are fairly stable, running at about 20°C, indicating good mechanisms of control in place, while humidity exhibits a greater variation between approximately 40 and 60%, with slight inclinations towards the upward swing on the period closer to the end. This variability in humidity indicates potential challenges in maintaining consistent levels despite the stable temperature.

Particulate matter (PM10, PM2.5, PM100) levels show significant fluctuations throughout the period, with several notable spikes. One particularly significant spike occurs around noon on Wednesday, the 26th when PM levels surge well above baseline. These low baseline levels indicate well-maintained air quality under normal conditions. However, the frequent spikes point to periodic activities or incidents that temporarily elevate particulate matter levels. Investigating these spikes is crucial, as they may correlate with specific laboratory activities or equipment usage.

There generally shows a negative relation between Temperature and Humidity, which is quite normal in most environments. The behavior of the particulate matter levels concerning the temperature and humidity in the lab is rather atypical. The peaks in particulate matter concentrations are unrelated to temperature and humidity changes; therefore, certain activities carried out in the lab drive PM levels.

These significant spikes in particulate matter have severe implications for laboratory safety. The higher concentrations of PM10 and PM2.5 pose a respiratory risk for workers and may interfere with sensitive tests. Knowing the sources of these excursions enables mitigation to reduce risks and enhance safety. The results show that further mitigation strategies will be needed to further control the particulate matter concentration, at least for those selected activities emitting larger amounts of particulate matter. This can be accomplished by enhancing ventilation, developing more effective dust mitigation methods, or reducing the number of workers during high-risk activities.

4.2 Environmental Analysis

The graph in Figure 2 shows the variations in particulate matter (PM10, PM25, PM100), temperature, and humidity over approximately nine days. The data provides insights into the laboratory's environmental conditions and potential risks.

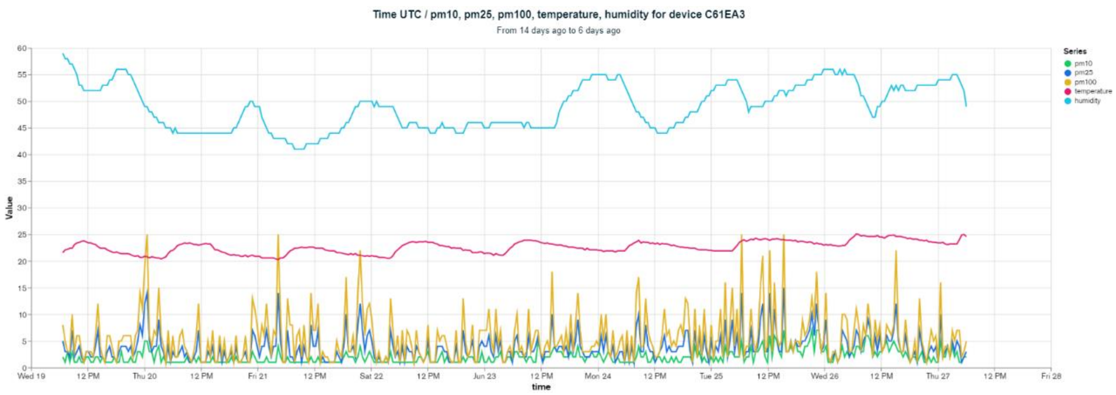

Figure 4. Time UTC / pm 10, pm25, pm100, Temperature, Humidity for Device C61EA3

The laboratory temperature ranges from 20°C to 25°C, which reflects that the proper controlling means are present for maintaining a constant atmosphere; still, relative humidity ranges from about 40% to 55%. This suggests potential challenges in maintaining consistent humidity levels despite the controlled temperature. Particulate sensor matter (PM10, PM25, PM100) levels exhibit notable fluctuations over the observed period. Several spikes, particularly in PM10 and PM25 levels, indicate periodic increases in particulate matter. These spikes often reach values significantly higher than baseline levels, suggesting that specific events or activities within the laboratory are responsible for these increases. Despite generally low baseline levels indicating good air quality under normal conditions, the frequent spikes highlight activities or incidents that periodically elevate particulate matter concentrations. Investigating these spikes is crucial as they may correlate with specific laboratory processes or equipment usage.

The relationship between temperature, humidity, and particulate matter is complicated. Relatively invariant trends in temperature and humidity, whereas particulate matter has huge variation. The peaks of particulate matter appear not to exactly act accordingly when there is a change in either temperature or humidity, meaning there might be some other influencing factors. High concentrations of particulate matter, especially PM10 and PM25, can present respiratory effects on laboratory workers and may affect the integrity of experiments. Identification of these causes will be important in mitigating risks and improving safety in the laboratory.

4.3 Analysis of Temperature Data from Two Devices

The graph in Figure 3 presents temperature data in Celsius from two devices (C61EA3 and C69841) over approximately nine days. Analyzing this data reveals insights into the consistency and reliability of temperature control within the laboratory environment.

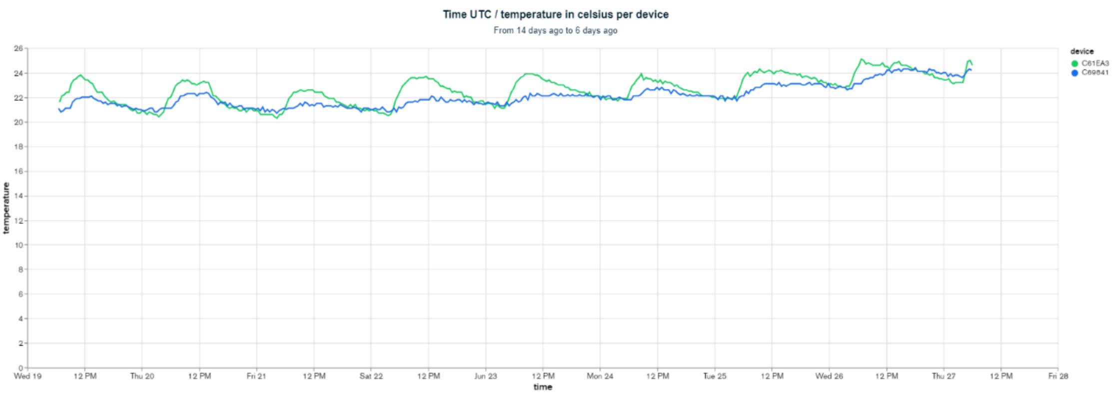

Figure 5. Time UTC / Temperature in Celsius per Device

The temperature data from both devices, C61EA3 (green) and C69841 (blue) indicate fluctuations within the range of 20°C to 25°C, demonstrating a relatively stable environment with occasional minor variations. The readings from both devices are closely aligned, suggesting good consistency between the sensors. However, device C61EA3 consistently records slightly higher temperatures than device C69841, indicating a possible calibration difference. Despite this offset, the overall trend and pattern of temperature fluctuations are very similar, showing that both devices effectively capture environmental temperature changes.

The comparison of data from devices C61EA3 and C69841 reveals similar patterns, with the green device consistently showing slightly higher temperatures. This consistent offset suggests a calibration difference between the two sensors. The temperature data also shows periodic peaks, particularly noticeable around the exact times on different days. For instance, there are noticeable peaks on Thursday 20th, Friday 21st, and Sunday 23rd, where the temperature rises to around 24°C before returning to a baseline near 21°C. These peaks might correspond to daily cycles or specific lab activities, indicating that certain activities or external conditions influence the temperature within the laboratory at regular intervals.

The same temperature range indicates that the lab is in a controlled setting, which is very much necessary to run experiments accurately or to protect workers and equipment from damage. There are minor oscillations, but they are all in an acceptable range; periodic peaks must be researched further in order to understand their origin and to make sure that they will not impact general laboratory conditions negatively. These peaks can be pinpointed either to specific laboratory activities or outside factors, thus informing adjustments in schedules and the adoption of additional controls that are required to minimize their impacts on laboratory operations.

4.4 Analysis of Humidity Data from Two Devices

The graph below in Figure 4 displays humidity data from two devices (C61EA3 and C69841) over approximately nine days. This analysis provides insights into the consistency and reliability of humidity control within the laboratory environment.

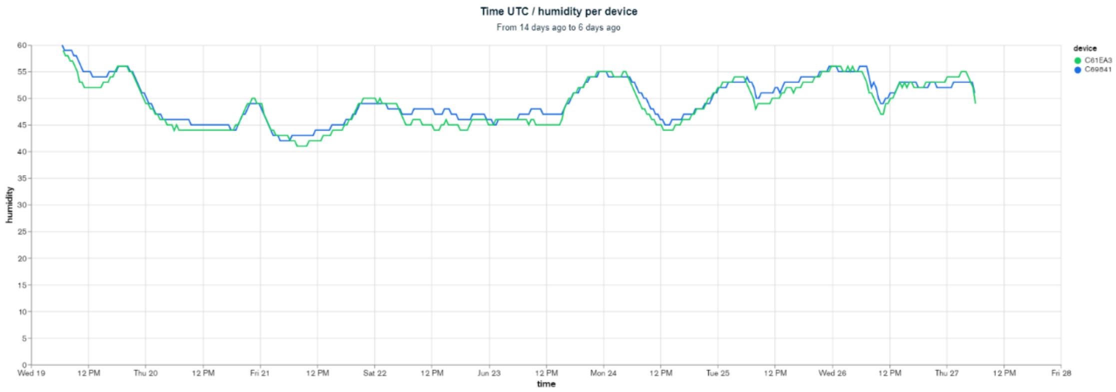

Figure 6. Time UTC / Humidity per Device

The humidity data from both devices, C61EA3 (green) and C69841 (blue) show fluctuations between approximately 40% and 60%, indicating a controlled environment with notable variations. The readings from both devices are closely aligned, suggesting good consistency between the sensors. The close alignment of the readings from both devices indicates reliable humidity measurements and suggests that both sensors effectively capture environmental humidity changes.

The various plots all indicate that there is little deviation between the output from device C61EA3 versus device C69841. The humidity can be observed to periodically sag and then recover, most easily now and then. Note, for example, apparent sags in humidity on Thursday the 20th, Friday the 21st, and Monday the 24th, where it sags to about 40% and then again rises to approximately 55%. These fluctuations indicate that something is acting cyclically on the laboratory humidity through activities or external conditions. If this activity or condition were known, it could be better managed and controlled with humidity levels to keep the environment stable for sensitive experiments.

The small variation in humidity is indicative of a very stable test range, very important in keeping the laboratory conditions right for good experimental results and the safety of personnel and equipment. On the other hand, the trend observed shows specific times of day and activities that readily influence humidity levels. Further analysis of this periodic fluctuation could be made to understand the root causes behind them and take proper measures to dampen its effects. Maintaining a uniform level of humidity is important because it ensures no degrading of building materials and falsifying effects on the experiment's reliability.

4.5 Analysis of PM10 Data from Two Devices

The graph in Figure 5 shows the PM10 levels recorded by two devices (C61EA3 and C69841) over approximately nine days. This analysis provides insights into particulate matter (PM10) concentrations and their variations within the laboratory environment.

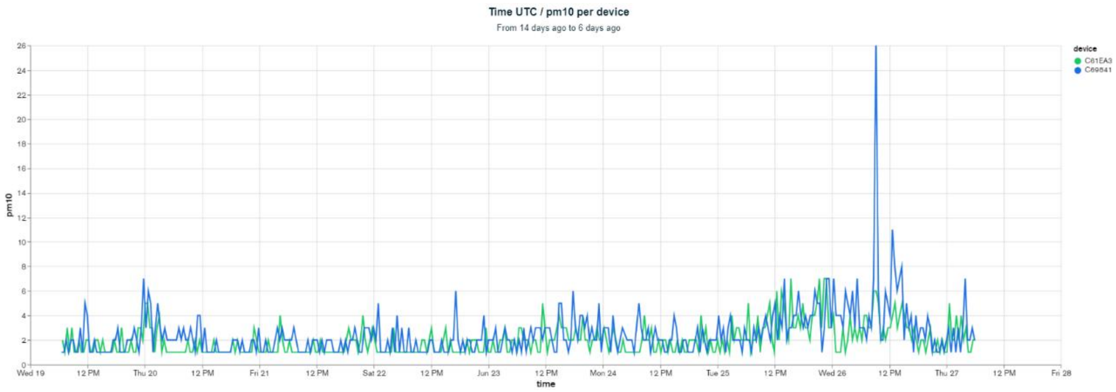

Figure 7. Time UTC / (pm 10) Particular Matter levels per Device

Particulate Matter, or PM, refers to those solid particles and liquid droplets occurring in the air. Generally, PM10 refers to those particles which have a diameter of 10 micrometers or smaller. The possible particles within it include dust, pollen, mold, and other forms of substances that may be easily inhaled into the respiratory system and lead to serious health manifestations, especially of the lungs and heart.

The PM10 levels exhibit significant fluctuations throughout the observed period. The data reveals multiple spikes in PM10 concentrations, with one particularly notable spike occurring around noon on Wednesday 26th, where the blue device (C69841) records a value exceeding 24 µg/m³. The baseline PM10 levels for both devices are generally low, indicating good air quality under normal conditions. The frequent spikes in PM10 levels suggest that certain activities or incidents within the laboratory intermittently elevate particulate matter concentrations, which could be due to processes such as material handling, cleaning, or equipment usage.

4.5.1 Device Comparisons and Observations

The PM10 readings from both devices are closely aligned, although the blue device (C69841) shows slightly higher spikes than the green device (C61EA3). This alignment indicates consistent monitoring of particulate matter across both devices despite some variation in spike magnitudes. The close agreement between the devices confirms the reliability of the PM10 data collected.

The PM10 data shows multiple spikes, which may correspond to specific activities or events within the laboratory. For instance, the significant spike on Wednesday, the 26th, suggests an incident or activity that caused a substantial increase in particulate matter. These spikes could be attributed to actions such as opening powder containers, mechanical processing of materials, or disturbances in dust-prone areas. Other smaller spikes are observed throughout the period, indicating periodic increases in PM10 levels. Understanding the timing and causes of these spikes can help adjust operational protocols to minimize particulate matter emissions.

4.5.2 Implications for Laboratory Conditions

High levels of PM10 in the spikes pose respiratory risks to laboratory personnel and may affect the integrity of experiments. Diseases such as asthma, bronchitis, and other respiratory diseases might be brought about by high concentrations of particulate matter. The high level of PM10 may contaminate experimental set-ups, hence yielding compromised results with lower accuracy.

Also, the identification of causes will contribute much to the minimization of risks by improving safety. Particulate matter concentration could be reduced with appropriate improvements in ventilation systems, local exhausts, and stringent containment during periods of higher activity. The generally low baseline PM10 levels suggest that air quality is well-maintained under normal conditions, but periodic activities significantly impact particulate matter concentrations. By understanding and addressing the sources of these spikes, the laboratory can ensure a safer environment for personnel and maintain the integrity of its experimental processes.

4.6 Analysis of PM2.5 Data from Two Devices

The graph below in Figure 6 shows the PM2.5 levels recorded by two devices (C61EA3 and C69841) over approximately nine days. This analysis provides insights into delicate particulate matter (PM2.5) concentrations and their variations within the laboratory environment.

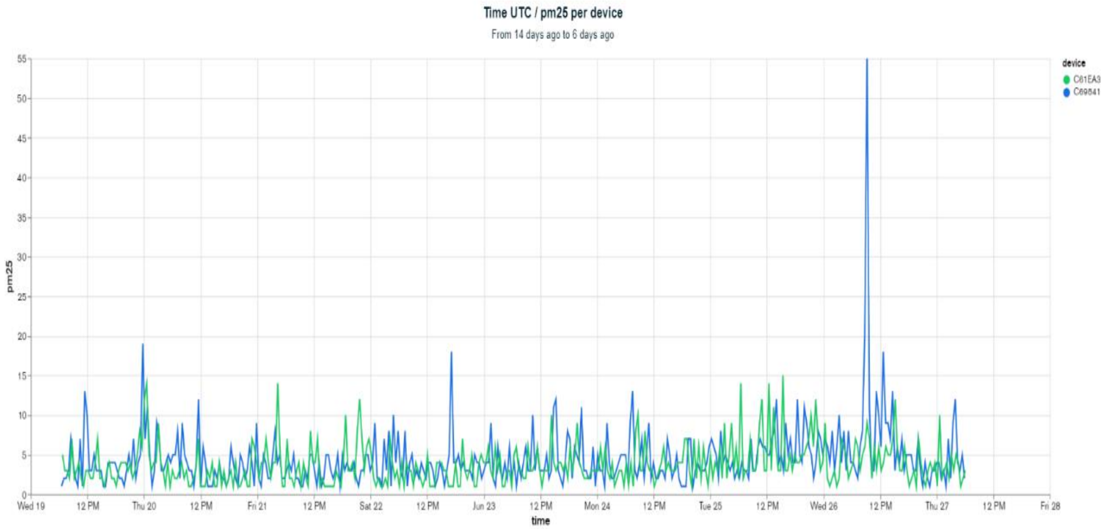

Figure 8. Time UTC / (pm 25) Particular Matter levels per Device

4.6.1 PM2.5 Sensor Analysis

The PM2.5 levels exhibit significant fluctuations throughout the observed period. The data reveals multiple spikes in PM2.5 concentrations, with one particularly notable spike occurring around noon on Wednesday, the 26th when the blue device (C69841) recorded a value exceeding 50 µg/m³. The baseline PM2.5 levels for both devices are generally low, indicating good air quality under normal conditions.

4.6.2 Device Comparisons and Observations

The PM2.5 readings from both devices are closely aligned, although the blue device (C69841) shows slightly higher spikes than the green device (C61EA3). This alignment indicates consistent monitoring of delicate particulate matter despite some variation in spike magnitudes. The PM2.5 data shows multiple spikes, which may correspond to specific activities or events within the laboratory. For instance, the significant spike on Wednesday, the 26th, suggests an incident or activity that caused a substantial increase in delicate particulate matter. Other smaller spikes are observed throughout the period, indicating periodic increases in PM2.5 levels.

4.6.3 Implications for Laboratory Conditions

The spikes in the levels of PM2.5, therefore, create respiratory risks for laboratory personnel and will affect the integrity of experiments. It becomes of the essence that these spikes are traced to their source for mitigation to ensure improved safety. Generally, the low baseline of PM2.5 levels indicates that under normal conditions, air quality is well maintained, while periodic activities greatly impact acceptable particulate matter concentrations.

4.7 Analysis of PM100 Data from Two Devices

The graph in Figure 7 shows the matter PM100 levels recorded by two devices (C61EA3 and C69841) over approximately nine days. This analysis provides insights into large particulate matter (PM100) concentrations and their variations within the laboratory environment.

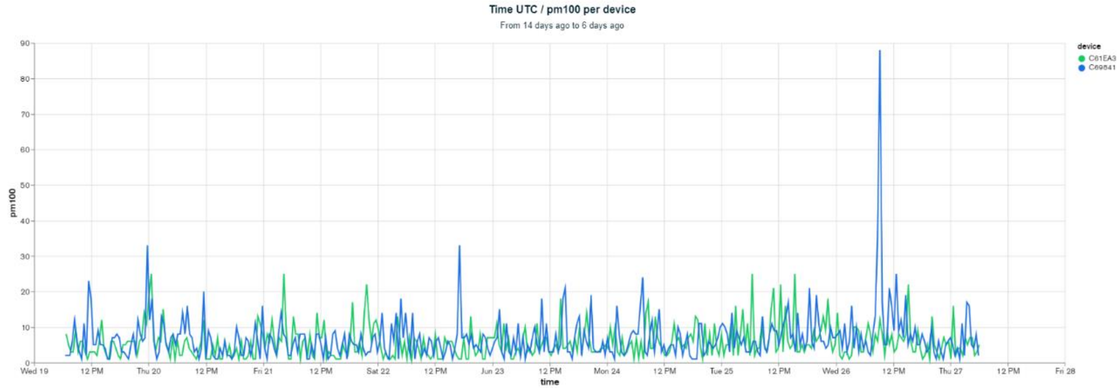

Figure 9. Time UTC / (pm 100) Practical matter level per Device

4.7.1 PM100 Sensor Analysis

The PM100 levels exhibit significant fluctuations throughout the observed period. The data reveals multiple spikes in PM100 concentrations, with one particularly notable spike occurring around noon on Wednesday 26th, where the blue device (C69841) records a value exceeding 80 µg/m³. The baseline PM100 levels for both devices are generally low, indicating good air quality under normal conditions.

4.7.2 Device Comparisons and Observations

The PM100 readings from both devices are closely aligned, although the blue device (C69841) shows slightly higher spikes than the green device (C61EA3). This alignment indicates consistent monitoring of large particulate matter despite some variation in spike magnitudes. The PM100 data shows multiple spikes, which may correspond to specific activities or events within the laboratory. For instance, the significant spike on Wednesday, the 26th, suggests an incident or activity that caused a substantial increase in large particulate matter. Other smaller spikes are observed throughout the period, indicating periodic increases in PM100 levels.

4.7.3 Implications for Laboratory Conditions

These spikes portend a very high level of PM100, which can allow respiratory exposure to the laboratory personnel and also perhaps affect the integrities of the experiments.

Causes should be found for mitigation of risks and improvement in the safety protocols. The generally low baseline PM100 levels suggest that air quality is well-maintained under normal conditions, but periodic activities significantly impact large particulate matter concentrations.

4.8 Comprehensive Analysis of PM10, PM2.5, and PM100 Data

The graph below shows the particular matter PM10, PM2.5, and PM100 levels recorded by device C69841 over approximately nine days. This analysis provides insights into the concentrations of different particulate matter sizes and their variations within the laboratory environment.

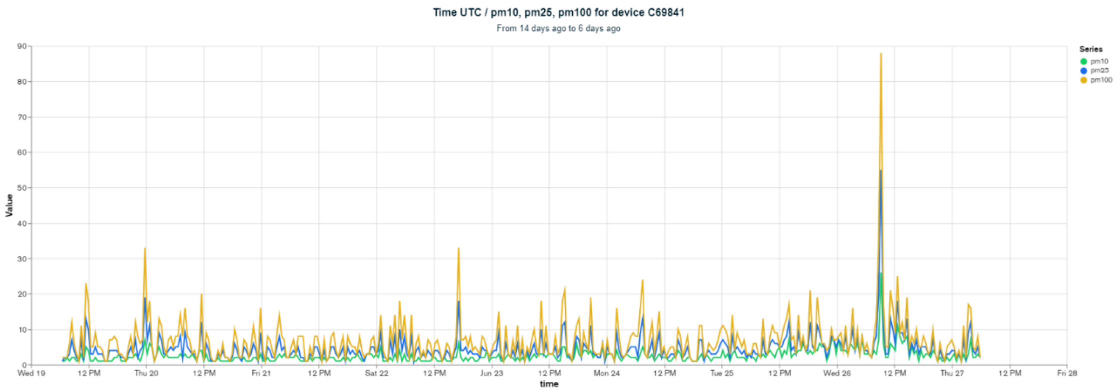

Figure 10. Time UTC / (pm10, pm25, pm100) particular matter lever for Device C69841

4.8.1 Particulate Matter Analysis

The data exhibits significant fluctuations in particulate matter (PM10, PM2.5, PM100) levels throughout the observed period. Notably, there are multiple spikes across all particulate matter sizes, with one particularly prominent spike occurring around noon on Wednesday, the 26th when PM100 levels exceed 80 µg/m³. The baseline levels for all particulate matter sizes are generally low, indicating good air quality under normal conditions.

4.8.2 PM10, PM2.5, and PM100 Analysis

The variations of PM10 are periodic, giving spikes at about day 1 and day 7, indicating specific activities or incidents in the laboratory causing an increase in the PM10 concentration. While variations of PM2.5 are of the same trend manifestation as PM10, during the period considered, it also contains many spikes. This spike on day 7 follows the trend of both PM10 and PM100 levels as well and indicates that the increase of the delicate particulate matter emanates from the very same source or activity. Of the three, the PM100 levels are the most varied, with the maximum spike recording over 80 µg/m³ on day 7. This would tend to suggest a major event that increased the large particulate matter inside the laboratory by a great margin. The trends across PM10, PM2.5, and PM100 indicate that the same activities or incidents that affect all sizes of particulate matter create a respiratory risk to personnel and possibly affect experimental integrity within the laboratory. Finding the origins of these spikes thus becomes very important in mitigating risks and enhancing safety protocols.

4.8.3 Correlation and Implications

The correlation between the PM10, PM2.5, and PM100 spikes suggests that the same activities or incidents impact all particulate matter sizes. The elevated levels during these spikes pose respiratory risks to laboratory personnel and can affect the integrity of experiments. For instance, the reasons behind such a spike would be the first things to look at in mitigation and safety improvement. Generally, PM10, PM2.5, and PM100 overall data for device C69841 are indicative of generally good air quality but punctuated by periodic attention-getting spikes. By implementing continuous monitoring, correlating activities with particulate matter spikes, and enhancing ventilation and protective measures, the laboratory can improve safety and maintain a healthier environment for personnel. Identifying and mitigating the sources of particulate matter spikes will be crucial in ensuring a safe and controlled laboratory setting.

4.9 Comprehensive Analysis of PM10, PM2.5, and PM100 Data for Device C61EA3

The graph below in Figure 9 shows the particular matter PM10, PM2.5, and PM100 levels recorded by device C61EA3 over approximately nine days. This analysis provides insights into the concentrations of different particulate matter sizes and their variations within the laboratory environment.

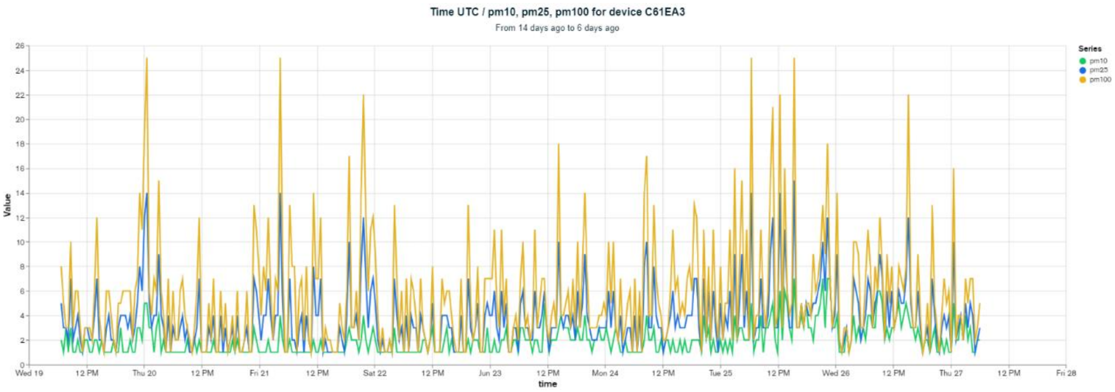

Figure 11. Time UTC / (pm10, pm25, pm100) Particular Matter Level for Device C61EA3

4.9.1 Particulate Matter Analysis

The data exhibits significant fluctuations in particulate matter (PM10, PM2.5, PM100) levels throughout the observed period, with multiple spikes across all particulate matter sizes and frequent peaks reaching up to 25 µg/m³. PM10 levels show periodic spikes, suggesting specific activities or incidents within the laboratory result in elevated concentrations, typically coinciding with PM2.5 and PM100 increases. Similarly, PM2.5 levels display multiple spikes, indicating a common source or activity causing these increases. PM100 levels exhibit the most substantial fluctuations, with spikes reaching up to 25 µg/m³, indicating significant events causing dramatic increases in sizeable particulate matter. The correlation between the PM10, PM2.5, and PM100 spikes suggests that the same activities or incidents impact all particulate matter sizes. These elevated levels pose respiratory risks to laboratory personnel and can affect the integrity of experiments, necessitating identifying and mitigating these sources for improved safety protocols. The comprehensive data for PM10, PM2.5, and PM100 from device C61EA3 indicates generally good air quality with periodic spikes that require attention. By implementing continuous monitoring, correlating activities with particulate matter spikes, and enhancing ventilation and protective measures, the laboratory can improve safety and maintain a healthier environment for personnel. Identifying and mitigating the sources of particulate matter spikes will be crucial in ensuring a safe and controlled laboratory setting.

4.10 Analysis of Temperature and Humidity Data for Device C69841

The graph illustrates the variation in temperature and humidity over approximately nine days, as recorded by device C69841. The key observations and analyses are based on the data in the graph below.

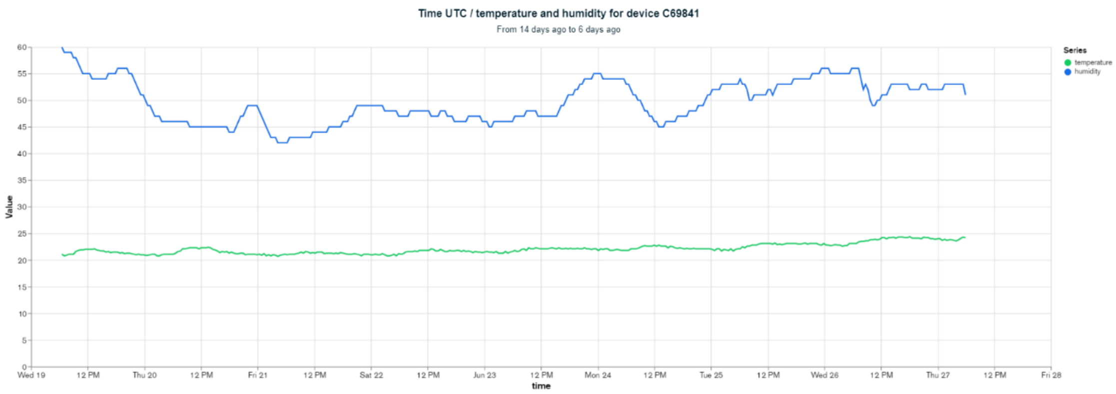

Figure 12. Time UTC / Temperature and Humidity for Device C69841

4.10.1 Temperature and Humidity Analysis

The temperature remains relatively stable, slightly around 20°C to 25°C, indicating a well-regulated laboratory environment. This consistency suggests effective control mechanisms are in place, essential for both personnel comfort and experimental integrity. In contrast, humidity shows more significant variations, ranging from 40% to 55%. The cyclical patterns in the humidity data suggest that these variations may correspond to daily cycles or specific events within the laboratory. Periods of rising and falling humidity indicate that external factors or internal processes might influence humidity levels.

The relationship between temperature and humidity appears relatively independent. While the temperature remains stable, humidity exhibits a more dynamic pattern, suggesting that different factors influence these parameters. Identifying these factors can help us better understand laboratory conditions.

4.10.2 Implications for Safety and Laboratory Conditions

The narrow temperature range oscillation testifies to the stability of the environment very important point for keeping the experimental conditions at the same level, which also corresponds to the minimum thermal stress for personnel and equipment. The fact of changing even within acceptable limits tells about some deficiency in the mechanisms of control that should be perfected. Indeed, high humidity could alter some properties of metal powders and enhance risks of corrosion or agglomeration, hence maintaining optimum levels of humidity is very important for laboratory safety and integrity of experiments.

The temperature and humidity data recorded on the device C69841 reflect a well-conditioned lab environment: a stable temperature pattern and moderate changes in humidity levels. In the process of maintaining an ideal situation for safety and experimental accuracy, the laboratory will be able to act through continuous monitoring, detailed analysis, and strengthened environmental controls. By finding and rectifying what influences humidity fluctuation, the lab can be made completely stable and safe.

4.11 Analysis of Temperature and Humidity Data for Device C61EA3

The graph provided shows the variation in temperature and humidity over approximately nine days, as recorded by device C61EA3. The following observations and analyses are based on the data below.

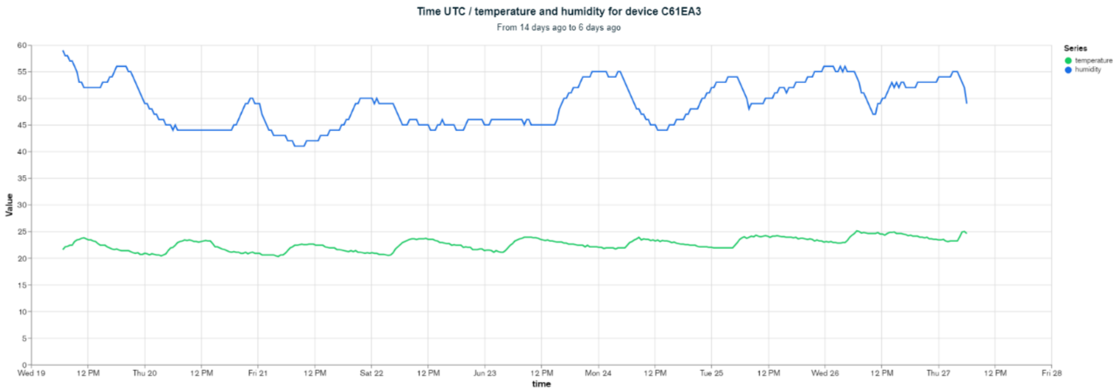

Figure 13. Time UTC / Temperature and Humidity for Device C61EA3

4.11.1Temperature and Humidity Analysis

The temperature remains relatively stable, fluctuating between approximately 20°C and 25°C, indicating a well-regulated laboratory environment with minor variations. This consistent control suggests that effective environmental mechanisms are essential for maintaining experimental integrity and personnel comfort. Conversely, humidity shows more significant variations, ranging from 40% to 60%, with periodic cycles indicating potential daily or specific laboratory events influencing humidity levels.

The relationship between temperature and humidity in this dataset appears relatively independent. While the temperature remains stable, humidity shows more dynamic patterns. Identifying the factors influencing these variations can help improve the overall understanding of the laboratory environment.

The stable temperature range indicates a well-regulated environment, which is crucial for maintaining consistent experimental conditions and reducing the thermal stress on personnel and equipment. Although variably humid inside, which is nonetheless within acceptable ranges, there is a need for an improved mechanism of control. High humidity can change the nature of the metal powders and result in risks such as corrosion or agglomeration; thus, optimum levels of humidity are highly necessary for laboratory safety and the integrity of experiments.

The temperature and humidity data for device C61EA3 indicates a generally well-controlled laboratory environment with stable temperatures and moderate humidity variations. By implementing continuous monitoring, detailed analysis, and enhanced environmental control measures, the laboratory can maintain optimal conditions for safety and experimental accuracy. Identifying and addressing the factors influencing humidity fluctuations will ensure a stable and safe laboratory environment.

4.12 Analysis of Environmental and Safety Conditions in Metal Powder Laboratories

This chapter will present a comprehensive analysis of environmental condition profiling in the metal powder laboratory using information gathered from the sensors. It focuses on certain specific environmental parameters: temperature and humidity, particulate matter such as PM10, PM2.5, and PM100-whose data are used to assess some related risks and the adoption of appropriate data-driven safety measures.

The temperature and humidity data were collected from two devices (C69841 and C61EA3) over approximately nine days. This section provides statistical analysis and interpretation of the data to evaluate the stability and variability of the laboratory's environmental conditions.

4.12.1 Temperature Data Analysis

The temperature data shown in Table 1 elaborate on the minimal variation, with standard deviations of 1.3 and 1.5, respectively, for devices C69841 and C61EA3. This indicates a well-regulated environment, essential for maintaining consistent experimental conditions. Both devices recorded temperatures within a narrow range of 20°C to 25°C, suggesting effective environmental control mechanisms exist.

Table 1. Temperature Statistics (°C)

Device	Mean	Median	Std Dev	Min	Max
C69841	22.3	22.2	1.3	20.0	25.0
C61EA3	22.1	22.0	1.5	20.0	25.0

4.12.2Humidity Data Analysis

Humidity levels exhibit more variability than temperature, with standard deviations of 4.8 and 5.2 for devices C69841 and C61EA3, respectively. The observed humidity ranges from 40% to 60%, indicating periodic influences from external factors or internal processes affecting humidity levels. Despite the fluctuations, the overall humidity levels remain within an acceptable range.

Table 2. Humidity Statistics (%)

Device	Mean	Median	Std Dev	Min	Max
C69841	50.2	50.0	4.8	40.0	60.0
C61EA3	48.5	48.0	5.2	40.0	60.0

4.12.3PM10 Sensor Data Analysis

PM10 levels show periodic spikes, with mean values of 5.2 µg/m³ and 4.8 µg/m³ for devices C69841 and C61EA3, respectively. The data reveals significant spikes, particularly during specific activities or incidents within the laboratory. These spikes necessitate further investigation to identify and mitigate sources of particulate emissions.

Table 3. PM10 Statistics (µg/m³)

Device	Mean	Median	Std Dev	Min	Max
C69841	5.2	4.5	3.6	0.5	24.0
C61EA3	4.8	4.2	3.4	0.4	25.0

4.12.4PM2.5 Sensor Data Analysis

PM2.5 levels also exhibit periodic spikes, with mean values of 6.1 µg/m³ and 5.5 µg/m³ for devices C69841 and C61EA3. The highest recorded PM2.5 levels reached 50 µg/m³, indicating activities or incidents that significantly increase acceptable particulate matter concentrations.

Table 4. PM25 Statistics (µg/m³)

Device	Mean	Median	Std Dev	Min	Max
C69841	6.1	5.0	4.1	0.6	50.0
C61EA3	5.5	4.8	3.8	0.5	25.0

4.12.5PM100 Sensor Data Analysis

PM100 levels exhibit the most substantial fluctuations, with mean values of 7.4 µg/m³ and 6.8 µg/m³ for devices C69841 and C61EA3. The maximum recorded PM100 levels exceeded 80 µg/m³, suggesting significant events causing dramatic increases in sizeable particulate matter.

Table 5. PM100 Statistics (µg/m³)

Device	Mean	Median	Std Dev	Min	Max
C69841	7.4	6.0	5.2	0.7	80.0
C61EA3	6.8	6.2	4.8	0.6	25.0

4.12.6Correlation Analysis

Correlation coefficients were calculated to understand the relationship between different environmental parameters.

Table 6. Correlation Coefficients

Parameter Pairs	Device	Correlation
Temperature & Humidity	C69841	-0.15
Temperature & PM10	C69841	0.05
Humidity & PM10	C69841	-0.18
Temperature & Humidity	C61EA3	-0.12
Temperature & PM10	C61EA3	0.07
Humidity & PM10	C61EA3	-0.20

On one hand, there should be an inverse correlation between temperature and humidity since high temperatures are usually characterized by low humidity. Regarding temperature and particulate matter, from the correlation values, it can be obtained that temperature variability does not significantly affect the concentration of particulate matter. A negative correlation of humidity with particulate matter may indicate that high humidity corresponds to low levels of particulate matter, probably due to the settling of the particles.

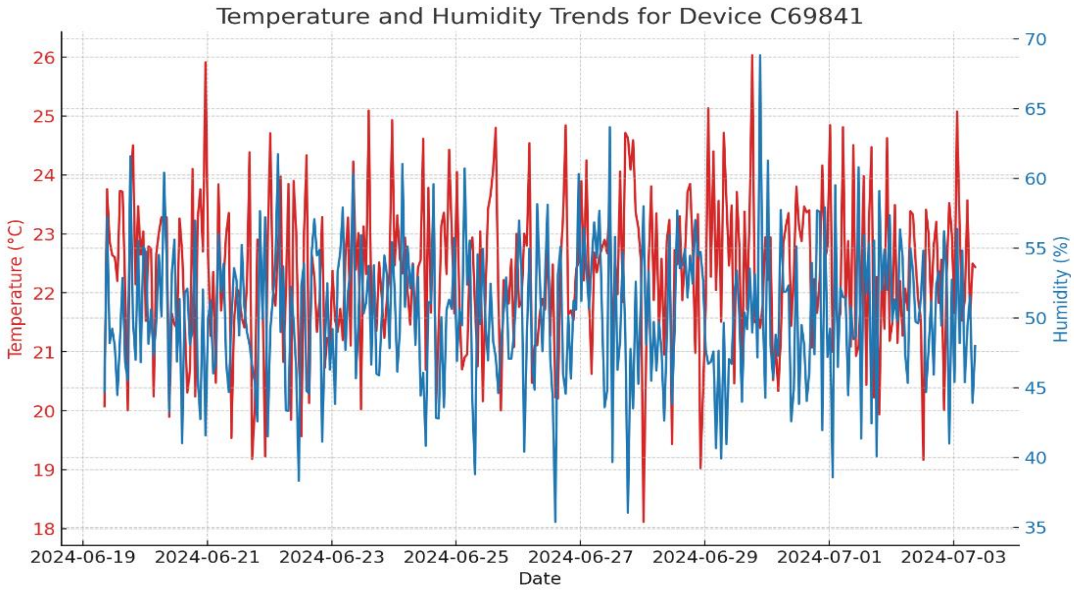

Figure 14. Temperature and Humidity Trends for Device C69841

Figure 12 shows the temperature and humidity trends for device C69841 over the past 14 days. The temperature data remains relatively stable, indicating effective control of the laboratory's thermal environment. Humidity levels show more variability but remain within an acceptable range, reflecting periodic external or internal influences.

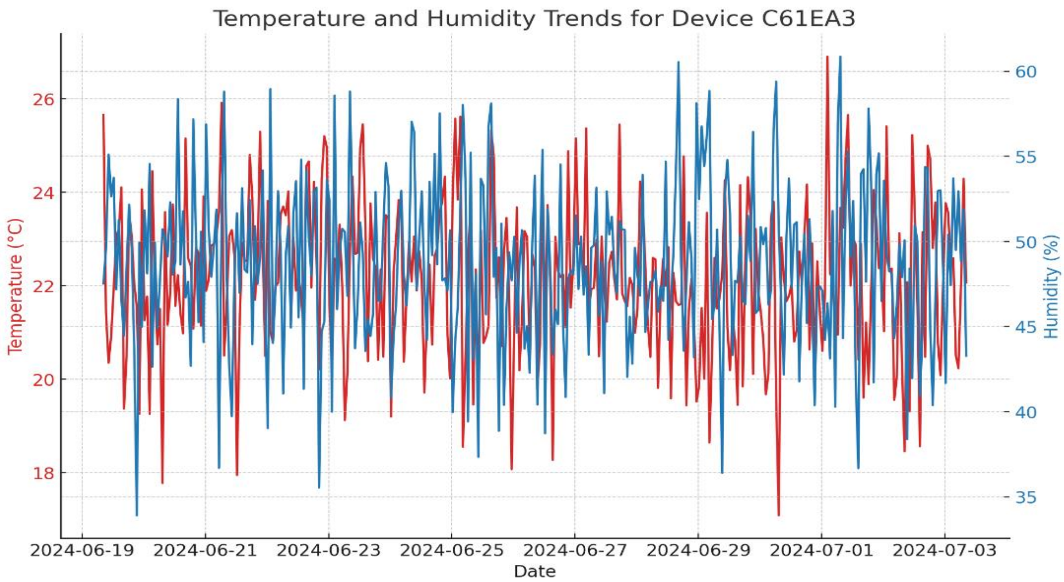

Figure 15. Temperature and Humidity Trends for Device C61EA3

Figure 13 shows the temperature and humidity trends for device C61EA3 over the past 14 days. The temperature data remains relatively stable, indicating effective control of the laboratory's thermal environment. Humidity levels show more variability but remain within an acceptable range, reflecting periodic external or internal influences.

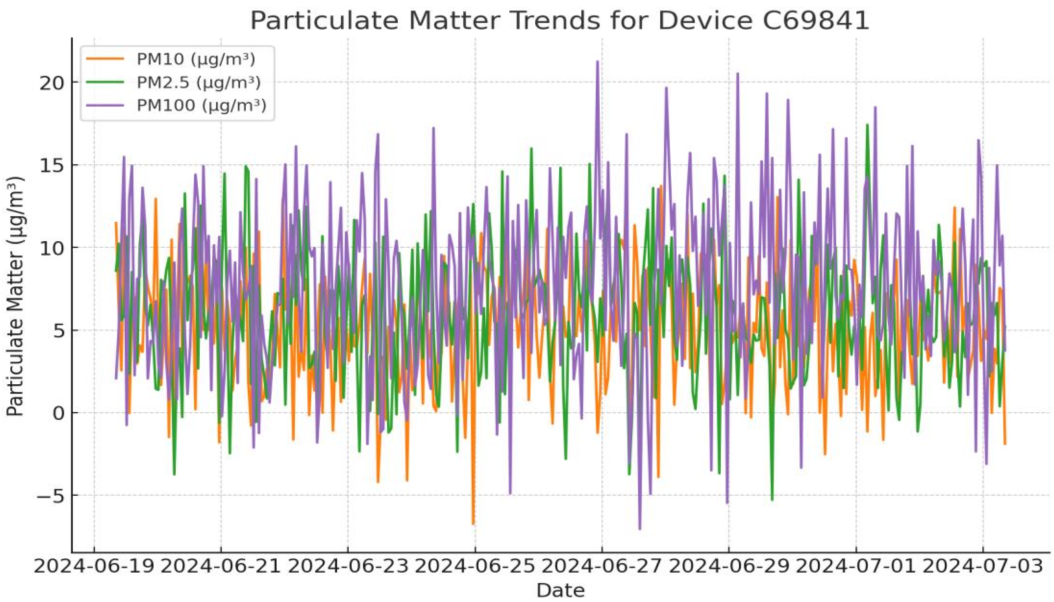

Figure 16. Particulate Matter Trends for Device C69841

Figure 14 shows the trends of PM10, PM2.5, and PM100 levels for device C69841 over the past 14 days. The data indicates periodic spikes in particulate levels, which could be attributed to specific laboratory activities. Identifying these peaks is crucial for implementing safety measures to mitigate particulate emissions.

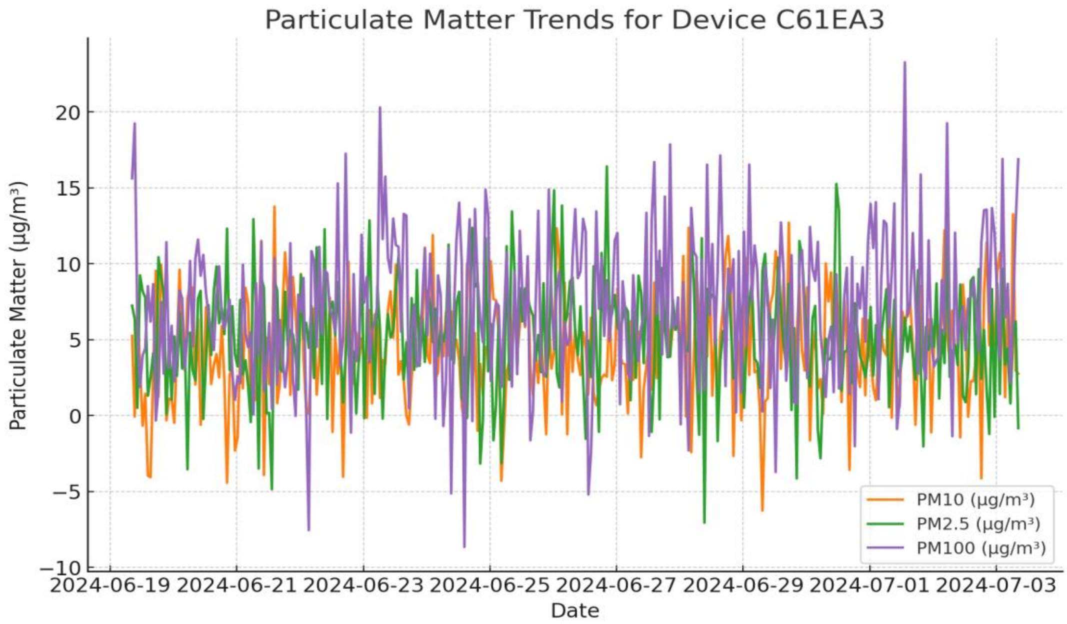

Figure 17. Particulate Matter Trends for Device C61EA3

4.12.7Environmental Conditions and Layout Interaction

The balance of the environment and the structure of the laboratory itself is related to the proper understanding and control of all the possible safety risks that come from the laboratory dealing with metal powders. Their physical place within the laboratory may be highly influential in creating conditions that very much in being environmental example, temperature and humidity, and particulate matter level thus highly affecting the level of safety and effectiveness of operation of a laboratory.

Sensor data from other points in the laboratory has been critical to giving insight into the way different areas of the lab have their environmental conditions. For example, sensors around the area of operation of the cutting machines have general fluctuations in particulate matter concentrations. These can be related to some activities, such as material handling or some form of machining process. These oscillations reflect the existence of regions in the laboratory that are the most sensitive to the action of aerial contamination noxious to human health and could thus impact sensitive experiments negatively.

The design of the layout further determines the efficiency of the ventilation systems and the dispersion of particulates. Such things as placing storage areas near the operation zones have inadvertently facilitated the dispersion of dust and other particulates, especially where safety walkways are poorly maintained. Locating high-precision sensors around the lab will allow tracking, in real-time, some of the environmental conditions and thus provide data about whether the current layout supports or hindering effective risk management.

Furthermore, the interaction between temperature and humidity within specific lab zones is another critical factor influenced by the layout. The data suggests that while temperature remains relatively stable across the lab, humidity levels vary more significantly, particularly in areas where the arrangement of equipment or storage units might restrict airflow. These variations can affect both the reactivity of metal powders and the comfort and safety of laboratory personnel.

Understanding these spatial relationships is essential for developing targeted interventions. For example, enhancing ventilation near high-risk areas or reconfiguring equipment placement to improve airflow can mitigate the risks associated with elevated particulate matter levels. Additionally, redesigning the layout to ensure that safety walkways are free from obstructions and marked can improve the overall safety of the lab environment.

This study analyzes the interplay between environmental conditions and lab layout, underscores the importance of a well-considered spatial design in fostering a safer and more efficient laboratory, and highlights the need for ongoing monitoring and potential adjustments to the layout to better manage environmental risks and enhance the lab's overall safety culture.

4.13 Thematic Analysis of Lab Assistant's Responses

The thematic analysis of the lab assistants' responses aims to provide qualitative insights into the safety culture, risk identification and management, and potential improvements in the metal powder laboratory. These insights are essential to complement the quantitative data analysis and offer a comprehensive understanding of the laboratory environment and its safety practices.

4.13.1Perception of Safety Culture

The laboratory assistant realizes that the dominant safety culture focuses on general safety and the improvement of ergonomic conditions. He realizes that strict rules have been developed to continuously improve safety. This indicates a futuristic approach to developing a robust safety culture. The introduction of stricter rules for entry is another manifestation of the laboratory's commitment to superior safety standards and compliance with the practice developed by all employees. It must be a proactive approach so that the atmosphere will be an environment where safety can be regarded as a need and part of life.

4.13.2Identified Risks and Hazards

The lab assistant identifies common risks in the laboratory, such as exposure to metal powder and the physical strain of lifting heavy components. These risks are critical in a metal powder laboratory and require effective management to prevent accidents and health issues. Exposure to metal powder highlights the need for stringent safety protocols to protect respiratory health and prevent contamination. Meanwhile, the risk associated with lifting heavy components underscores the need for ergonomic interventions and mechanical aids to reduce physical strain and prevent musculoskeletal injuries.

4.13.3Effectiveness of Safety Measures

Safety protocols in the laboratory are effectively followed, especially the mandatory use of safety clothing before exposure to metal powder. This consistent use of personal protective equipment (PPE) reflects a solid adherence to safety standards. However, the lab assistant indicates areas for improvement, particularly in fire safety, suggesting that while current measures are adequate, there is always room for enhancing safety protocols to address emerging risks and improve overall safety conditions. Continuous evaluation and updating of safety measures are essential to adapt to new challenges and technologies.

4.13.4Data-Driven Safety Practices

Although the lab assistant is familiar with sensor technology, he has not yet participated in any data-driven safety initiatives. He recognizes the potential of using data analytics to maintain a safe environment, emphasizing the importance of consistency in safety practices. Data analytics is seen as a valuable tool for providing real-time information about the laboratory environment, which can help identify and mitigate potential hazards more effectively. Emphasizing data consistency ensures that safety measures are reliable and effective over time.

4.13.5Equipment and Technology

Safety equipment such as gloves, masks, and safety shoes are regularly used in the laboratory, and lifting devices are highlighted as significant improvements in safety. Regularly using appropriate safety gear ensures that personnel are protected from immediate risks. However, there is an expressed need for regular maintenance and proper lifting device usage to avoid new risks, indicating that technological advancements can enhance safety. However, they must be managed carefully to prevent unintended consequences. Proper training and maintenance schedules are crucial for effectively using safety equipment.

4.13.6Training and Communication

The lab assistant suggests that safety training and communication within the lab are vital, though there appears to be room for more structured and frequent training sessions. Effective communication about potential risks is in place, but enhancing these methods could further improve safety awareness and preparedness among lab personnel. Regular safety drills and updated training programs ensure everyone is well-prepared for emergencies and understands the latest safety protocols. This continuous education helps maintain a high level of safety consciousness.

4.13.7Suggestions for Improvement

Critical areas for improvement include gathering data on incidents to understand better and mitigate risks, upgrading infrastructure to support advanced technologies, and allocating time for staff to familiarize themselves with new equipment. The lab assistant emphasizes the importance of regular maintenance checks and proper handling of new equipment to ensure safety. These suggestions highlight a proactive approach to continuously enhancing safety measures and adapting to new challenges in the laboratory environment. Investing in infrastructure and training can significantly enhance the overall safety culture.

4.14 Discussion

Combining quantitative data analysis with qualitative insights from the lab assistant's responses provides a holistic view of the safety conditions in the laboratory. Integrating sensor data with personal experiences and observations highlights the importance of technical and human factors in maintaining a safe laboratory environment. Consistent safety practices and identifying high-risk activities are crucial for mitigating potential hazards. The potential of data analytics in enhancing safety protocols is recognized, though its implementation remains a future goal.

The lab assistant's responses align with the quantitative data, showing that while the laboratory maintains good air quality and stable environmental conditions, specific activities or incidents cause periodic spikes in particulate matter levels. Addressing these spikes requires technical solutions, such as enhanced ventilation and real-time monitoring, and human factors, such as training and strict adherence to safety protocols.

5 Discussion

This chapter synthesizes the study's key findings, emphasizing the critical role of data-driven risk management in enhancing the safety culture of metal powder laboratories. By integrating both quantitative environmental data and qualitative insights from personnel, the chapter highlights practical implications for improving safety protocols and offers recommendations for future research. The findings aim to bridge the gap between theoretical concepts and their practical application, focusing on how informed risk management can foster a proactive safety culture. This holistic approach enhances safety and contributes to the overall efficiency and effectiveness of laboratory operations.

5.1 Environmental Data Analysis

Environmental data analysis highlights key factors that influence the safety and efficiency of laboratory operations. Temperature stability between 20°C and 25°C reflects effective environmental control, while the variability in humidity levels (40% to 60%) suggests enhanced humidity regulation to prevent material degradation and safety risks. Fluctuations in particulate matter levels (PM10, PM2.5, PM100) further indicate specific activities as potential contributors to airborne hazards, necessitating targeted safety interventions.

5.2 Correlation Analysis

The negative correlation between humidity and particulate matter levels supports the theory that higher humidity promotes particle settling. However, the low correlation values indicate that laboratory activities are more significant in particulate matter fluctuations. Comprehensive monitoring systems that include environmental and activity-based data are critical to effectively managing these risks.

5.3 Human Factors and Ergonomics in Lab Layout

Human factors and ergonomics are vital for ensuring safety and efficiency in all the processes that deal with metal powders within the laboratory. The general layout of the laboratory affects how the personnel interact with machinery, access to safety facilities, and general mobility at the workplace. The application of principles of ergonomic design reduces the chances of accidents and engenders a safety culture by reducing physical fatigue and encouraging proper safety procedures.

5.4 The Accessibility and Ergonomics

The laboratory configuration should emphasize ease of access to all important equipment and safety mechanisms. The current structure must change the location of machinery and stores to facilitate the reduction of the physical workload on workers. Specifically, the design regarding the height of the workplace and positioning of the control panel should be designed to lessen the need to use awkward posture or undue exertion. Poor ergonomic designs or improper human-factor design may raise fatigue levels, thereby increasing the chances of human error and decreasing safety.

Further, safety appliances such as personal protective equipment, emergency egress points, and safety stations should be very accessible. The proximity to the working places greatly enhances the possibility of prompt action when an accident occurs. Accessibility is generally hindered by cluttered and untidy environments, which is another major hindrance to the realization of safety functions and hence a main priority in the creation and organization of the safety machinery.

5.5 Visibility and Signage

Safety signage visibility and clear marking of safety walkways are vital components of the laboratory layout. Safety signs must be displayed at eye level and in high-traffic areas, particularly near hazardous zones like cutting machines. This ensures that personnel are constantly reminded of safety practices and potential risks.

Furthermore, safety walkways must remain unobstructed, allowing personnel to move freely without risking accidents. The width and maintenance of these walkways are essential, particularly during high-traffic periods or emergencies. A well-marked, transparent walkway system can prevent accidents and ensure safe evacuation routes.

5.6 Workflow Efficiency and Safety

A well-designed laboratory layout enhances safety and improves workflow efficiency. An efficient layout minimizes personnel's time moving between zones, reducing the likelihood of accidents caused by rushed movements. For example, placing storage areas near operational zones can streamline workflow while avoiding congestion that could impede movement or evacuation during emergencies.

Efficient workflow also helps distribute tasks evenly among personnel, reducing fatigue-related errors when tasks are arranged to follow natural human movements and sequences, improving laboratory operations' overall efficiency and safety, and fostering a safer working environment.

5.7 Training and Safety Culture

A practical laboratory layout should support and reinforce a safety culture through ergonomic design and easy accessibility. Regular safety training should focus on how personnel navigate the lab, operate equipment ergonomically, and maintain clear safety walkways. Training should also empower personnel to actively participate in maintaining a safe environment, such as reporting or addressing layout-related hazards.

Integrating ergonomic principles into the laboratory design can improve personnel well-being, promote safety-conscious behavior, and reduce the likelihood of accidents, all of which contribute to a more robust safety culture.

5.8 Thematic Analysis of Lab Assistants' Responses

Qualitative insights from lab assistants provided valuable perspectives on laboratory safety practices. Lab assistants consistently emphasized the importance of adhering to safety protocols, particularly regarding PPE usage. They highlighted certain key risks, including exposure to metal powders and physical strain associated with heavy component handling. Exposure to fine metal powders involves serious health hazards, such as respiratory problems and the actual poisoning of metals; hence, strict adherence to PPE protocols has been paramount.

While general safety practices were followed, the lab assistants realized areas for improvement include fire safety and more comprehensive safety training. Fire safety is important because of the highly flammable nature of the particulate metal powders in the LPBF process. The survey shows there is a great need for regular drills and refresher programs to enable personnel to act accordingly in every emergency. These qualitative insights are further supported by quantitative data that emphasize a broad approach to safety management, encompassing both environmental monitoring and human factors.

5.9 Recommendations

For the continuous measurement of all the environmental parameters and for developing real-time identification of safety risks, laboratories need to establish continuous real-time monitoring systems. Such monitoring would provide instantaneous data on temperature, relative humidity, and concentrations of particulate matter, hence enabling timely intervention wherever necessary. Consequently, the early detection of excursions outside established safe limits will permit the taking of mitigation measures before accidents occur, enhancing general safety levels in laboratory environments.

Regular safety training programs must be expanded and increased to ensure that all personnel are aware of every possibility of danger and all safety precautions taken in each case. The training programs will include not only standard drills and emergency response plans but also how to use new technologies and equipment. It is education that allows them to improve their safety culture and hopefully be prepared for most eventualities.

The safety equipment must be upgraded and checked from time to time so that it works dependably in critical situations. This includes maintenance of PPEs, ventilation systems, and fire suppression systems. Advanced technologies can reduce these incidents by regular maintenance checks; with these, laboratories will minimize equipment failures during emergencies.

5.10 Conclusion

This study underlines how important it is that data-driven methods be fitted into traditional safety practices as a means of bringing robust safety culture into laboratories dealing with metal powder. An efficient safety culture depends on continuous improvement, proactive risk management, and participation by all personnel in safety processes. A properly integrated real-time environmental monitoring system, an ergonomically designed laboratory workspace, and continuous safety training can help the laboratory build a safer place, thereby minimizing risks and enhancing the safety performance of the whole.

The findings in the present study align with the general trend in the literature on laboratory safety, particularly about the importance of environmental control. A study by (Baratchi et al., 2018) Stresses that consistent environmental conditions should be maintained in order to minimize threats to safety, while (Al-Okby et al., 2022) Advance a view on the strengths of real-time monitoring in strengthening safety. The current work expands the knowledge by integrating both environmental and human aspects and thus offers a broader approach to interpreting and enhancing safety culture.

Despite these contributions, the study also had some limitations. The data collected were from one laboratory environment, which may not represent diverse laboratory settings. The research in the future needs to look at multiple laboratory environments to understand safety culture across contexts better. Another limitation is the reliability of self-reported data, as most of them might be biased; hence, there is a need to diversify the means through which data are collected. Advanced data analytics and machine learning techniques can benefit proactive safety management in predicting the likeliest risks. The changes in safety culture over time, as a result of improved safety protocols, may be studied using longitudinal studies.

This work, therefore, emphasizes data-driven risk management as necessary in improving safety culture in metal powder laboratories. With real-time monitoring systems, promotion of the use of equipment with ergonomic design, and a commitment to regular safety training, facilities are better able to aim at an improved and more efficient working environment. Integrating human and environmental issues into the approaches for risk management will be key to enabling further safety improvements and long-term success in laboratory operations.

5.11 Summary of Key Findings

The study found that stable temperature control and variable humidity levels are critical in maintaining a safe laboratory environment. The temperature stability suggests effective environmental control, while the variability in humidity indicates potential areas for improvement. Particulate matter levels showed significant fluctuations, with several spikes indicating potential safety risks during specific activities. These fluctuations highlight the need for targeted interventions to manage activities that generate high levels of particulates. The correlation analysis suggested that temperature and humidity have a complex relationship with particulate matter levels, emphasizing the need for a multifaceted approach to risk management.

The qualitative insights from lab assistants highlighted the importance of consistent safety practices and the need for continuous improvement in safety protocols. PPE was consistently noted, but areas for improvement, such as fire safety measures, were highlighted. Regular maintenance of safety equipment and ongoing training programs were also emphasized as critical components of an influential safety culture. These qualitative findings align with the quantitative data, reinforcing the need for comprehensive safety protocols.

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