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Miller's Pyramid as a Predictor of Undergraduate Students' Practical Competence in Preventing Chemical Laboratory Accidents

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Abstract

Preventing accidents in chemistry laboratories is a critical concern, as laboratory activities involve chemical hazards, equipment risks, and procedural errors. One of the main contributing factors to laboratory accidents is inadequate student competence during practical activities. However, systematic predictors for assessing practicum competence are still rarely implemented. This study aims to examine the effectiveness of Miller's Pyramid as a predictor of students' practicum competence in preventing work-related accidents in chemistry laboratories. The research employed a descriptive evaluative design. The participants consisted of students from the Chemistry Department who were involved in laboratory practicums. The object of the study was students' practicum competence based on the four levels of Miller's Pyramid: *knows, knows how, shows,* and *does*. Data were collected through written tests, interviews, and direct observations using structured assessment rubrics. The collected data were analyzed descriptively and presented in percentage form. Student competence was categorized as good when at least 70% of the indicators at each Miller's Pyramid level were achieved. The results showed that students' competence at all levels of Miller's Pyramid met the established criteria, indicating good overall practicum competence. Furthermore, the findings demonstrate that Miller's Pyramid can effectively function as a predictor of students' practicum competence related to laboratory safety. In conclusion, the application of Miller's Pyramid provides a comprehensive framework for assessing and improving student competence, thereby contributing to the prevention of work accidents in chemistry laboratories.

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INTRODUCTION

Laboratory practice plays a crucial role in supporting the success of chemistry learning because it allows students to test and verify theories that have been previously studied (Akhmad Al-Bari & Saputri, 2020). Through laboratory activities, students' mastery of chemical concepts is strengthened as they are directly involved in experimental processes. Practical work provides opportunities for students to observe phenomena, analyze data, validate concepts, and draw scientific conclusions (Komisia et al., 2022). In addition, laboratory practice helps develop critical thinking and problem-solving skills. Despite these benefits, laboratory activities also involve potential risks of workplace accidents. Therefore, the implementation of chemistry laboratory practice must be accompanied by serious attention to occupational health and safety aspects.

Workplace accidents in chemistry laboratories can be caused by various factors, including unsafe working environments and improper use of laboratory equipment (Erviando et al., 2020). Human factors, particularly the attitudes and behaviors of laboratory users, are among the main contributors to laboratory accidents. Inadequate supervision during practical sessions further increases the likelihood of accidents (Mantiri et al., 2020). Numerous efforts have been made to control laboratory accidents, such as evaluating health, safety, and environmental management systems (Lestari et al., 2019) and implementing chemical risk assessments (Fatemi et al., 2022). Other strategies include promoting occupational health and safety culture in chemistry education laboratories (Ahmad & Susilawati, 2023), optimizing occupational safety management (Husna et al., 2022), and providing safety education to improve students' knowledge of laboratory safety (Citerawati et al., 2023). Ultimately, all accident prevention efforts converge on the human element as the central factor in laboratory activities (Cahyaningrum, 2020).

Humans play a key role in accident prevention because they possess knowledge and skills that are reflected in their competence. Miller's Pyramid of competence explains the relationship between knowledge, skills, and behavior through four hierarchical levels, namely *knows*, *knows how*, *shows*, and *does* (Setyowati, 2015; Lele et al., 2020). The application of Miller's Pyramid can be used as a framework for continuous competency development in laboratory practice. Competency development becomes effective when educational processes are systematically designed and delivered to ensure meaningful integration of knowledge and skills. Monitoring the impact of learning processes and evaluating competency achievement are essential during chemistry laboratory activities (Williams et al., 2016). Therefore, it is important to investigate the application of Miller's Pyramid as a predictor of students' practical competence in preventing workplace accidents in chemistry laboratories.

METHODS

This study was designed with two laboratory practice stages based on the stages of Miller's Pyramid. Each laboratory practice followed the four levels of Miller's Pyramid, namely competency level 1 (*knows*), competency level 2 (*knows how*), competency level 3 (*shows*), and competency level 4 (*does*). After completing each stage, an evaluation was conducted for every level of Miller's Pyramid, followed by the second laboratory practice using the same stages as in the first laboratory practice. The overall research design is illustrated in Figure 1.

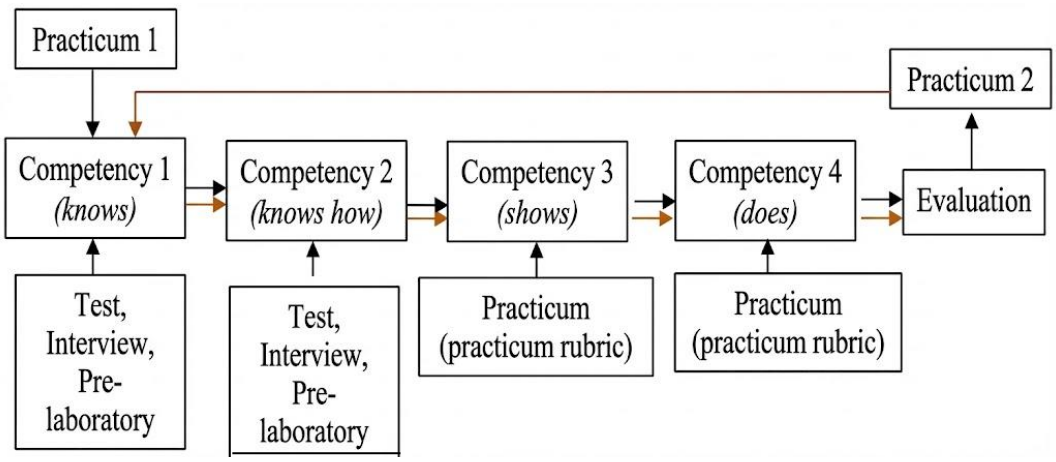

Figure 1. Research Design

The subjects of this study were 60 undergraduate students from the Department of Chemistry who participated in laboratory practice in the Physical Chemistry and Analytical Chemistry Laboratories. The object of the study was students' practical competence based on Miller's Pyramid. Data were collected during each laboratory practice session to assess students' competencies at each level of Miller's Pyramid. Data for competency level 1 (*knows*) and competency level 2 (*knows how*) were obtained through written tests and interviews conducted during the pre-laboratory sessions. Data for competency level 3 (*shows*) and competency level 4 (*does*) were collected during laboratory practice using structured laboratory performance rubrics. All collected data were subsequently evaluated comprehensively. The data obtained at each stage of the laboratory practice were converted into percentages and presented in graphical form. The data were analyzed to determine students' practical competence across the four levels of Miller's Pyramid. Students' competence was categorized as good if at least 70% of the criteria for each competency level were achieved. The development of each competency level within Miller's Pyramid was compared and analyzed in relation to findings from previous studies. Final conclusions were drawn based on the dominant percentage trends observed across competency levels.

RESULT AND DISCUSSION

The study was conducted during the even semester of the 2023/2024 academic year in physical chemistry laboratory practice. The laboratory activities included the determination of the equilibrium constant of a weak acid using conductometry (Laboratory Practice 1) and surface tension measurement (Laboratory Practice 2). The laboratory sessions were carried out by six student groups. Miller's Pyramid consists of four competency components, namely competency levels 1, 2, 3, and 4. The achievement of each competency component was compared between Laboratory Practice 1 and Laboratory Practice 2 to examine the development of students' practical competence, particularly in relation to the prevention of workplace accidents in chemistry laboratories. The comparison of competency level 1 based on Miller's Pyramid is presented in Figure 2. As shown in Figure 2, the average scores of all components within competency level 1 increased. The only component that did not show improvement was experimental apparatus design, which can be attributed to differences in the primary instruments used in the two laboratory practices. Laboratory Practice 1 employed a conductometer as the main instrument, whereas Laboratory Practice 2 utilized a Du Noüy tensiometer.

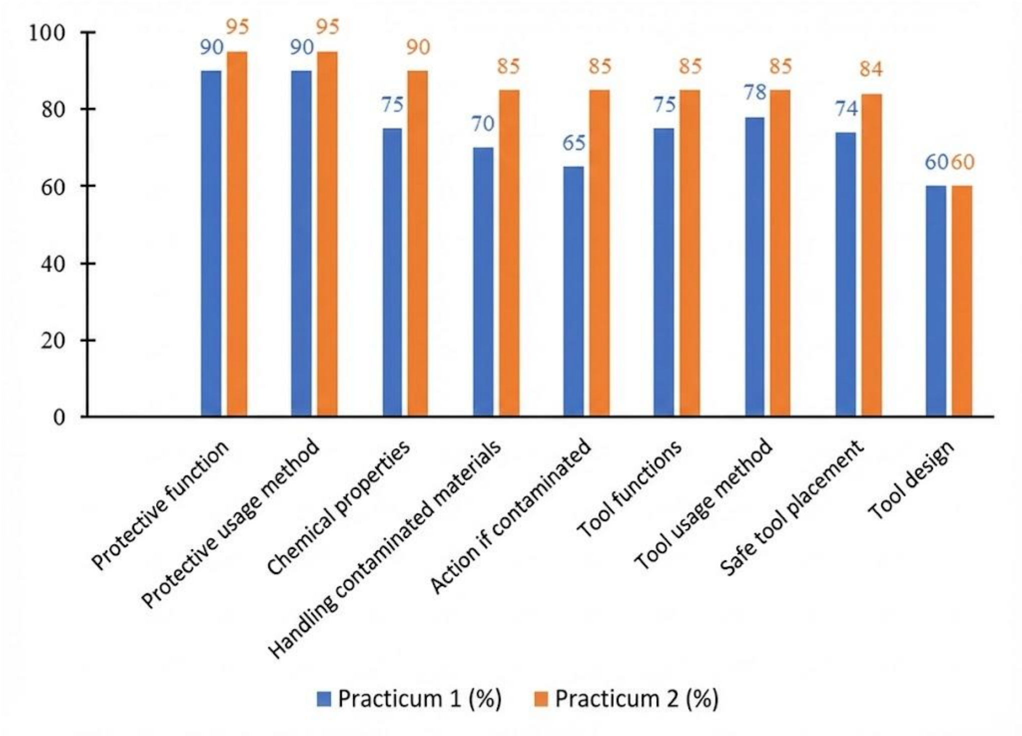

Figure 2. Comparison of Miller's Pyramid Competency Level 1 between Laboratory Practices 1 and 2

The comparison of competency level 2 based on Miller's Pyramid for Laboratory Practices 1 and 2 is presented in Figure 3. As shown in the figure, two components did not exhibit improvement, namely material handling and the actions required when contamination by laboratory chemicals occurs. Deficiencies in these components indicate weaknesses in students' understanding of the properties of chemical substances. This finding is supported by data revealing persistent gaps in students' comprehension of chemical characteristics encountered during laboratory practice. Such deficiencies in knowledge have a significant impact on occupational safety and laboratory security (Putra et al., 2022). The comparison of competency level 3 based on Miller's Pyramid is illustrated in Figure 4. The results show that all components of competency level 3 demonstrated improvement. However, one component did not show an increase despite having the highest mastery percentage, namely the use of personal protective equipment. This component remains consistent across all laboratory practices and does not change between sessions. This consistency enhances students' preparedness, enabling them to clearly understand the required actions during laboratory activities (Septiawati & Trisnawati, 2023).

Accuracy in the use of materials and laboratory equipment showed the lowest mastery percentage among all components. This finding is consistent with the weaknesses identified in each laboratory practice. The results indicate that students' knowledge and skills require further intensive training, particularly in weighing materials and selecting appropriate measuring instruments. These skills cannot be developed solely through reading but must be acquired through direct hands-on practice. In several laboratory sessions, it was observed that not all students were actively involved, with some only recording and observing without participating in experimental procedures. This condition suggests that students' *work-based learning and research* (WBLR) competencies have not yet developed optimally, even though WBLR provides extensive opportunities for learners to acquire experience, qualifications, and reflective practical knowledge (Fergusson, 2022).

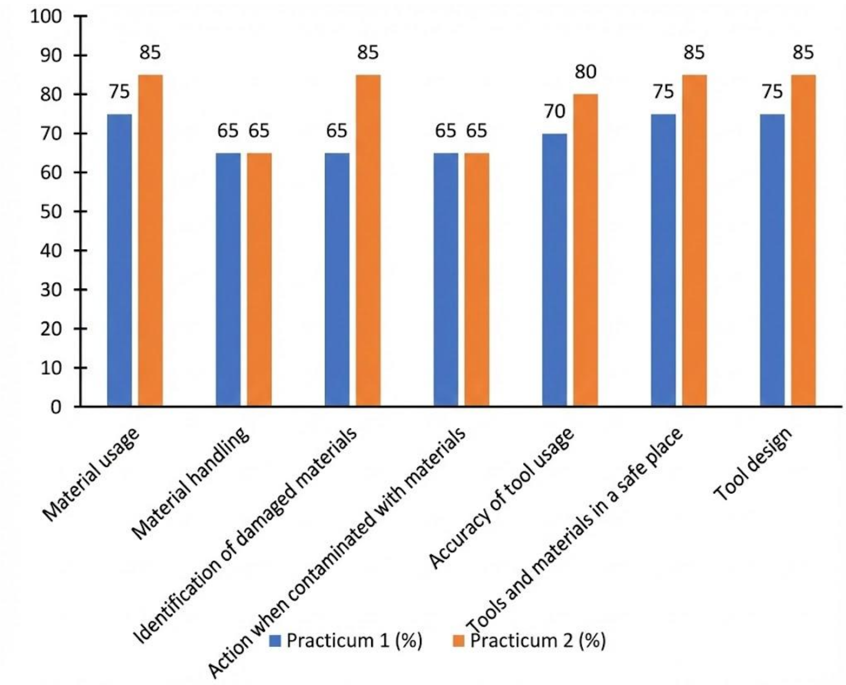

Figure 3. Comparison of Miller's Pyramid Competency Level 2 in Practical Session 1 and Practical Session 2

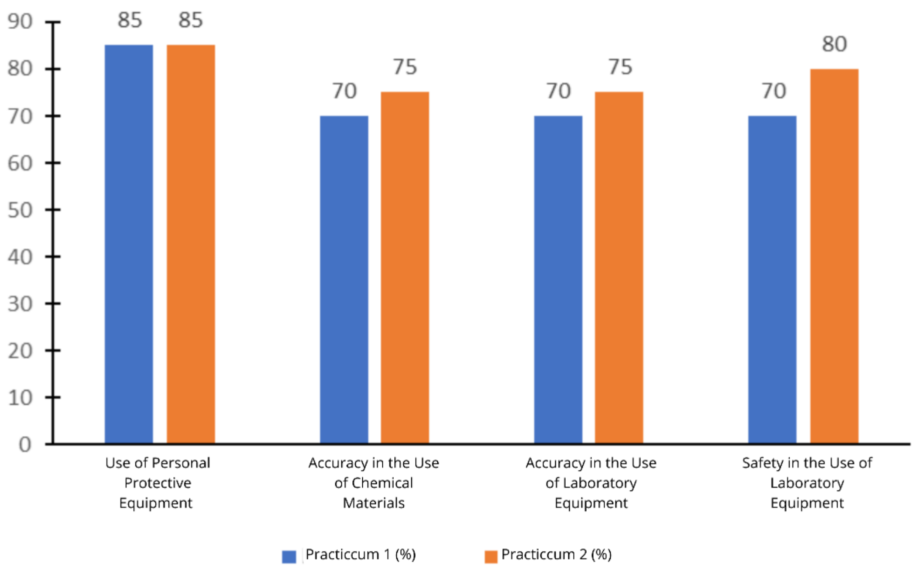

Figure 4. Comparison of Miller's Pyramid Competency Level 3 in Practical Session 1 and Practical Session 2

The comparison of Level 4 competency of Miller's Pyramid between Practical Sessions 1 and 2 is presented in Figure 5. This level reflects the initiative and appropriate actions demonstrated by practicum students to prevent accidents in the chemistry laboratory. Based on the assessed aspects of Level 4 competency, all components showed improvement, indicating better initiative and decision-making among students. The emergence of such initiative and actions is influenced by two groups of factors, namely environmental factors and individual factors. Each individual possesses an internal safety performance program, while the role of Miller's Pyramid in occupational safety and health lies in fostering a positive organizational climate through the implementation of an effective occupational safety and health management system. This is closely related to organizational commitment to preventing occupational accidents and work-related illnesses, as well as to improving overall work productivity (Sinaga & Sinaga, 2022).

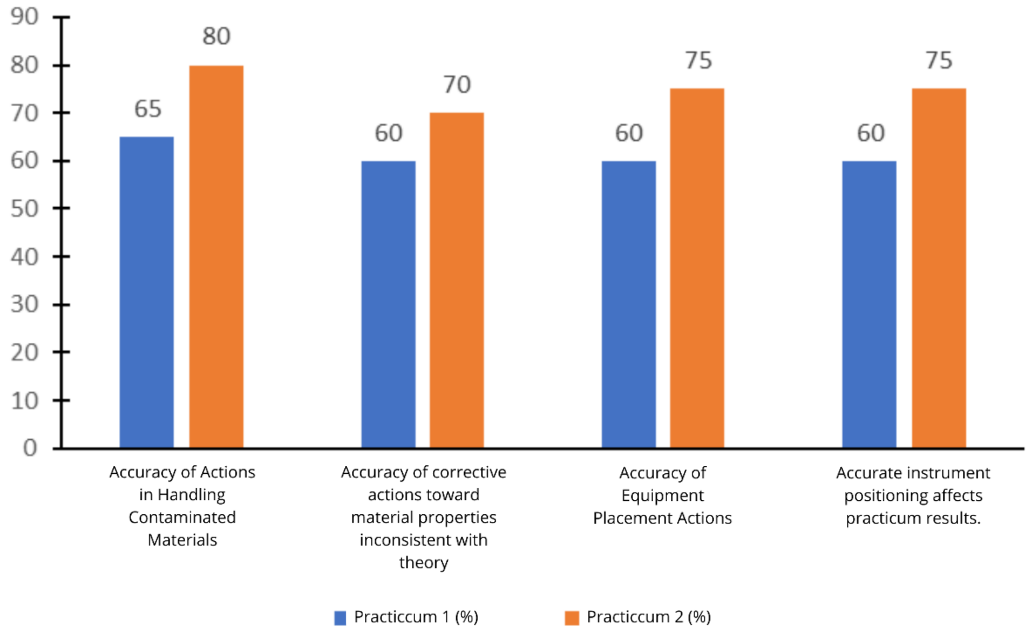

Figure 5. Comparison of Miller's Pyramid Competency Level 4 in Practical Session 1 and Practical Session 2

The comparison of all components of the Miller's Pyramid is presented in Figure 6. The figure indicates that students' practicum competencies improved across all aspects, ranging from knowledge to practical skills. This improvement reflects the ongoing development of students' skills. Skill development is defined as a process of continuous formation or transformation of professional and personal qualities, including mastering new approaches to solving professional problems, developing professional thinking patterns, overcoming negative attitudes and inhibiting past experiences, and strengthening motivational and operational aspects of professional activities. Furthermore, students increasingly emerge as active subjects in the process of continuous learning (Kalyani, 2020). Consequently, the risk of occupational accidents in the laboratory can be reduced, leading to improved laboratory safety.

Students' perceptions of the implementation of the Miller's Pyramid during practicum activities are presented in Figure 7. The evaluated aspects include collaboration, motivation, empathy, and comfort. The results show that students' levels of collaboration, motivation, and empathy exceed 70%. This outcome is attributed to the application of the Miller's Pyramid, which requires students to progressively achieve competence during practicum activities. These demands enhance motivation and encourage collaboration among students to achieve shared goals. The emergence of a sense of togetherness subsequently increases empathy among students, which ultimately fosters a comfortable learning environment during practicum sessions (Dwi Stiawan, 2024).

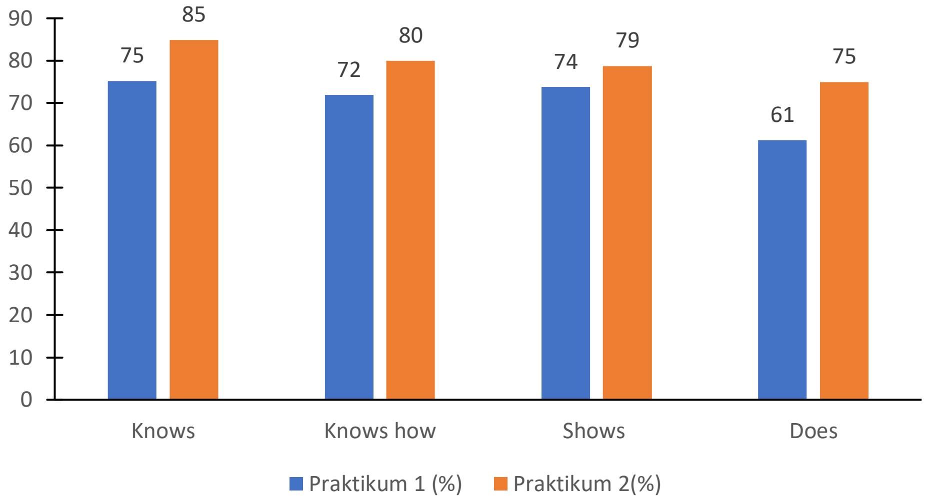

Figure 6. Comparison of Miller's Pyramid Competencies in Practicum 1 and Practicum 2

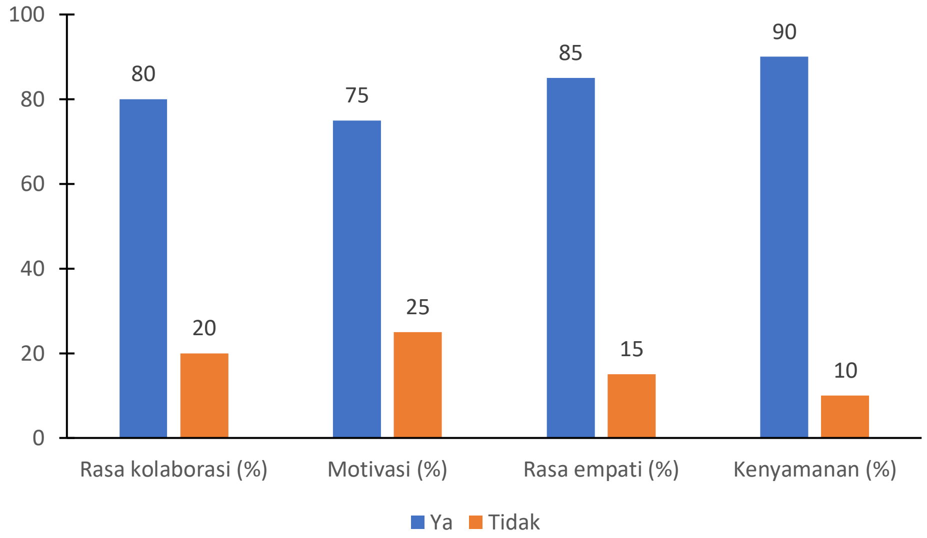

Figure 7. Students' Perceptions of the Implementation of Miller's Pyramid

CONCLUSION

The findings of this study indicate that Miller's Pyramid can be effectively used as a predictor of students' practical competence in preventing occupational accidents in chemistry laboratories. The implementation of Miller's Pyramid enables a systematic assessment and development of students' competencies, ranging from conceptual knowledge (*knows*), procedural understanding (*knows how*), observable performance (*shows*), to real laboratory actions (*does*). The results demonstrate that students' practical competencies across all stages of Miller's Pyramid were categorized as good, with consistent improvement observed throughout the practicum sessions. Furthermore, students showed highly positive responses to the implementation of Miller's Pyramid, as it enhanced safety awareness, learning motivation, collaboration, and comfort during laboratory activities. Therefore, Miller's Pyramid is not only appropriate as a competency evaluation framework but also serves as a strategic approach for strengthening occupational safety and health practices in chemistry education laboratories.

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