JPPIPA 11(5) (2025)

Jurnal Penelitian Pendidikan IPA

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# Research Trends in Virtual Laboratories Based on STEM in Science Learning and Their Impact on Science Process Skills through Bibliometric Analysis (2020-2024) and The Contribution of Indonesia

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Received: February 17, 2025
Revised: March 20, 2025
Accepted: May 25, 2025
Published: May 31, 2025

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DOI: 10.29303/jppipa.v11i5.10692



**Abstract:** This paper aims to analyze the scientific trend of research on the impact of virtual laboratories on STEM-based science learning and their influence on students' science process skills through bibliometric study and to explore how the contribution of Indonesian researchers in the Scopus database from 2020 to 2024. The sample was composed of 7 documents in total. The results revealed that scientific publication on the impact of virtual laboratories on STEM-based science learning and their influence on students' science process skills has been increasing. In the last five years, seven countries have contributed to writing journal articles related to on the impact of virtual laboratories on STEM-based science learning and their influence on students' science process skills. The seven countries are Indonesia, Brazil, Rwanda, Zimbabwe, the United States, Spain, and Mexico. There is one journal from Indonesia that discusses on the impact of virtual laboratories on STEM-based science learning and their influence on students' science process skills in the last five years, namely a journal written by Usman et al. (2021) and published in the Journal of Physics: Conference Series, Yogyakarta State University, Indonesia. The research findings could aid related researchers to recognize the trend of impact of virtual laboratories on STEM-based science learning and their influence on students' science process skills research globally and recommend directions for further research.

**Keywords:** Bibliometric study; Science process skill; STEM; Virtual laboratories.

## Introduction

The integration of technology in education has significantly transformed the teaching and learning process, particularly in STEM (Science, Technology, Engineering, and Mathematics) disciplines (Zhan & Niu, 2023). Among these advancements, virtual laboratories have emerged as an innovative solution to enhance experiential learning in science education (Chan et al., 2021). Virtual laboratories offer interactive and immersive environments that simulate real-world scientific experiments, enabling students to explore concepts beyond traditional methods (Verawati & Purwoko, 2024). The flexibility and accessibility of these

**How to Cite:**
Wintribrata, B. H., Indriyanti, D. R., & Fianti, F. (2025). Research Trends in Virtual Laboratories Based on STEM in Science Learning and Their Impact on Science Process Skills through Bibliometric Analysis (2020-2024) and The Contribution of Indonesia. *Jurnal Penelitian Pendidikan IPA*, *11*(5), 144–151. https://doi.org/10.29303/jppipa.v11i5.10692

tools make them highly suitable for modern educational needs, especially in contexts where resources and physical laboratories are limited (Ali, 2020). As a result, they have gained increasing attention from researchers and educators worldwide for their potential to improve science process skills and engagement (Onu et al., 2024).

Science, Technology, Engineering, and Mathematics education plays a critical role in preparing students for the demands of the 21st century, fostering creativity, problem-solving skills, and interdisciplinary knowledge (AlAli, 2024). Science, as a core component of STEM, requires a strong emphasis on practical experiences to develop critical thinking and investigative abilities (Hacıoğlu & Gülhan, 2021). However, traditional laboratory setups often face challenges such as cost, safety concerns, and limited access (Bhute et al., 2021). Virtual laboratories, integrated with STEM frameworks, address these challenges by providing a cost-effective and scalable alternative (Alnagrat et al., 2022). This makes them a pivotal resource for advancing science education and equipping students with the skills needed for future scientific inquiry and innovation (Aithal & Maiya, 2023).

Science process skills are essential competencies that allow students to engage in scientific inquiry effectively (Chen et al., 2020). These skills include observation, experimentation, data analysis, hypothesis formulation, and critical evaluation (Jamil et al., 2024). Virtual laboratories support the development of these skills by offering realistic simulations of scientific phenomena (Groenewald et al., 2024). By engaging with these platforms, students can actively participate in designing experiments, manipulating variables, and analyzing outcomes, fostering a deeper understanding of scientific concepts (Ateş & Köroğlu, 2024). The impact of virtual laboratories on enhancing these skills has become a focal point for research, especially in understanding how they contribute to student achievement in STEM education (Sellberg et al., 2024).

Bibliometric analysis is a powerful method for evaluating research trends, identifying key contributors, and mapping the landscape of academic disciplines (Hassan & Duarte, 2024). By analyzing publication outputs, citations, and keywords, researchers can uncover patterns and insights that guide future studies (Klarin, 2024). In the context of virtual laboratories in STEM education, bibliometric analysis provides valuable data on how these tools are being studied globally, the impact of such studies, and the evolution of research themes over time (Lopes et al., 2024). This approach also highlights the geographical distribution of research efforts, shedding light on the contributions of various countries and institutions to this growing field (Ikhwani et al., 2024).

Over the past decade, there has been a noticeable increase in studies focusing on virtual laboratories in STEM education (Deriba et al., 2024). Researchers have explored diverse aspects, including their design, implementation, and impact on learning outcomes (Fakhri et al., 2024). Emerging themes indicate a shift toward integrating artificial intelligence and machine learning to enhance interactivity and personalization in virtual laboratories (Moemeke, 2024). Additionally, studies have started to address the role of these tools in promoting equity in education, ensuring students from underprivileged backgrounds have access to quality STEM learning experiences (Gichuru, 2024). These trends signify a dynamic research area that continues to evolve with technological advancements (Al Hamad et al., 2024).

Indonesia, as a developing nation, has shown growing interest in leveraging virtual laboratories for science education (Ramadhani et al., 2024). Several studies have been conducted to assess their effectiveness in improving science process skills and bridging gaps in resource availability (Dwivedi et al., 2024). The government's emphasis on STEM education and digital transformation has further accelerated research and implementation efforts (AlAli & Wardat, 2024). Despite challenges such as digital literacy and infrastructure limitations, Indonesian researchers and institutions have made notable contributions to the global discourse on virtual laboratories. Their work often incorporates unique cultural and educational contexts, adding diversity and depth to the body of knowledge in this field (Nash et al., 2024).

This study aims to analyze the research trends in virtual laboratories based on STEM education in science learning from 2020 to 2024. By employing bibliometric analysis, the study seeks to uncover patterns, key contributors, and thematic developments in this domain. Particular attention is given to the impact of virtual laboratories on science process skills and the contributions of Indonesian researchers to the global research landscape. The findings are expected to provide valuable insights for educators, policymakers, and researchers, guiding the future development and implementation of virtual laboratories to enhance science education worldwide.

This study focused on the research trends in virtual laboratories based on STEM in science learning and their impact on science process skills through bibliometric analysis (2020-2024) and the contribution of Indonesia with six research questions:
a) To what extent is the profile of publication output on virtual laboratories based on STEM in science learning during 2020-2024?
b) How is the distribution of publications on virtual

laboratories based on STEM across countries and institutions in the world? c) Who are the leading authors in researching virtual laboratories based on STEM in science learning? d) What are the visualization results of research trends on virtual laboratories based on STEM in science learning and their impact on science process skills?

## Method

The study adhered to the principles of bibliometric analysis as outlined by previous researchers (Dong et al., 2012; Kulakli & Osmanaj, 2020; Yang et al., 2017). The first author has extensive experience in conducting bibliometric studies (Suprapto et al., 2021). For this study, the Scopus database was selected as the primary source, given its extensive collection of journals and conference proceedings, which are highly regarded by the scientific community for their reliability, relevance, and consistent publication standards. The research process began with an online search conducted from June 1 to June 7, 2024. The step-by-step methodology is presented in Figure 1. To identify relevant literature, the researchers used the search query "Virtual Laboratories STEM Science Learning" in the title, keywords, and abstract fields, focusing on the publication period between 2020 to 2024.

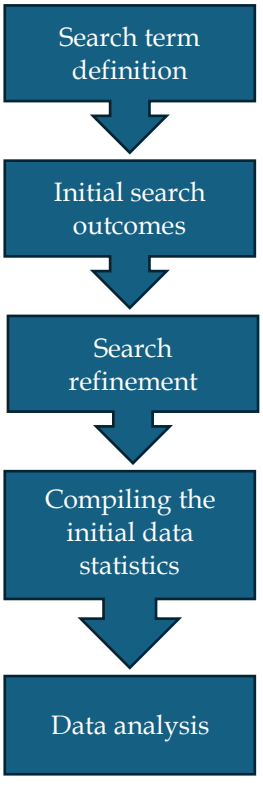


**Figure 1.** Five steps in conducting bibliometric analysis (Masitoh et al., 2021; Schmeisser, 2013; Setyaningsih, 2018)

A total of 7 documents met the filtering criteria out of 16 documents identified during the entire search period (see Figure 2). This selection highlights the rigorous process of refining the dataset to ensure only relevant and high-quality records were included for analysis. The data were saved in .ris and .csv formats, providing flexibility for subsequent analytical tasks and ensuring compatibility with various tools. These records were then processed using a combination of software for bibliometric and network analysis, with Microsoft Excel playing a central role in organizing and visualizing the data (Juandi et al., 2024).

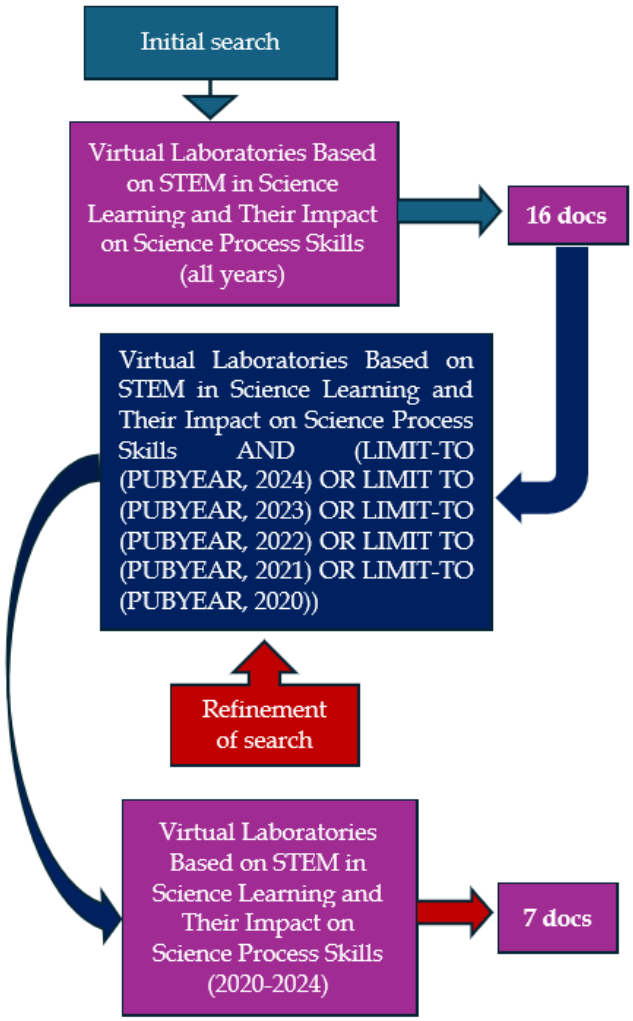


**Figure 2.** Illustration of initial and refinement search

## Result and Discussion

*Sublication Output, Document Sources, and Language Sources*

A total of 7 journal documents were identified from the Scopus database during the period of 2020 to 2024. The publication output, as shown in Figure 1, experienced fluctuations across these years. In 2020, only 1 document was published, followed by an increase to 2

documents in 2021. However, no publications were recorded in 2022, reflecting a temporary decline in research activity. The number of documents increased again to 2 publications in both 2023 and 2024, demonstrating a recovery and stabilization in output. All 7 documents came exclusively from journal sources, with no contributions from books, conference proceedings, or other document types. Furthermore, English was the sole language used in all the identified documents, highlighting the global accessibility and consistency of the research publications during this period. The data also suggests a stabilization in research output during the most recent years (2023–2024), reflecting renewed research activity in the field.

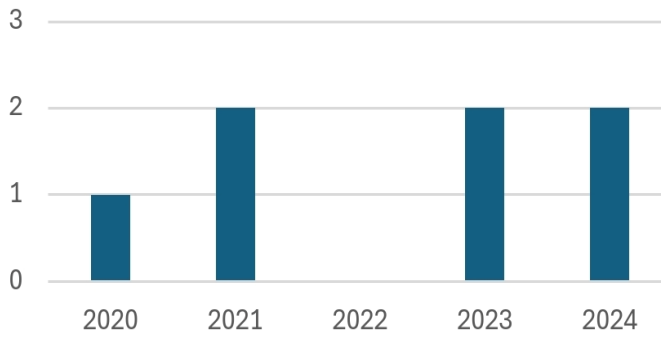


**Figure 3.** The number of documents on the last five years (2020-2024)

*Publication Distribution of Countries and Institutes*

Based on the data provided, each country contributed equally, producing 1 article each. Indonesia, Brazil, Rwanda, Zimbabwe, the United States, Spain, and Mexico all demonstrated uniform contributions with no single country showing dominance over the others. This equal distribution highlights a balanced effort among these nations, without any country exhibiting a higher level of production or growth during the observed period. The data reflects a trend of uniformity rather than disparity in contributions across all represented countries.

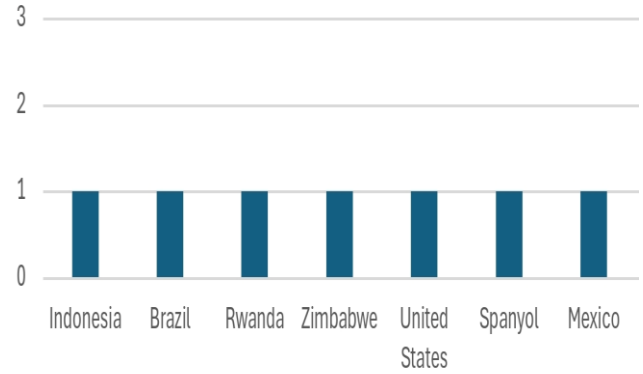


**Figure 4.** Number of documents based on countries 2020-2024

Based on the data of Virtual Laboratories in STEM Science Learning and their impact on Science Process Skills from 2020 to 2024, contributions were distributed evenly across various institutions. Universitas Negeri Yogyakarta (Indonesia), Universitas Federal Santa Catarina (Brazil), Universitas Rwanda (Rwanda), and Universitas Great Zimbabwe (Zimbabwe) each contributed one document. Similarly, Universidad Autónoma de Guadalajara (Mexico), Purdue University and University of Louisville (United States), as well as Universitas Salamanca, University of Leon (Spain), and Instituto Politécnico de Bragança (Portugal) also produced one document each. This uniform distribution of documents highlights a balanced participation from institutions across different countries. No single institution or country demonstrated dominance, reflecting a shared interest and effort in the exploration of virtual laboratories in STEM education globally.

**Table 1.** Number of documents of Virtual Laboratories Based on STEM in Science Learning and Their Impact on Science Process Skills (2020-2024) across institution

| Institution | Number of Documents |
|---|---|
| Universitas Negeri Yogyakarta, Indonesia | 1 |
| Universitas Federal Santa Catarina, Brasil | 1 |
| Universitas Rwanda, Rwanda | 1 |
| Universitas Great Zimbabwe, Zimbabwe | 1 |
| Universidad Autónoma de Guadalajara, Meksiko | 1 |
| Purdue University dan University of Louisville, Amerika Serikat | 1 |
| Universitas Salamanca (Spanyol), University of Leon (Spanyol), and Instituto Politécnico de Bragança (Portugal) | 1 |

*Top Authors in Researching of ethnoscience*

Based on the data of top authors researching virtual laboratories in STEM science learning and their impact on science process skills from 2020 to 2024, all listed authors contributed equally with one document each. Authors such as Aqlan Faisal, Asunda Paul, Azzam Israa, and Bilessimo Simone, among others, showed balanced contributions. The uniform output indicates no dominant researcher or group, reflecting a collaborative effort across various individuals. Researchers like Breidi Farid, Campos-Rodríguez Armando, Conde Miguel A, and Garcia-Penalvo Francisco Jose also contributed to the global effort in exploring this field. This even distribution highlights a widespread and collective interest in advancing research on virtual laboratories and STEM education.

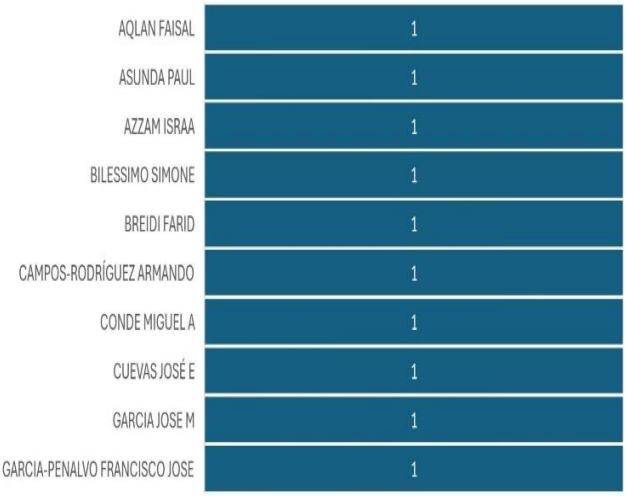


**Figure 5.** Authors in researching of Virtual Laboratories Based on STEM in Science Learning and Their Impact on Science Process Skills (2020-2024)

**Table 2.** Top citation of article of all years

| Author (s) | Journal | ∑ citations |
|---|---|---|
| Nungu et al. (2023) | Education and Information Technologies | 25 |
| Silva et al. (2020) | Journal of Information Technology Education: Research | 18 |
| Usman & Huda (2021)) | Journal of Physics: Conference Series | 17 |
| Mamani et al. (2021) | SIIE 2021 - 2021 International Symposium on Computers in Education | 8 |
| Zárate-Navarro et al. (2024) | Education for Chemical Engineers | 1 |
| Chapungu et al. (2023) | COVID-19 in Zimbabwe: Trends, Dynamics and Implications in the Agricultural, Environmental and Water Sectors | 0 |
| Azzam et al. (2024) | ASEE Annual Conference and Exposition, Conference Proceedings | 0 |

*Visualization of Research Trends on ethnoscience based on bibliometrix Software*

Among those 7 papers related to virtual laboratories in STEM science learning and their impact on science process skills research in the Scopus database, the researchers visualized the research trends on this topic assisted with bibliometrix software. The image represents a network visualization of research trends related to virtual laboratories based on STEM in science learning and their impact on science process skills from 2020 to 2024. The visualization is divided into three clusters, indicated by the green, red, and blue nodes, each representing specific research focuses. The green cluster highlights research themes related to learning systems, simulation, and information and communication technologies, indicating a strong link to technological applications supporting e-learning. The red cluster is more centralized around the keywords e-learning, virtual lab, and laboratories, showing its connection to science education and virtual environments. This central position suggests that research on virtual labs bridges the integration of technology and educational systems, emphasizing its role in enhancing science learning outcomes.

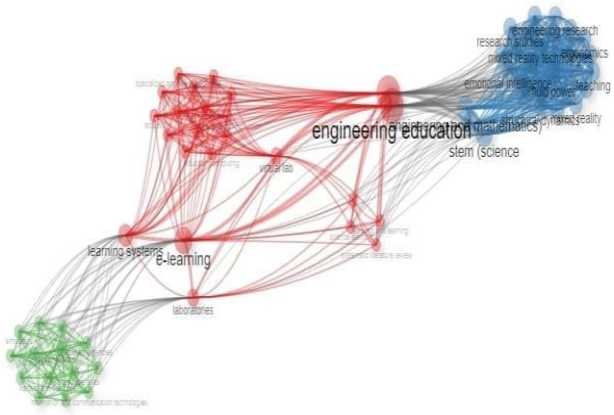


**Figure 6.** Network visualization of research trends related to virtual laboratories based on STEM in science learning and their impact on science process skills from 2020 to 2024.

The blue cluster focuses on engineering education, STEM (science, technology, engineering, and mathematics), and related themes like mixed reality, research studies, and fluid power, reflecting the connection to advanced engineering research and applied sciences. The presence of emotional intelligence and ergonomics indicates an emerging focus on human factors and learning effectiveness in virtual lab applications. The links between clusters emphasize interdisciplinary research, where technology, engineering, and education converge to improve science learning and process skills. Overall, the visualization reveals that virtual laboratories in STEM education have fostered interconnected research domains, demonstrating their critical role in integrating innovation, e-learning systems, and science process skill development.

## Conclusion

In this work, the authors used bibliometric methods to analyze research trends on the impact of virtual laboratories in STEM-based science learning and their influence on students' science process skills from 2020 to

2024. The study identified significant contributions from seven countries: Indonesia, Brazil, Rwanda, Zimbabwe, the United States, Spain, and Mexico, with each country producing one document. Indonesia made its contribution through a study conducted by Usman et al. (2021), which was published in the Journal of Physics: Conference Series from Universitas Negeri Yogyakarta. This research highlights the importance of virtual laboratories in enhancing students' science process skills, such as experimentation, observation, and data analysis, while also improving learning outcomes. The bibliometric analysis revealed a balanced global interest in virtual laboratories, providing valuable insights into their educational impact and setting directions for future research in STEM learning innovation.

**Acknowledgments**
The author team would like to thank all parties involved in this research so that it could be completed.

**Author Contributions**
Bunaya Hanif Wintribrata: Preparation of research concepts and designs, data collection, data analysis, manuscript writing and editing. Dyah Rini Indriyanti: Guidance during research and manuscript writing. Fianti: Guidance during research and manuscript writing.

**Funding**
There are no funding sources that support this research.

**Conflicts of Interest**
The authors declare that there are no relevant conflicts of interest related to this research.

## References

Aithal, P. S., & Maiya, A. K. (2023). Innovations in higher education industry--Shaping the future. *International Journal of Case Studies in Business, IT, and Education (IJCSBE)*, *7*(4), 283–311. Retrieved from https://ssrn.com/abstract=4674658

Al Hamad, N. M., Adewusi, O. E., Unachukwu, C. C., Osawaru, B., & Chisom, O. N. (2024). Counselling as a tool for overcoming barriers in stem education among underrepresented groups. *Engineering Science & Technology Journal*, *5*(1), 65–82. https://doi.org/10.51594/estj.v5i1.728

AlAli, R. (2024). Enhancing 21st century skills through integrated STEM education using project-oriented problem-based learning. *Geo Journal of Tourism and Geosites*, *53*(2), 421–430. https://doi.org/10.30892/gtg.53205-1217

AlAli, R., & Wardat, Y. (2024). Empowering education through digital transformation: Confronting educational wastage in basic education schools in Jordan. *International Journal of Innovative Research and Scientific Studies*, *7*(3), 1148–1162. https://doi.org/10.53894/ijirss.v7i3.3144

Ali, W. (2020). Online and remote learning in higher education institutes: A necessity in light of COVID-19 pandemic. *Higher Education Studies*, *10*(3), 16–25. Retrieved from https://eric.ed.gov/?id=ej1259642

Alnagrat, A. J. A., Ismail, R. C., & Idrus, S. Z. S. (2022). The Opportunities and challenges in virtual reality for virtual laboratories. *Innovative Teaching and Learning Journal*, *6*(2), 73–89. https://doi.org/10.11113/itlj.v6.91

Ateş, H., & Köroğlu, M. (2024). Online collaborative tools for science education: Boosting learning outcomes, motivation, and engagement. *Journal of Computer Assisted Learning*, *40*(3), 1052–1067. https://doi.org/10.1111/jcal.12931

Azzam, I., Breidi, F., & Aqlan, F. (2024). Teaching Manufacturing Assembly Processes Using Immersive Mixed Reality. *2024 ASEE Annual Conference \& Exposition*. https://doi.org/10.18260/1-2--48063

Bhute, V. J., Inguva, P., Shah, U., & Brechtelsbauer, C. (2021). Transforming traditional teaching laboratories for effective remote delivery—A review. *Education for Chemical Engineers*, *35*, 96–104. https://doi.org/10.1016/j.ece.2021.01.008

Chan, P., Van Gerven, T., Dubois, J.-L., & Bernaerts, K. (2021). Virtual chemical laboratories: A systematic literature review of research, technologies and instructional design. *Computers and Education Open*, *2*, 100053. https://doi.org/10.1016/j.caeo.2021.100053

Chapungu, L., Chikodzi, D., & Dube, K. (2023). *COVID-19 in Zimbabwe: Trends, Dynamics and Implications in the Agricultural, Environmental and Water Sectors*. Springer. https://doi.org/10.1007/978-3-031-21472-1

Chen, Y.-C., Pan, Y.-T., Hong, Z.-R., Weng, X.-F., & Lin, H.-S. (2020). Exploring the pedagogical features of integrating essential competencies of scientific inquiry in classroom teaching. *Research in Science & Technological Education*, *38*(2), 185–207. https://doi.org/10.1080/02635143.2019.1601075

Deriba, F. G., Saqr, M., & Tukiainen, M. (2024). Assessment of accessibility in virtual laboratories: a systematic review. *Frontiers in Education*, *9*, 1351711. https://doi.org/10.3389/feduc.2024.1351711

Dong, B., Xu, G., Luo, X., Cai, Y., & Gao, W. (2012). A bibliometric analysis of solar power research from 1991 to 2010. *Scientometrics*, *93*(3), 1101–1117. https://doi.org/10.1007/s11192-012-0730-9

Dwivedi, Y. K., Jeyaraj, A., Hughes, L., Davies, G. H., Ahuja, M., Albashrawi, M. A., Al-Busaidi, A. S., Al-Sharhan, S., Al-Sulaiti, K. I., Altinay, L., & others.

(2024). "Real impact": Challenges and opportunities in bridging the gap between research and practice--Making a difference in industry, policy, and society. In *International Journal of Information Management*. Elsevier. https://doi.org/10.1016/j.ijinfomgt.2023.102750

Fakhri, M. M., Ahmar, A. S., Isma, A., Rosidah, R., & Fadhilatunisa, D. (2024). Exploring generative AI tools frequency: Impacts on attitude, satisfaction, and competency in achieving higher education learning goals. *EduLine: Journal of Education and Learning Innovation*, *4*(1), 196–208. https://doi.org/10.35877/454RI.eduline2592

Gichuru, J. (2024). Enhancing STEM education through equity, diversity, inclusion and decolonization. In *Global Perspectives on STEM Education: Theory and Practice*. Springer. https://doi.org/10.1007/978-3-031-60676-2_3

Groenewald, E. S., Kumar, N., Avinash, S. I., & Yerasuri, S. (2024). Virtual laboratories enhanced by AI for hands-on informatics learning. *Journal of Informatics Education and Research*, *4*(1), 1–21. Retrieved from https://jier.org/index.php/journal/article/view/600

Hacıoğlu, Y., & Gülhan, F. (2021). The effects of STEM education on the students' critical thinking skills and STEM perceptions. *Journal of Education in Science Environment and Health*, *7*(2), 139–155. https://doi.org/10.21891/jeseh.771331

Hassan, W., & Duarte, A. E. (2024). Bibliometric analysis: a few suggestions. *Current Problems in Cardiology*, 102640. https://doi.org/10.1016/j.cpcardiol.2024.102640

Ikhwani, I., Rahayuningsih, S., Yuniarti, E., Kusuma, H. S., Darmokoesomo, H., & Putra, N. R. (2024). Mapping the trend of evolution: a bibliometric analysis of biopesticides in fruit crop protection. *Journal of Plant Diseases and Protection*, *131*(3), 645–664. https://doi.org/10.1007/s41348-024-00879-0

Jamil, M., Hafeez, F. A., & Muhammad, N. (2024). Critical thinking development for 21st century: Analysis of Physics curriculum. *Journal of Social \& Organizational Matters*, *3*(1), 1–10. https://doi.org/10.56976/jsom.v3 i1.45

Juandi, T., Kaniawati, I., Samsudin, A., & Riza, L. S. (2024). The Application of Rasch Model to Analyse the Validity and Reliability of an Instrument for Reflective Thinking Skills on Topic of Wave-Particle Dualism. *Kappa Journal*, *8*(2), 270–277. https://doi.org/10.29408/kpj.v8i2.27049

Klarin, A. (2024). How to conduct a bibliometric content analysis: Guidelines and contributions of content co-occurrence or co-word literature reviews. *International Journal of Consumer Studies*, *48*(2), e13031. https://doi.org/10.1111/ijcs.13031

Kulakli, A., & Osmanaj, V. (2020). Global research on big data in relation with artificial intelligence (A bibliometric study: 2008-2019). *iJOE*, *16*(2) Retrieved from https://www.learntechlib.org/d/218019/

Lopes, R. M., Braga, L. A. M., Serrão, A. S. R., Teixeira, L. do A., Comarú, M. W., de Souza, R. A., de Souza, C. A. M., & Mota, F. B. (2024). Virtual reality to teach students in laboratories: A bibliometric and network analysis. *Journal of Chemical Education*, *101*(2), 501–513. https://doi.org/10.1021/acs.jchemed.3c00925

Mamani, N. M., García-Peñalvo, F. J., Conde, M. Á., & Gonçalves, J. (2021). A systematic mapping about simulators and remote laboratories using hardware in the loop and robotic: Developing STEM/STEAM skills in pre-university education. *2021 International Symposium on Computers in Education (SIIE)*, 1–6. https://doi.org/10.1109/SIIE53363.2021.9583622

Moemeke, C. D. (2024). Artificial Intelligence and Machine Learning in enhancing Science Learning Experiences: Exploring Possibilities and Concerns. *NIU Journal of Educational Research*, *10*(2), 59–72. https://doi.org/10.58709/niujed.v10i2.2000

Nash, B. L., Dunham, H., Murdter-Atkinson, J., & Mosley Wetzel, M. (2024). A culturally sustaining approach to multimodal literacies: Building from students' funds of knowledge in field-based teacher education. *Literacy Research and Instruction*, *63*(2), 151–175. https://doi.org/10.1080/19388071.2022.2153766

Nungu, L., Mukama, E., & Nsabayezu, E. (2023). Online collaborative learning and cognitive presence in mathematics and science education. Case study of university of Rwanda, college of education. *Education and Information Technologies*, *28*(9), 10865–10884. https://doi.org/10.1007/s10639-023-11607

Onu, P., Pradhan, A., & Mbohwa, C. (2024). Potential to use metaverse for future teaching and learning. *Education and Information Technologies*, *29*(7), 8893–8924. https://doi.org/10.1007/s10639-023-12167-9

Ramadhani, D. G., Yamtinah, S., Saputro, S., Sarwanto, S., & Masykuri, M. (2024). From screen to bench: unpacking the shifts in chemistry learning experiences during the COVID-19 transition. *Chemistry Teacher International*, *6*(1), 19–33. https://doi.org/10.1515/cti-2023-0039

Sellberg, C., Nazari, Z., & Solberg, M. (2024). Virtual laboratories in stem higher education: a scoping review. *Nordic Journal of Systematic Reviews in Education*, 2. https://doi.org/10.23865/njsre.v2.5766

Silva, E., Pinto, K. P., Ferreira, C. M., Belladonna, F. G.,

De-Deus, G., Dummer, P. M. H., & Versiani, M. A. (2020). Current status on minimal access cavity preparations: a critical analysis and a proposal for a universal nomenclature. *International Endodontic Journal*, *53*(12), 1618–1635. https://doi.org/10.1111/iej.13391

Suprapto, N., Sukarmin, S., Puspitawati, R. P., Erman, E., Savitri, D., Ku, C.-H., & Mubarok, H. (2021). Research trend on TPACK through bibliometric analysis (2015-2019). *International Journal of Evaluation and Research in Education (IJERE)*, *10*(4), 1375. https://doi.org/10.11591/ijere.v10i4.22062

Usman, M., & Huda, K. (2021). Virtual lab as distance learning media to enhance student's science process skill during the COVID-19 pandemic. *Journal of Physics: Conference Series*, *1882*(1), 12126. https://doi.org/10.1088/1742-6596/1882/1/012126

Verawati, N. N. S. P., & Purwoko, A. A. (2024). Literature review on the use of interactive labs technology in the context of science education. *International Journal of Ethnoscience and Technology in Education*, *1*(1), 76–96. https://doi.org/10.33394/ijete.v1i1.12154

Yang, L., Sun, T., & Liu, Y. (2017). A bibliometric investigation of flipped classroom research during 2000-2015. *International Journal Of Emerging Technologies In Learning (Ijet)*, *12*(06), 178–186. https://doi.org/10.3991/ijet.v12i06.7095

Zárate-Navarro, M. A., Schiavone-Valdez, S. D., Cuevas, J. E., Warren-Vega, W. M., Campos-Rodr\'\iguez, A., & Romero-Cano, L. A. (2024). STEM activities for heat transfer learning: Integrating simulation, mathematical modeling, and experimental validation in transport phenomena education. *Education for Chemical Engineers*, *49*, 81–90. https://doi.org/10.1016/j.ece.2024.06.004

Zhan, Z., & Niu, S. (2023). Subject integration and theme evolution of STEM education in K-12 and higher education research. *Humanities and Social Sciences Communications*, *10*(1), 1–13. Retrieved from https://www.nature.com/articles/s41599-023-02303-8