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Human Factors and Behavioral Aspects of Cleanroom Safety

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Abstract

Cleanrooms are critical environments in various industries, where stringent control of environmental conditions is essential for ensuring product quality and safety. Despite the implementation of safety protocols, accidents and incidents continue to occur, emphasizing the need to understand the human factors and behavioral aspects influencing cleanroom safety. This research investigates the human factors, ergonomic considerations, and safety practices in cleanroom environments, aiming to enhance safety measures and prevent accidents. A survey-based approach was employed to assess awareness, adherence to safety protocols, perception of risk, stress, and motivations for safety among cleanroom personnel. The study also explored the influence of demographic factors on safety behavior and analyzed posture effects, pain, and discomfort. Additionally, the research utilized the Analytic Hierarchy Process (AHP) to prioritize safety measures based on stakeholders' preferences and judgments. The findings highlight the importance of chemical safety training, equipment suitability, and ergonomic considerations in promoting cleanroom safety. By addressing these factors, organizations can foster a culture of safety, prevent accidents, and ensure compliance with regulatory standards. The insights gained from this research contribute to improving safety practices and enhancing the well-being of personnel working in cleanroom environments.

Keywords

Cleanroom Safety, Human Factors, Behavioral Aspects, Risk Perception and Ergonomics

1. Introduction

Cleanrooms are critical regulated environments in sectors such as pharmaceuticals, biotechnology, semiconductor fabrication, and healthcare. They are in-

tended to decrease the presence of airborne particles, dust, microorganisms, and other contaminants, assuring the high quality and dependability of the goods [1]. Ensuring cleanroom safety is critical for sustaining product quality and protecting personnel's health. However, cleanroom conditions can provide hazards to workers, including chemical exposures, ergonomic stresses, and microbiological contamination [2].

To achieve these goals, cleanrooms are meant to limit contamination by controlling airborne particles, germs, dust, and other contaminants, resulting in high product quality and reliability. These specialized settings follow tight rules, such as ISO 14644-1, which divides cleanrooms into nine categories based on particle count per cubic meter of air, ranging from the strictest ISO 1 to the least demanding ISO 9 [3]. The environmental controls include strict temperature, humidity, and pressure controls, as well as deliberately arranged airflow patterns to prevent particle migration. In a cleanroom, furniture, and equipment are designed to create as few particles as possible, while materials and surfaces are easy to clean and non-shedding [4].

Moreover, the relative relevance of cleanroom safety criteria is determined by their capacity to ensure a controlled environment when used together. Contamination control, environmental management, and safety protocol adherence are all important requirements [5]. Sub-criteria include particular measures like ISO classifications, temperature and humidity controls, ventilation patterns, and the use of non-shedding materials. These measures are crucial because they have a direct influence on contamination control and cleanroom efficiency [6].

Safety requirements comprise tight gowning regulations for personnel, limited access, adherence to standard operating procedures, frequent cleaning and maintenance, constant monitoring of environmental conditions, and well-defined emergency response plans [7]. These elements are crucial as they ensure the prevention of contamination and protect both the products and the workers [8]. To improve safety procedures and lower hazards like chemical exposure, ergonomic stresses, and possible microbiological contamination, ergonomic interventions and extensive training programs are essential [9].

Introduction to human factors and behavioral issues affecting cleanroom safety procedures is critical for developing effective safety management solutions. Individual behavior, perception, cognition, and ergonomics are all examples of human factors [10] [11]. Research has shown that well-designed training programs are critical for enhancing workers' comprehension of safety standards and their ability to deal with crises [12] [13]. Furthermore, employing ergonomic treatments to enhance posture and reduce physical strain can significantly lower the risk of workers having musculoskeletal problems [14].

Further investigation is required to get a thorough comprehension of the complex correlation between behavioral features and human variables in cleanroom environments. By finding and fixing the underlying causes of these issues, organizations may enhance safety procedures and provide better work conditions for cleanroom workers, which will boost output and promote worker

well-being.

The goal of the study was to investigate how behavioral aspects and human variables affect the way cleanroom safety protocols are implemented. The main goals of this research are to evaluate how well-informed and conscientious cleanroom workers are about safety procedures; to pinpoint the biggest obstacles to upholding safety standards; to investigate how cleanroom workers perceive risk, cope with stress, and feel motivated to stay safe; to analyze the effects of ergonomic factors on posture, pain, and discomfort; and to look into how demographic factors affect safety behavior and perceptions in cleanroom environments.

2. Methodology

The research methodology used to investigate the human factors and behavioral aspects influencing cleanroom safety practices among 357 participants was a cross-sectional survey design, with data collected to provide insights into the current state of cleanroom safety across diverse industries such as pharmaceuticals, electronics, biotechnology, and aerospace. The participants were recruited via convenience sampling to guarantee representation from a variety of cleanroom facilities, which increased the breadth and depth of the study's results.

The participants were given a well-designed survey instrument online as part of the data-gathering procedure. This structured questionnaire was designed to collect quantitative information on several important topics, including demographics, perceptions of hazards, stress levels, adherence to safety procedures, and ergonomic concerns. Following that, condensing answers, examining correlations between variables, and evaluating hypotheses regarding how demographic factors impact safety behavior and perceptions were done using quantitative analytic approaches such as regression analysis, correlation analysis, and descriptive statistics. To further enhance the study findings and provide stakeholders' preferences a voice in safety measures, an Analytic Hierarchy Process (AHP) analysis will also be carried out.

Ethical concerns were crucial throughout the investigation, and the research was ethically approved to maintain standards and protect participant rights. Participants were given explicit instructions and were guaranteed that they may resign from the research at any moment without penalties. Throughout the study process, robust procedures were put in place to preserve participant privacy and anonymity, demonstrating a commitment to ethical behavior. In conclusion, this chapter offered a detailed review of the study methods used to explore human factors and behavioral characteristics that influence cleanroom safety. The next chapters go over the study findings and their implications for improving cleanroom safety management and directing future research efforts.

3. Results

The outcomes of the study are presented, encompassing both the results ob-

tained from the analysis of survey data and the utilization of the Analytic Hierarchy Process (AHP) to rank cleanroom safety measures by priority. The examination delves into diverse facets of cleanroom safety procedures, comprising awareness and compliance with safety protocols, the perception of risk, levels of stress, drivers for prioritizing safety, the quality of posture, and levels of pain and discomfort.

3.1. Demographic Characteristics of Participants

Figure 1 shows a diverse distribution of people across age groups in the study population. The age group of 20 to 39 years appears as the most prevalent, accounting for around 74.23% of the overall population, showing a large presence of young adults. Following that, the age range of 40 to 59 years forms around 19.89% of the population, demonstrating a smaller but significant cohort when compared to the younger demographic. Furthermore, those aged 0 to 19 make up roughly 3.08% of the overall population, indicating a small number of children and adolescents. Finally, the senior age group of 60 to 79 years represents around 2.80% of the population, demonstrating a tiny but significant presence of the elderly. The gender distribution of the population under survey is shown in Figure 2. With 220 people, the male population makes up a sizable majority of 61.62% of the entire population. This implies that there are a significant number of men in the town. On the other hand, there are 137 females, or around 38.38% of the total population, which is a lower but still significant number. Though they are underrepresented in comparison to men, women are nonetheless a significant portion of the population polled.

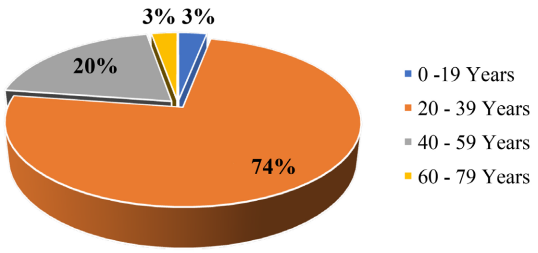

Figure 1. Age distribution.

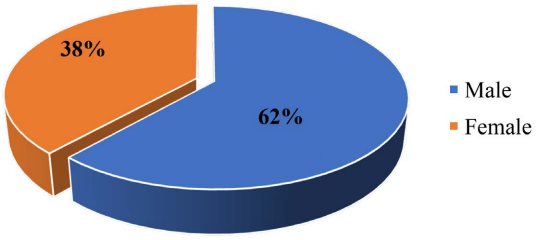

Figure 2. Gender distribution.

3.2. Cleanroom Safety Practices and Procedures

The study reveals that cleanroom workers are generally aware of safety protocols

and committed to following them, ensuring a safe working environment. However, they face challenges in maintaining safety standards, such as a lack of proper training, insufficient equipment, and time constraints as shown in Figure 3. Approximately 19.39% of respondents identified a lack of proper training as a challenge, while 26.43% identified insufficient equipment as a challenge. Time constraints also impact workers' ability to adhere to safety protocols.

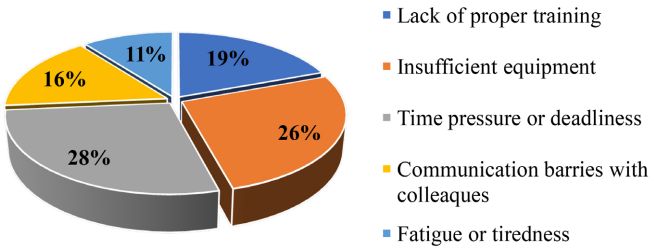

Figure 3. Percentage of the main challenges.

Respondents' perceptions as shown in Table 1 of risk levels in cleanroom environments are diverse, with the majority identifying it as moderate (22.97%) or high (25.21%). A significant proportion perceive the risk as low (31.09%), while a smaller proportion believe it is extremely high (13.73%). Understanding and addressing perceived risks is crucial for fostering a culture of safety within cleanroom facilities.

Table 1. Perception of risk.

Risk Perception	Frequency	Percentage
Extremely Low	25	7.00
Low	111	31.09
Moderate	82	22.97
High	90	25.21
Extremely High	49	13.73

Stress levels in cleanroom environments are also high as summarized in Table 2, with 40.90% and 14.85% of respondents agreeing or strongly agreeing with these factors. These stressors can affect workers' well-being and safety performance, and addressing these stressors and implementing strategies to mitigate their impact is critical for creating a healthy and safe work environment for cleanroom employees.

Table 2. Stress.

Stress	Frequency	Percentage
Strongly Disagree	18	5.04
Disagree	58	16.25

Continued

Neutral	82	22.97
Agree	146	40.90
Strongly Agree	53	14.85

Also, the study reveals that personal safety is the primary motivator for cleanroom workers to follow safety protocols, with 32% citing it as a significant factor. Concern for colleagues' safety is also a significant factor, with 22% expressing concern as shown in (Figure 4). Regulatory compliance and fear of repercussions are additional motivators. This highlights the importance of a comprehensive safety culture in cleanroom environments.

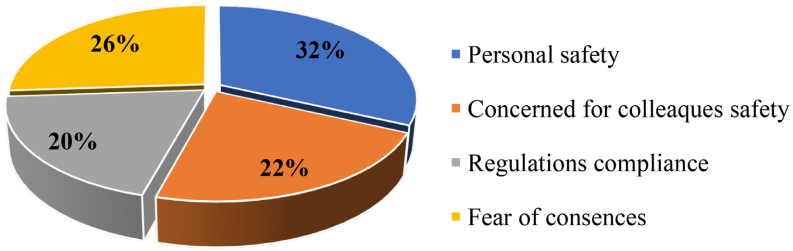

Figure 4. Motivations for safety.

3.3. Posture Effects, Pain, and Discomfort

The study reveals that as shown in Figure 5 cleanroom workers generally rate their posture quality as good (53.50%) or very good (13.17%), with a smaller proportion rating it as poor (18.77%) or extremely poor (14.57%). This suggests that while a significant number of workers find their posture satisfactory, there is still room for improvement, especially among those who rate it as poor or very poor. The data also shows that cleanroom workers report varying levels of pain and discomfort, with the majority reporting moderate or moderately severe discomfort. A significant proportion reported severe or extremely severe pain and discomfort, highlighting the prevalence of musculoskeletal issues and ergonomic strains among workers. The study underscores the need for ergonomic interventions and workplace health and safety initiatives to reduce discomfort and prevent occupational injuries.

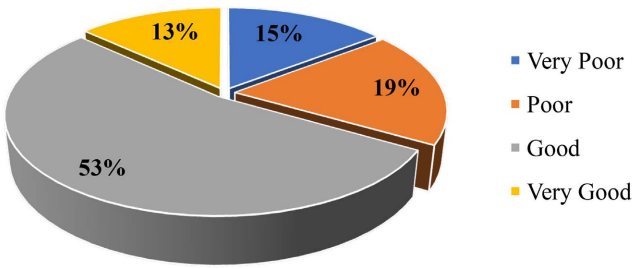

Figure 5. Posture quality.

Moreover, the investigation's findings indicate that a notable proportion of cleanroom workers experience discomfort, with a sizeable number expressing varied degrees of pain. To be more precise as shown in Table 3, 26.29% experienced fairly severe discomfort, 21.01% severe discomfort, 12.89% extremely severe discomfort, and 26.89% reported moderate discomfort. This emphasizes how vital it is to implement occupational health and safety programs to treat musculoskeletal problems and ergonomic pressures. Regression research also shows how demographic variables affect safety perceptions and behavior. While gender and BMI also play significant effects, older workers—who account for around 74.23% of the population aged 20 to 39—show higher levels of compliance with safety standards. Compared to male respondents, female respondents—who make up around 38.38% of the studied population—generally express slightly higher positive impressions of safety.

Table 3. Pain and discomfort.

Pain and Discomfort	Frequency	Percentage
Mild	64	17.93
Moderate	96	26.89
Moderately Severe	76	21.29
Severe	75	21.01
Very Severe	46	12.89

On the other hand, the regression investigation provides significant insights into how demographic variables influence cleanroom worker safety behavior and attitudes. Older workers had much greater compliance with safety standards ($p < 0.001$). Gender and BMI, albeit having reduced impacts, nonetheless play important roles. Gender ($p = 0.026$) and BMI ($p = 0.001$) had a beneficial impact on safety behavior. Age ($p < 0.001$) and BMI ($p = 0.014$) both had a substantial impact on safety perceptions, with older employees and those with greater BMI performing better. Furthermore, female respondents seem to have somewhat higher positive safety views than male respondents ($p = 0.015$). These findings highlight the relevance of demographics in promoting safety and well-being in cleanroom environments.

3.4. Analytic Hierarchy Process (AHP) Analysis

The Analytic Hierarchy Process (AHP) analysis was conducted to prioritize safety measures in cleanroom environments based on stakeholders' preferences and judgments. The analysis involved constructing a hierarchical structure of criteria and sub-criteria related to cleanroom safety, performing pairwise comparisons, and calculating priority weights for each criterion and sub-criterion.

The average matrix of the three decision makers' judgments for training and equipment showed that the priority weights for training were approximately

0.429 for Hazard Recognition, 0.297 for Emergency Response, and 0.274 for Chemical Safety. For equipment, the priority weights were approximately 0.229 for Reliability, 0.288 for Suitability, 0.264 for Ease of Use, and 0.219 for Compatibility.

The aggregated priority weights for training and equipment were less than 0.1, indicating that the decision makers' judgments are relatively consistent compared to random judgments. The highest aggregated priority weight for training was "Chemical Safety", followed by "Hazard Recognition" (0.2377) and "Emergency Response" (0.2117). This suggests that chemical safety training is perceived as the most critical factor for cleanroom safety, followed by hazard recognition and emergency response training.

Furthermore, among the other factors evaluated, the consistency of judgments for training and equipment was less than 0.1, indicating that the decision makers' judgments are relatively consistent compared to random judgments.

4. Discussion

The study's findings offer valuable insights into different facets of cleanroom safety practices, human factors, and behavioral aspects. They illuminate the challenges encountered by cleanroom workers and the factors that influence their safety behavior and perceptions. These findings align with prior studies in the field, emphasizing the significance of addressing ergonomic factors, fostering a safety culture, and comprehending the influence of demographic characteristics on safety outcomes.

The findings suggest that cleanroom workers generally have a high level of awareness and compliance with safety protocols. A considerable number of participants showed agreement or strong agreement with safety practices. These findings are consistent with prior research that highlights the significance of efficient safety training and strict adherence to protocols in cleanroom environments [3]. Nevertheless, the recognition of obstacles such as inadequate training and insufficient equipment highlights the necessity for continuous investment in safety education and resources to assist cleanroom workers.

The way respondents perceive risk, stress, and motivations for safety in cleanroom settings is influenced by a complex interaction of human factors that affect safety behavior. The acknowledgment of moderate to high levels of risk indicates an awareness of the inherent dangers that exist in cleanroom environments. The need for organizational support and stress management interventions is emphasized by the reported levels of stress and pressure. These interventions are necessary to reduce the negative effects of workplace stressors on the well-being of cleanroom workers [15]. The study identified several motivations for safety, such as personal safety, concern for colleagues, and fear of consequences. These motivations align with previous research that highlights the importance of both intrinsic and extrinsic motivators in promoting safety compliance [16].

The evaluation of posture excellence, pain, and discomfort emphasizes the ergonomic difficulties encountered by cleanroom workers and their consequences for occupational health and safety. Although most participants rated their posture positively, a considerable number of them reported experiencing varying degrees of pain and discomfort, ranging from moderate to very severe. The results of this study align with prior research that emphasizes the high occurrence of musculoskeletal disorders and ergonomic strains among cleanroom workers as a result of extended periods of standing and repetitive tasks [17]. Ensuring ergonomic factors are addressed and promoting proper posture techniques are crucial for preventing workplace injuries and improving worker well-being in cleanroom environments.

The regression analyses demonstrate the impact of demographic variables, such as age, gender, and BMI, on safety behavior and perceptions within the cleanroom. Previous research by Isa and his colleagues has shown that older employees exhibit greater safety compliance and risk perception, which aligns with the notion that experience and maturity play a significant role in safety outcomes [14]. There are noticeable differences in safety behavior and perceptions based on gender, as female respondents tend to have slightly more positive safety perceptions than males. Moreover, Body Mass Index (BMI) has a notable and favorable impact on safety behavior and perceptions, underscoring the significance of physical well-being and fitness in enhancing safety results in the workplace.

Finally, the AHP analysis enabled the prioritization of safety measures within cleanroom environments based on stakeholders' preferences. The results indicated that chemical safety training and equipment suitability are perceived as the most critical factors influencing cleanroom safety. These findings can inform decision-making processes regarding resource allocation and the development of targeted interventions to enhance cleanroom safety.

5. Conclusions

This study has conducted a thorough examination of the human factors, behavioural aspects, and ergonomic considerations that impact cleanroom safety practices. By conducting surveys and performing statistical analyses, researchers have discovered important insights into the present condition of cleanroom safety awareness, compliance with protocols, and the difficulties encountered by workers.

The research has emphasized the significance of addressing human factors and behavioral aspects in promoting safety in cleanrooms. Significant factors that influence safety behaviors and outcomes in cleanroom environments include risk perception, motivations for safety, stress levels, and ergonomic strains. Furthermore, it was discovered that demographic variables such as age, gender, and level of experience have an impact on the formation of safety attitudes and behaviors among cleanroom workers. Also, the priority weights obtained from

the AHP analysis indicate the relative importance of criteria and sub-criteria influencing cleanroom safety. Chemical safety training and equipment suitability emerge as the most critical factors based on their higher priority weights.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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