Journal of the Institute for Educational Research
Volume 57 • Number 2 • December 2025 • 203–226
UDC: 37.015.31:5
37.091.39::001.891.53
Received 13.9.2025.; accepted 2.12.2025.

ISSN 0579-6431
ISSN 1820-9270 (Online)
DOI: 10.2298/ZIPI2502203P
Original research paper

A META-ANALYTICAL STUDY OF THE EFFECTS OF VIRTUAL AND HANDS-ON LABORATORY WORK ON AFFECTIVE LEARNING OUTCOMES IN THE NATURAL SCIENCES*

Katarina Putica • ORCID: 0000-0002-5609-2368
University of Belgrade – Innovative Centre of the Faculty of Chemistry, Belgrade, Serbia

Jelena Stanišić** • ORCID: 0000-0003-3137-4753
Institute for Educational Research, Belgrade, Serbia

ABSTRACT

Innovations in the field of natural sciences have significantly improved the quality of modern everyday life. Yet, students commonly have a negative attitude towards the natural sciences due to the abstract nature of the subject content and the receptive approach to learning. Affective learning outcomes in this field can be improved through both hands-on and virtual laboratory work. However, previous (quasi-)experimental studies comparing their effectiveness in this regard have yielded highly conflicting results. To better understand which laboratory work type more positively influences affective learning outcomes in the natural sciences, this meta-analysis synthesized the results of 22 pertinent (quasi-)experimental studies published in the past 20 years. Virtual laboratory work proved to have statistically significantly higher effectiveness. Furthermore, the meta-regression showed that virtual laboratories' effectiveness was moderated by the approach to experimental work and the type of Likert scale used to evaluate affective outcomes. The results revealed a significantly higher effectiveness of guided versus open inquiry and a significantly higher mean *g* value when using a four-point versus a five-point Likert scale. These findings point to fruitful approaches to improving affective learning outcomes in the natural sciences, along with modes of evaluating their achievement. They also highlight the necessity of devoting special attention to the development of instruments for evaluating the effects of different laboratory activity types on affective learning outcomes. Further research is needed to examine the role of open versus guided inquiry in achieving these outcomes.

Keywords:
virtual laboratories, hands-on laboratories, affective learning outcomes, natural sciences, meta-analysis.

* **To cite this article:** Putica, K. & Stanišić, J. (2025). A meta-analytical study of the effects of virtual and hands-on laboratory work on affective learning outcomes in the natural sciences. *Zbornik Instituta za pedagoška istraživanja, 57*(2), 203–226. DOI: 10.2298/ZIPI2502203P

** E-mail: jstanisic@ipi.ac.rs

INTRODUCTION

With the modern world characterized by ever-accelerating changes, the significance of science and technology has certainly come to the foreground. Accordingly, scientific literacy has become increasingly recognized as one of the key competences for modern living that should be systematically developed during the education process (Ševkušić & Kartal, 2017). According to the definition provided by the OECD (2016), a scientifically literate person can explain phenomena scientifically, evaluate and design scientific research, interpret data scientifically, and thus actively engage in reasoned discourse about science and technology. The definition also recognizes the affective component of scientific literacy, which pertains to students' motivation and affinity for the natural sciences (OECD, 2016). In line with relevant authorities' recommendations, the goal of science education is to equip all citizens with the skills necessary to live and work in a knowledge society and support the development of critical thinking and scientific reasoning, which constitute the basis for making decisions grounded in reliable and adequate information (High Level Group on Science Education, 2007). Hence, individuals can be considered scientifically literate only if they are able to recognize the purpose and significance of the application of scientific knowledge in diverse contexts (Milinković et al., 2017).

Motivation and positive attitudes towards learning are crucial to the development of students' scientific literacy and permanent interest in science. They decisively shape both the learning process and student achievement (Lalić-Vučetić & Mirkov, 2023). This is supported by the results of international TIMSS research in Serbia, which highlighted students' self-confidence and attitudes towards the natural sciences as crucial predictors of their achievement in this field (Jošić et al., 2021).

The 21st century has witnessed natural science advancements that have greatly improved the quality of everyday life. And yet, research has shown that most students still exhibit negative attitudes towards this field (Hornsey, 2020; Rutjens et al., 2018). Both research findings and teaching practice insights indicate that students find natural science content to be distinctly challenging, primarily due to the complexity of the concepts (Milanović-Nahod et al., 2003). Some of the key causes of students' struggles include the concepts' abstract nature and the large number of variables in scientific concepts, along with terminological issues often stemming from the fact that many words have different meanings in everyday and scientific language. Problems also arise due to incompatibility between the structure of scientific disciplines and students' cognitive structure (Gabel & Bunce, 1994; Krajcik, 1991; Stavy, 1995, as cited in Milanović-Nahod et al., 2003). The aforementioned issues are aggravated by the fact that natural science education still mainly relies on receptive learning, which is not conducive to active cognitive engagement and a deep mastery of the content (Osborne et al., 2003). Hence, it is clear that overcoming difficulties in understanding complex scientific concepts hinges on the development of approaches that encourage interaction, experimental activity, and critical thinking among students.

The absence of students' active engagement during receptive learning negatively reflects on student motivation for mastering natural science content (Tas & Cakir, 2014). Compared to more active approaches, receptive learning results in poorer understanding of the content, which causes increased anxiety in knowledge evaluation situations (Nicol et al., 2022), along with low student self-efficacy (Tsai et al., 2011). Furthermore, due to the lack of direct contact with chemical substances and processes, students do not develop an awareness of the significance of their application in everyday life, which reduces students' interest in the natural sciences and contributes to their perception of the content as abstract (Aikenhead, 2006). Finally, the abstractness of natural science content is also related to the fact that fully grasping physical, chemical, and biological processes requires their visualization at the submicroscopic level, being that submicroscopic structures such as atoms, electron beams, or cell organelles are invisible to the naked eye (Taber, 2013).

Building on the understanding that scientific literacy encompasses not only cognitive dimensions but also attitudes, beliefs, and motivation (Lalić-Vučetić & Mirkov, 2023), contemporary pedagogy has increasingly focused on the significance of affective learning outcomes in the natural sciences. Affective learning outcomes pertain to emotional components of the learning process and range from initial readiness to receive information to integrating beliefs, ideas, and attitudes into stable value systems. According to Bloom et al. (1964), the affective domain of learning encompasses five levels, from directing attention to the content and readiness to respond, through accepting and organizing values, to the highest level, which involves building a stable system of attitudes, conscience, and self-awareness.

Experimental work in hands-on laboratories allows students to actively manipulate chemicals and laboratory equipment and overcome most of the aforementioned factors that negatively impact affective learning outcomes in the natural sciences (George-Williams et al., 2018). However, equipping hands-on laboratories is financially demanding (Winkelman et al., 2017), and there are multiple reasons why this type of experimental work can give rise to negative emotions. For instance, research has revealed that many students are afraid that using toxic chemicals can jeopardize their health (Ali et al., 2022). Their uneasiness can be further amplified by the fact that manual laboratory work requires keen focus and precision in a range of fine motor activities (Taramopoulos et al., 2012). Students also tend to feel great pressure because once they start a laboratory procedure, they cannot pause it or undo several steps to correct mistakes made in the process (Rutjens et al., 2018). Furthermore, hands-on experiments generally take a long time to complete, which is why it is hardly ever possible to redo them within a single laboratory session (Asiksoy, 2023). Finally, a relatively common situation in hands-on laboratory work that causes a strong sense of dissatisfaction is one in which all the experimental procedures are completed correctly, but the desired results are not achieved due to the imprecision of certain measuring instruments (Rutjens et al., 2018). It is also important to emphasize that hands-on laboratory work does not allow for the visualization of submicroscopic structures (Potkonjak et al., 2016). Thus, it does not remove a significant cause of abstractness and consequently, students' negative attitude towards natural science content.

On the other hand, in virtual laboratory experiments, students use equipment and chemicals simulated on computers (Ma & Nickerson, 2006). Hence, experimental activities that require expensive equipment and hazardous substances in hands-on conditions can be conducted with minimal expenses and health risks (Winkelman et al., 2017). A great advantage of virtual laboratories is also reflected in the fact that, in case of error, students can stop the experimental procedure at any point and undo several steps (Nicol et al., 2022). Furthermore, the shorter duration allows for experiments to be repeated multiple times within the allotted time (Daineko et al., 2017). Laboratory work is also simplified by the fact that it does not require a constant focus on executing fine manual movements, and there are no issues with the precision of measurement instruments, which increases result accuracy (Pyatt & Sims, 2012). All these characteristics of virtual experiments significantly reduce the likelihood of failure, which facilitates the development of student self-efficacy, makes laboratory work more enjoyable, and contributes to higher motivation for learning natural science content (Husnaini & Chen, 2019). Moreover, the effective visualization of submicroscopic structures allows virtual laboratories to significantly reduce the abstractness of content in this field (Herga et al., 2016). On the other hand, virtual experiments can cause negative emotions in students who have insufficient experience in using information and communications technology (Priest et al., 2014). This type of laboratory work is also not suitable for tactile learners, who need direct manual contact with substances and laboratory equipment in order to successfully acquire new knowledge (Nicol et al., 2022). Finally, an insufficiently realistic virtual laboratory environment and the absence of certain real-world stimuli (e.g., substance scent and texture) can negatively affect student motivation and engagement in this type of laboratory work (Ali et al., 2022).

Considering that both virtual and hands-on laboratories possess characteristics that positively and negatively impact affective learning outcomes in the natural sciences, it is not surprising that existing (quasi-)experimental studies comparing their effects have yielded conflicting results. Whereas certain studies reported significantly greater effectiveness of virtual laboratories (e.g., Akpan & Strayer, 2010; Gambari et al., 2013), some studies found the two laboratory approaches to be equally effective (e.g., Oymak & Ogan-Bekrioglu, 2017; Ratamun & Osman, 2018), and in several studies, hands-on laboratories proved significantly more effective (e.g., Mutlu & Sesen, 2020; Waziri & Belel, 2023). To clarify the effects of virtual and hands-on laboratories on affective learning outcomes in the natural sciences, it is necessary to synthesize the results of previous (quasi-)experimental research on this subject. However, certain limitations plague all existing systematic reviews and meta-analyses synthesizing conclusions on the effects of the two laboratory types in this field.

Firstly, Ma and Nickerson (2006) performed a systematic review that showed that virtual laboratories had rarely been used in natural science education before 2005. Brinson (2015) detected the first noticeable increase in the number of studies on this subject during the period between 2005 and 2015, with a significant portion of research focusing on affective learning outcomes. However, in this systematic review, hands-on laboratories were compared with *nontraditional* laboratories, which included both virtual and remote laboratories, with 86% of studies focusing on affective learning outcomes reporting equal or greater effectiveness of nontraditional laboratories. Unlike Brinson's study, certain systematic reviews only focused on one natural science subject. In reviews in the fields of biology (Byukusenge et al., 2022) and chemistry (Chan et al., 2021) that covered the period between 2000 and 2020, only about 20% of included studies compared the effects of virtual versus hands-on laboratories on affective learning outcomes. Based on their results, virtual laboratories proved more effective than hands-on laboratories in the field of biology, whereas no differences in effectiveness were observed in the field of chemistry. Finally, Swastika et al. (2024) performed a systematic review of research published between 2010 and 2023, but only focused on certain affective learning outcomes. The review showed that virtual laboratories proved more effective than their hands-on counterparts in nearly 60% of studies on encouraging students' positive attitude towards the natural sciences and around 65% of studies focusing on the development of students' self-efficacy in this field.

Due to reliance on quantitative data and the use of statistical methods to synthesize research results, meta-analyses are generally considered more objective than systematic reviews (Ahn & Kang, 2018). However, the few existing meta-analytical studies in this field have mostly compared the overall effectiveness of virtual versus hands-on laboratories. Tsihouridis et al. (2019) conducted a meta-analysis of 106 studies published between 1978 and 2018 (most of them conducted after 2005) and established that hands-on and virtual laboratories had equal total effectiveness. On the other hand, Santos & Prudente (2022) analyzed the results of 15 studies published between 2015 and 2020, whereas Syhwin et al. (2022) synthesized the results of 24 studies published between 2013 and 2021, and both meta-analyses showed that virtual laboratories had a significantly greater total effectiveness, with the former identifying a moderate effect and the latter reporting a large effect size. Finally, Antonio and Castro (2023) conducted a meta-analysis of 15 studies on student academic achievement in physics published between 2017 and 2020 and found that virtual laboratories had a significantly greater effectiveness, reporting a large effect size.

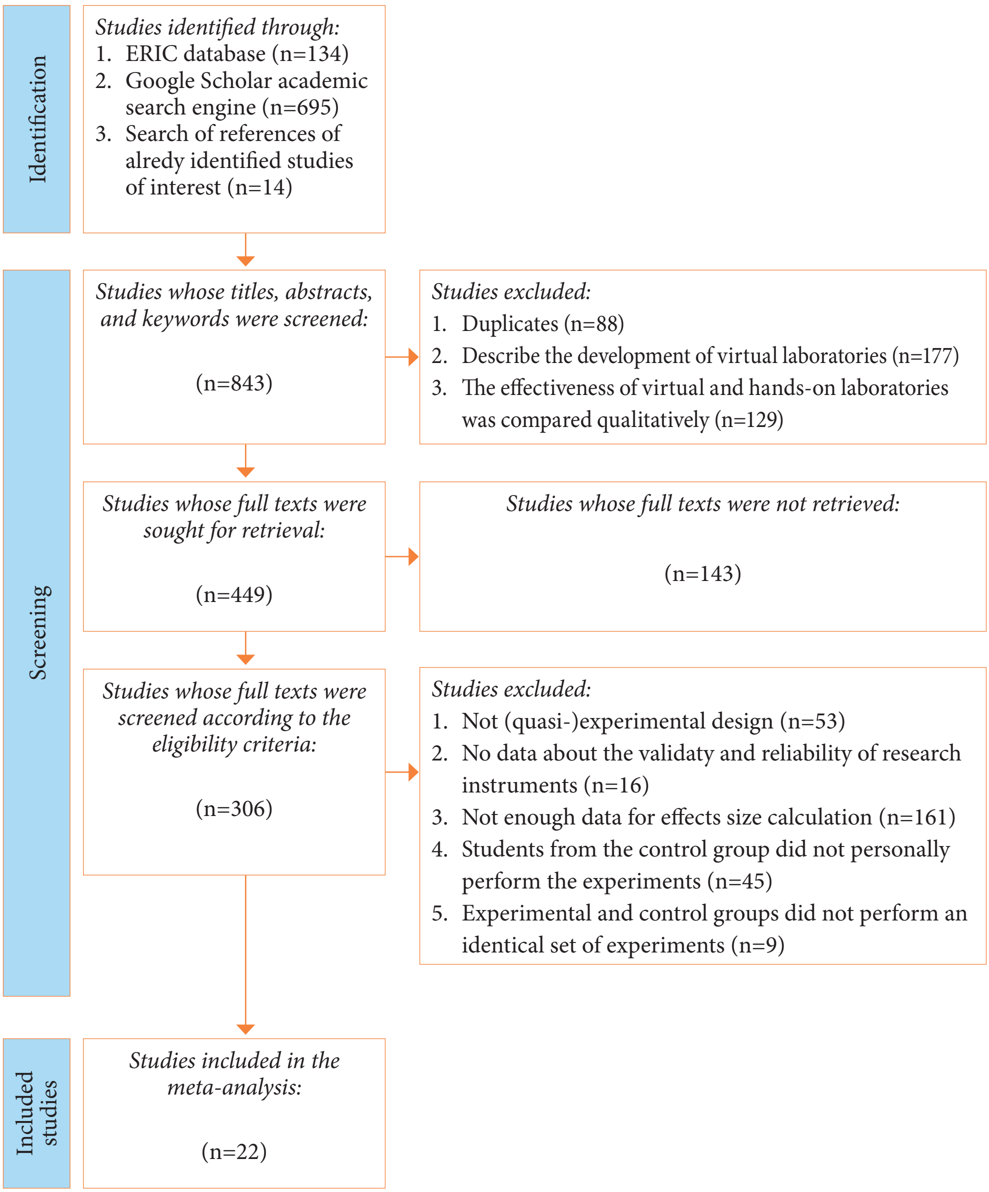
Having in mind the need for a synthesized conclusion regarding the effects of virtual and hands-on laboratories on affective learning outcomes, the fact that such conclusions are more objective when derived via meta-analysis, and the absence of existing meta-analytical studies on this subject, the first aim of this research was to meta-analytically determine whether virtual laboratories are more effective than their hands-on counterparts in terms of improving affective learning outcomes in the natural sciences. The second aim was to employ meta-regression to identify variables moderating the effectiveness of virtual laboratories.

METHOD

Literature search and study relevance criteria

As shown in Figure 1, studies included in this meta-analysis were selected with the application of the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol (Moher et al., 2009).

FIGURE 1. PRISMA flow chart



Firstly, during May 2025, a literature search was performed that encompassed peer-reviewed papers in English published in scientific journals between 2005 and 2025. The search was limited to literature in English due to its easy accessibility to international researchers, whereas the timespan was determined based on the rarity of virtual laboratory use in natural science education before 2005 (Ma & Nickerson, 2006). Considering that the use of at least two electronic information sources significantly reduces the likelihood of potentially relevant studies going undetected (Ewald et al., 2022), the literature search relied on the *Education Resources and Information Center (ERIC),* a database specializing in educational research, and the *Google Scholar* academic search engine. The keywords pertained to the laboratory approaches whose effectiveness was compared (virtual laboratories AND real laboratories OR hands-on laboratories), natural science subjects (chemistry OR physics OR biology OR science), and the most commonly explored affective factors in pedagogical research in this field (attitude OR motivation OR interest OR enjoyment OR self-efficacy OR anxiety). As recommended by Escueta et al. (2020), relevant studies were also sought within the reference lists of already identified studies of interest. This allowed for the identification of 843 potentially relevant papers (829 using electronic databases and 14 via reference search).

In the subsequent step, the identified studies' titles, abstracts, and keywords were screened to eliminate duplicates, papers describing the development of virtual laboratories aimed at improving affective learning outcomes, and studies that qualitatively compared the effectiveness of virtual versus hands-on laboratories. After also eliminating studies, whose full texts were not retrieved, the remaining 306 papers were analyzed in their entirety in order to identify studies relevant to this meta-analysis. Relevant studies were characterized by a (quasi-)experimental design, data collection relying on valid and reliable instruments, precisely reported sample sizes, and sufficient statistical parameters (arithmetic means and standard deviations, or the values of the t-, F-, or χ^2-test) necessary to calculate effect size. It was likewise important to determine whether control group participants personally conducted experiments in a hands-on laboratory (i.e., that they did not merely observe the teacher's demonstration, which is often the case due to efforts to reduce the cost of chemicals and equipment used), as well as whether experimental and control groups performed an identical set of laboratory activities. Finally, the application of these criteria resulted in the identification of 22 relevant studies.

Data coding

For all studies included in this meta-analysis, data were collected for the following variables, which were treated as potential moderators of virtual laboratories' effectiveness:

1. Geographical location;
2. Education level;
3. Natural science subject;
4. Sample size;
5. Laboratory work duration in weeks;
6. Virtual laboratory design (2D or 3D);
7. Work mode (individual or group work);
8. Approach to experimental work (open inquiry or guided inquiry);
9. Mode of evaluating affective outcomes (only after or both before and after laboratory work);
10. Likert scale type (four-point or five-point scale).

An overview of the aforementioned data is provided in Supplement 1.

Calculating effect size

In pedagogical research, the most common effect size indices are Cohen's *d* and Hedge's *g* (Kraft, 2020). Whereas the application of Cohen's *d* leads to effect size overestimation in studies with up to 50 participants, the value of Hedge's *g* does not depend on sample size (Hedges & Olkin, 1985). Considering that this meta-analysis encompassed 17 studies with more than 50 participants and five studies with smaller samples, Hedge's *g* was used as the effect size index. For each study, one *g* value was calculated and interpreted following the principles also applied to Cohen's *d* (Cohen, 1992). Thus, a value under 0.2 indicated a negligible effect, 0.2 to 0.49 a small effect, 0.50 to 0.79 a moderate effect, and 0.80 and over a large effect.

Assessing heterogeneity and selecting the model for calculating the mean Hedge's *g* value

Heterogeneity indicates that differences in effect size values for the studies included in the meta-analysis are not mere consequences of sampling errors, but reflect actual differences in the ways the studies were designed and conducted (Higgins et al., 2009). In the present meta-analysis, the heterogeneity of the obtained *g* values was assessed using the *Q* test and the I^2 index. If the statistically significant Q test and the I^2 value greater than 50% indicate heterogeneity, as is most commonly the case, the mean effect size values are calculated using the random-effects model. Based on this model, due to the actual between-study differences, the true effect size values are not identical for all studies encompassed by the meta-analysis, which further means that differences between the calculated effect size values are not exclusively caused by sampling errors (Borenstein et al., 2010). On the other hand, in the absence of heterogeneity, the mean effect size value is calculated using the fixed-effect model. According to this model, differences in the calculated effect size values emerge exclusively due to sampling errors, and the true effect size value is equal for all included studies (Borenstein et al., 2010). To conduct this meta-analysis, including heterogeneity testing and the consequent application of the adequate model for computing the mean Hedge's *g* value, the JASP (JASP Team, 2025) statistical software was used.

Publication bias

Publication bias constitutes one of the main factors that negatively affect the validity of meta-analysis results. It occurs due to the fact that papers are far more rarely published in scientific journals if they report no significant differences in the effectiveness of experimental versus traditional approaches or prove the traditional approach to be significantly more effective (Higgins et al., 2009). In this study, publication bias was tested using a funnel plot with the application of Egger's (Egger et al., 1997) and Begg-Mazumdar (Begg & Mazumdar, 1994) statistical tests. The symmetrical funnel plot and the statistically nonsignificant results of the aforementioned tests indicated the absence of publication bias.

Meta-regression

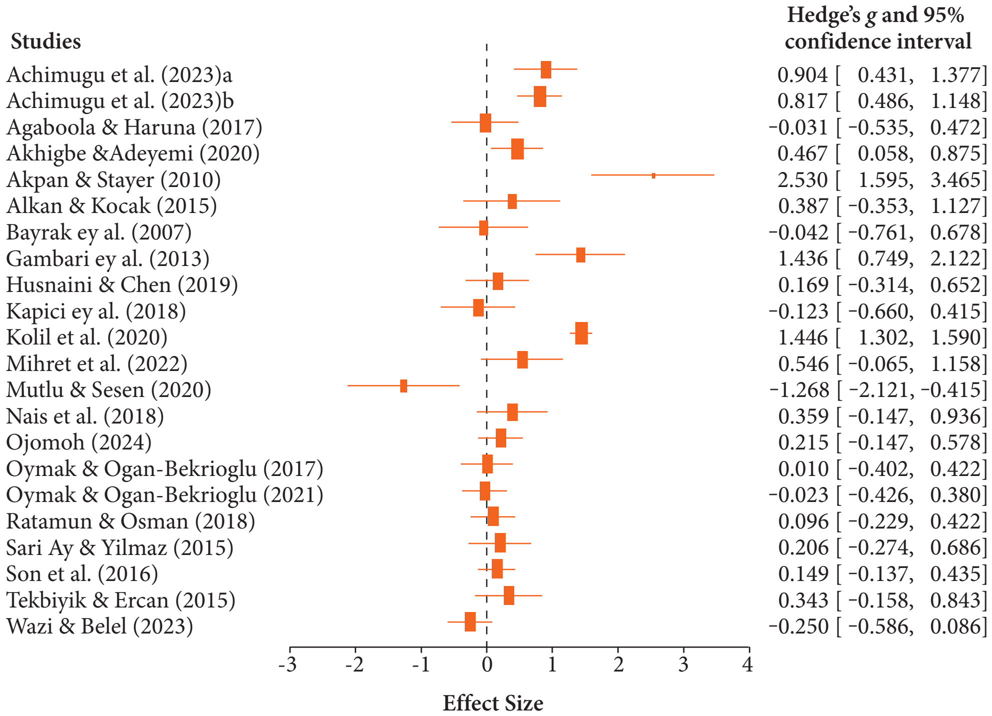
A single-variable meta-regression analysis was conducted to establish which of the 10 previously defined variables significantly affected the heterogeneity of the calculated *g* values, that is, which of them moderated the effectiveness of virtual laboratories. This analysis type requires a minimum of 10 studies per variable (Higgins et al., 2019). According to Borenstein et al. (2017), the significance threshold should be set at $p<0.100$.

RESULTS AND DISCUSSION

Out of the 22 studies included in this meta-analysis, eight were conducted in Africa, eight in Europe, four in Asia, and two in North America. A total of 13 studies were conducted at secondary schools, seven were conducted at the university level, and two focused on primary school students. The meta-analysis encompassed studies with a total sample size of 2,967 students. In 50% of the studies, samples ranged between 51 and 100 participants. Eleven studies focused on physics, six on chemistry, four on biology, and one on several natural science subjects. Laboratory work duration ranged between one and 16 weeks, with the most common duration (14 studies) being one to four weeks. In 20 studies, 2D virtual laboratories were used, whereas two studies involved the use of 3D virtual laboratories. In thirteen studies, laboratory activities were performed individually, and in nine studies, they were conducted through group work. In 15 studies, students engaged in step-by-step guided inquiry projects, whereas the open-inquiry method was employed in seven studies. Finally, 18 studies evaluated affective learning outcomes both before and after the completion of laboratory work, whereas four studies only conducted the evaluation after laboratory activities were completed. For the evaluation of affective learning outcomes, 14 studies used a five-point Likert-type scale and eight studies used a four-point Likert scale.

Presented in Figure 2 is a forest plot of Hedge's *g* values and corresponding 95% confidence intervals for all studies included in this meta-analysis. Hedge's *g* values were negative for six studies and positive for the remaining 16.

FIGURE 2. Forest plot



Given the statistically significant *Q* test (p=0.007) and the I^2 value of 89.36%, which indicated heterogeneity, the mean Hedge's *g* value was computed using the random-effects model. The obtained results (Table 1) showed that, on average, virtual laboratories had a small, positive, and statistically significant effect on affective learning outcomes in the natural sciences.

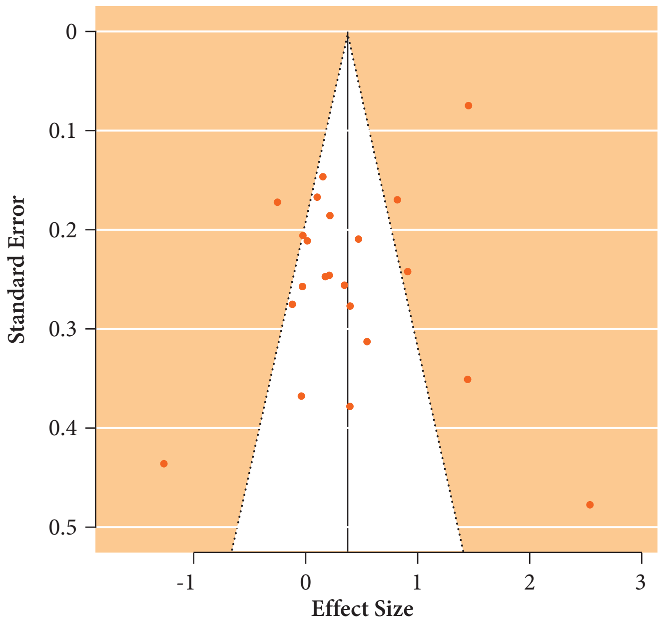
TABLE 1. Meta-analysis results after applying the random-effects model

Hedge's *g*	*SE*	*z*	*p*	95% confidence interval	
				Lower bound	Upper bound
0.370	0.137	2.695	0.007	0.101	0.639

As previously emphasized, existing meta-analyses of virtual and hands-on laboratory application in natural science subjects have only compared the overall effectiveness of these approaches and their effects on students' academic achievement, with most meta-analyses reporting a moderate (Santos & Prudente, 2022) or large (Antonio & Castro 2023; Syahwin et al., 2022), positive, and statistically significant effect of virtual laboratories. The present study's results expand on previous findings, showing that although the identified positive effect was somewhat smaller, virtual laboratories proved to have a significantly greater potential for improving affective learning outcomes in the natural sciences compared to hands-on laboratories.

The symmetrical funnel plot (Figure 3) and the statistically nonsignificant results of Egger's (p=0.850) and Begg-Mazumdar (p=0.178) tests indicated the absence of a negative impact of publication bias on the validity of the results of this meta-analysis.

FIGURE 3. Funnel plot



Finally, the results of the meta-regression revealed that virtual laboratories' effectiveness was not moderated by geographical location (p=0.105), sample size (p=0.306), education level (p=0.825), natural science subject (p=0.816), laboratory work duration (p=0.432), individual versus group work (p=0.674), virtual laboratory design (p=0.278), or the mode of evaluating affective learning outcomes (p=0.298). However, the scale type used to evaluate affective learning outcomes did emerge as a moderator (p<0.001). The expected mean Hedge's g value for studies employing a five-point Likert scale was lower by 0.817 than the expected mean Hedge's g value for studies that used a four-point Likert scale. A possible explanation for this finding can lie in the fact that a four-point scale only contains positive and negative responses, whereas a five-point scale also features a neutral response. Namely, research has shown that students whose attitudes are not neutral often choose the neutral option if they believe that their true responses are not socially desirable (Kankaraš & Capecchi, 2024). Considering that teachers and other education authorities constantly emphasize the significance of hands-on laboratory work as the cornerstone of high-quality natural science education, it is possible that some students who had positive attitudes towards virtual laboratories tried to moderate their attitudes by choosing the neutral option, which decreased virtual laboratories' mean effect size when a five-point Likert scale was used.

The second moderator identified in this study was the approach to experimental work (p=0.031). The expected mean Hedge's g value for studies based on open inquiry (with students independently determining the order of experimental steps) was lower by 0.589 than the expected mean Hedge's g value for studies based on guided inquiry. This result is in line with the findings of a previous study in the field of chemistry that found that students preferred guided to open inquiry and believed that it more greatly contributed to the acquisition of new knowledge (Chatterjee et al., 2009), as well as the results of a study in the field of biology in which guided inquiry proved significantly more successful than open inquiry in terms of supporting the development of students' self-efficacy (Gormally et al., 2009). In great part, these results can be explained by the fact that experimental activities based on open inquiry are far more cognitively demanding compared to guided laboratory work (Kang & Keinonen, 2018). Likewise, when independently determining the correct sequence of experimental steps, students are more than likely to experience failure at some point, which can lead to disappointment and fear of the negative consequences of not completing the experiment within the designated timeframe. On the other hand, when the teacher provides the correct sequence of experimental steps, students find it far easier to achieve the desired outcomes of laboratory work, which results in positive emotions, but can also lead to an unjustified sense of superiority (Gormally et al., 2009).

CONCLUSION

As one of the key competences for lifelong learning, scientific literacy does not only refer to the understanding and knowledge of scientific concepts and processes, but also encompasses critical thinking, understanding the nature of science, and developing affective aspects, including attitudes, beliefs, and motivation to engage with science. This study employed meta-analysis to establish whether virtual laboratories are more effective than their hands-on counterparts in terms of improving affective learning outcomes in the natural sciences. Another aim was to use meta-regression to identify variables moderating virtual laboratories' effectiveness.

The meta-analysis revealed that, on average, virtual laboratories had a small, positive, and statistically significant effect on affective learning outcomes in the natural sciences. Compared to hands-on laboratories, virtual laboratories showed a significantly higher potential for improving affective learning outcomes. These findings indicate that a well-designed and pedagogically integrated digital environment can more greatly contribute to the development of students' interest, motivation, and positive attitudes towards the natural sciences. Still, it should be emphasized that virtual laboratories are not meant to replace but supplement traditional laboratory activities. Students' direct, hands-on experience with the subject matter is a prerequisite to fully achieving learning outcomes, particularly in the affective domain. It is necessary to create a stimulating learning environment that simultaneously contributes to the development of both cognitive and affective aspects of students' scientific literacy.

The meta-regression results revealed that virtual laboratories' effectiveness was not moderated by geographical location, sample size, education level, natural science subject, laboratory work duration, work mode (individual or group), virtual laboratory design, or mode of evaluating affective learning outcomes. However, the type of Likert scale for evaluating affective outcomes and the approach to experimental work emerged as significant moderators that could affect the obtained results.

Meta-analyses allow both researchers and teachers to rely on the synthesis of the results of a vast number of studies to reach reliable conclusions on the effectiveness of different teaching methods. Furthermore, these analyses reveal inconsistencies in research findings and highlight topics and problems that merit further research. Our study findings indicate that researchers should particularly focus on devising instruments for evaluating the effects of certain types of laboratories on affective learning outcomes. They further point to the need for further research on experimental activities, that is, the roles of open and guided inquiry in achieving affective learning outcomes.

Finally, when interpreting the obtained results and recommendations, it is important to bear in mind certain limitations of this meta-analysis. First of all, the literature search relied on only two electronic data sources (the ERIC database and the Google Scholar academic search engine). Hence, it is possible that the analysis did not encompass a certain number of relevant studies indexed in other electronic sources, such as Scopus and Web of Science. Furthermore, the set criteria limited the search to high-quality, peer-reviewed literature that was easily available to an international audience. However, this may have resulted in the exclusion of some relevant studies within gray literature, as well as studies in languages other than English. Finally, another limitation stemmed from treating affective learning outcomes as a single, unitary construct due to the fact that the paucity of available relevant studies currently precludes meta-analysis of virtual and hands-on laboratories' effects on distinct affective learning outcomes in the natural sciences.

Note. This research was funded by the Ministry of Science, Technological Development, and Innovation of the Republic of Serbia (Contract No. 451-03-136/2025-03/200288 and 451-03-136/2025-03/200018). The research pertained to the United Nations' Sustainable Development Goal 4 (Quality Education), defined in the 2030 Agenda for Sustainable Development.

REFERENCES

Achimugu, L., Achufusi, N. N., Negedu, S. A., & Salami, D. (2023a). Adapting to virtual laboratory teaching strategy during Covid-19: Its effects on physics students' attitude in Kogi state, Nigeria. *Journal of Science, Technology and Mathematics Pedagogy*, *1*(1), 97–108.

Achimugu, L., Oguche, M. D., Igboegwu, N. E., & Ben, K. (2023b). Improving students' attitude towards practical chemistry using virtual laboratory package: Implications for global security challenges. *Scope*, *13*(2), 981–988.

Agboola, O. S., & Haruna, J. O. (2017). Effects of physical and virtual laboratory experimentation on students' learning outcomes in basic science in Ife central local government area, Osun state. *Journal of Curriculum and Instruction*, *10*(2), 186–198.

Ahn, E. J., & Kang, H. (2018). Introduction to systematic review and meta-analysis. *Korean Journal of Anesthesiology*, *71*(2), 103–112. DOI: 10.4097/kjae.2018.71.2.103

Aikenhead, G. S. (2006). *Science education for everyday life: Evidence-based practice*. Teachers College Press.

Akhigbe, J. N., & Adeyemi, A. E. (2020). Using gender responsive collaborative learning strategy to improve students' achievement and attitude towards learning science in virtual and hands-on laboratory environment. *Journal of Pedagogical Research*, *4*(3), 241–261. DOI: 10.33902/JPR.2021063948

Akpan, J., & Strayer, J. (2010). Which comes first: The use of computer simulation of frog dissection or conventional dissection as academic exercise? *Journal of Computers in Mathematics and Science Teaching*, *29*(2), 113–138.

Ali, N., Ullah, S., & Khan, D. (2022). Interactive laboratories for science education: A subjective study and systematic literature review. *Multimodal Technologies and Interaction*, *6*(10), Article 85. DOI: 10.3390/mti6100085

Alkan, F., & Kocak, C. (2015). Chemistry laboratory applications supported with simulation. *Procedia-Social and Behavioral Sciences*, *176*, 970–976.

Antonio, R. P., & Castro, R. R. (2023). Effectiveness of virtual simulations in improving secondary students' achievement in physics: A meta-analysis. *International Journal of Instruction*, *16*(2), 533–556. DOI: 10.29333/iji.2023.16229a

Asiksoy, G. (2023). Effects of virtual lab experiences on students' achievement and perceptions of learning physics. *International Journal of Online & Biomedical Engineering*, *19*(11), 31–41. DOI: 10.3991/ijoe.v19i11.39049

Bayrak, B., Kanli, U., & Ingec, S. K. (2007). To compare the effects of computer-based learning and the laboratory-based learning on students' achievement regarding electric circuits. *Turkish Online Journal of Educational Technology*, *6*(1), Article 2.

Begg, C. B., & Mazumdar, M. (1994). Operating characteristics of a rank correlation test for publication bias. *Biometrics*, *50*(4), 1088–1101. DOI: 10.2307/2533446

Bloom, B. S., Krathwohl, D. R., & Masia, B. B. (1964). *Taxonomy of educational objectives: The classification of educational goals. Handbook II: Affective domain*. David McKay Company.

Borenstein, M., Hedges, L. V., Higgins, J. P., & Rothstein, H. R. (2010). A basic introduction to fixed-effect and random-effects models for meta-analysis. *Research Synthesis Methods*, *1*(2), 97–111. DOI: 10.1002/jrsm.12

Borenstein, M., Hedges, L. V., Higgins, J. P. T., & Rothstein, H. (2017). *Regression in meta-analysis*. Biostat.

Brinson, J. R. (2015). Learning outcome achievement in non-traditional (virtual and remote) versus traditional (hands-on) laboratories: A review of the empirical research. *Computers & Education*, *87*(4), 218–237. DOI: 10.1016/j.compedu.2015.07.003

Byukusenge, C., Nsanganwimana, F., & Tarmo, A. P. (2022). Effectiveness of virtual laboratories in teaching and learning biology: A review of literature. *International Journal of Learning, Teaching and Educational Research*, *21*(6), 1–17. DOI: 10.26803/ijlter.21.6.1

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*(10), Article 100053. DOI: 10.1016/j.caeo.2021.100053

Chatterjee, S., Williamson, V. M., McCann, K., & Peck, M. L. (2009). Surveying students' attitudes and perceptions toward guided-inquiry and open-inquiry laboratories. *Journal of Chemical Education*, *86*(12), 1427–1432. DOI: 10.1021/ed086p1427

Cohen, J. (1992). Quantitative methods in psychology: A power primer. *Psychological Bulletin*, *112*(1), 155–159. DOI: 10.1037/0033-2909.112.1.155

Daineko, Y., Dmitriyev, V., & Ipalakova, M. (2017). Using virtual laboratories in teaching natural sciences: An example of physics courses in university. *Computer Applications in Engineering Education*, *25*(1), 39–47. DOI: 10.1002/cae.21777

Egger, M., Smith, G. D., Schneider, M., & Minder, C. (1997). Bias in meta-analysis detected by a simple, graphical test. *The BMJ*, *315*(7109), 629–634. DOI:10.1136/bmj.315.7109.629

- Escueta, M., Nickow, A. J., Oreopoulos, P., & Quan, V. (2020). Upgrading education with technology: Insights from experimental research. *Journal of Economic Literature*, *58*(4), 897–996. DOI:10.1257/jel.20191507
- Ewald, H., Klerings, I., Wagner, G., Heise, T. L., Stratil, J. M., Lhachimi, S. K., Hemkens, L. G., Gartlehner, G., Armijo-Olivo, S., & Nussbaumer-Streit, B. (2022). Searching two or more databases decreased the risk of missing relevant studies: A meta research study. *Journal of Clinical Epidemiology*, *149*, 154–164. DOI: 10.1016/j.jclinepi.2022.05.022
- Gambari, A. I., Falode, O. C., Fagbemi, P. O., & Idris, B. (2013). Efficacy of virtual laboratory on the achievement and attitude of secondary school students in physics practical. *Research in Curriculum Studies*, *9*(1), 9–20.
- George-Williams, S. R., Ziebell, A. L., Kitson, R. R., Coppo, P., Thompson, C. D., & Overton, T. L. (2018). What do you think the aims of doing a practical chemistry course are? A comparison of the views of students and teaching staff across three universities. *Chemistry Education Research and Practice*, *19*(2), 463–473. DOI: 10.1039/C7RP00177K
- Gormally, C., Brickman, P., Hallar, B., & Armstrong, N. (2009). Effects of inquiry-based learning on students' science literacy skills and confidence. *International Journal for the Scholarship of Teaching and Learning*, *3*(2), Article 16. DOI: 10.20429/ijsotl.2009.030216
- Hedges, L., & Olkin, I. (1985). *Statistical methods for meta-analysis*. Academic Press.
- Herga, N. R., Čagran, B., & Dinevski, D. (2016). Virtual laboratory in the role of dynamic visualisation for better understanding of chemistry in primary school. *Eurasia Journal of Mathematics, Science and Technology Education*, *12*(3), 593–608. DOI: 10.12973/eurasia.2016.1224a
- Higgins, J. P., Thompson, S. G., & Spiegelhalter, D. J. (2009). A re-evaluation of random-effects meta-analysis. *Journal of the Royal Statistical Society Series A: Statistics in Society*, *172*(1), 137–159. DOI:10.1111/j.1467-985X.2008.00552.x
- Higgins, J., Thomas, J., Chandler, J., Cumpston, M., Li, T., Page, M., & Welch, V. A. (Eds.) (2019). *Cochrane handbook for systematic reviews of interventions* (2nd ed.). John Wiley & Sons.
- High Level Group on Science Education (2007). *Science Now: A renewed pedagogy for the future of Europe*. Office for Official Publications of the European Communities. https://www.eesc.europa.eu/sites/default/files/resources/docs/rapportrocardfinal.pdf
- Hornsey, M. J. (2020). Why facts are not enough: Understanding and managing the motivated rejection of science. *Current Directions in Psychological Science*, *29*(6), 583–591. DOI: 10.1177/0963721420969364
- Husnaini, S. J., & Chen, S. (2019). Effects of guided inquiry virtual and physical laboratories on conceptual understanding, inquiry performance, scientific inquiry self-efficacy, and enjoyment. *Physical Review Physics Education Research*, *15*(1), Article 010119. DOI: 10.1103/PhysRevPhysEducRes.15.010119
- JASP Team. (2025). *JASP* (Version 0.95.3) [Computer software]. https://jasp-stats.org.
- Jošić, S., Teodorović, J., i Jakšić, I. (2021). Faktori postignuća učenika iz matematike i prirodnih nauka: TIMSS 2019 u Srbiji [Factors shaping student achievement in mathematics and the natural sciences: TIMSS 2019 in Serbia]. U I. Đerić, N. Gutvajn, S. Jošić i N. Ševa (ur.), *TIMSS 2019 u Srbiji: rezultati međunarodnog istraživanja postignuća učenika četvrtog razreda osnovne škole iz matematike i prirodnih nauka* (str. 45–65). Institut za pedagoška istraživanja.
- Kang, J., & Keinonen, T. (2018). The effect of student-centered approaches on students' interest and achievement in science: Relevant topic-based, open and guided inquiry-based, and discussion-based approaches. *Research in Science Education*, *48*(4), 865–885. DOI: 10.1007/s11165-016-9590-2
- Kankaraš, M., & Capecchi, S. (2025). Neither agree nor disagree: Use and misuse of the neutral response category in Likert-type scales. *Metron*, *83*(1), 111–140. DOI: 10.1007/s40300-024-00276-5
- Kapici, H. O., Koca, E. E., & Akcay, H. (2018). Effects of writing to learn activities in hands-on and virtual laboratory environments. *The Eurasia Proceedings of Educational and Social Sciences*, *9*, 48–51.

Kolil, V. K., Muthupalani, S., & Achuthan, K. (2020). Virtual experimental platforms in chemistry laboratory education and its impact on experimental self-efficacy. *International Journal of Educational Technology in Higher Education*, *17*(1), Article 30. DOI: 10.1186/s41239-020-00204-3

Kraft, M. A. (2020). Interpreting effect sizes of education interventions. *Educational Researcher*, *49*(4), 241–253. DOI:10.3102/0013189X20912798

Lalić-Vučetić, N., & Mirkov, S. (2023). Motivacija za učenje prirodnih nauka i matematike: istraživanje TIMSS u Srbiji [Motivation for learning science and mathematics: TIMSS research in Serbia]. *Inovacije u nastavi*, *36*(3), 1–19.

Ma, J., & Nickerson, J. V. (2006). Hands-on, simulated, and remote laboratories: A comparative literature review. *ACM Computing Surveys*, *38*(3), Article 7. DOI:10.1145/1132960.1132961

Mihret, Z., Alemu, M., & Assefa, S. (2022). Effects of blending virtual and real laboratory experimentation on pre-service physics teachers' attitudes toward physics electricity and magnetism laboratories. *Science Education International*, *33*(3), 313–322. DOI: 10.33828/sei.v33.i3.7

Milanović-Nahod, S., Šaranović-Božanović, N. i Šišović, D. (2003). Uloga pojmova u nastavi prirodnih nauka [The role of concepts in science teaching]. *Zbornik Instituta za pedagoška istraživanja*, *35*, 111–130.

Milinković, J., Jablanović Marušić, M. i Dabić Boričić, M. (2017). Postignuće učenika iz matematike: glavni nalazi, trendovi i nastavni program [Achievement of students in mathematics: Main findings, trends and curriculum]. U M. Marušić Jablanović, N. Gutvajn i I. Jakšić (ur.), *TIMSS 2015 u Srbiji* (str. 27–50). Institut za pedagoška istraživanja.

Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G., The PRISMA Group. (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *PLOS Medicine*, *6*(7), Article e1000097. DOI: 10.1371/journal.pmed.1000097

Mutlu, A., & Sesen, B. A. (2020). Comparison of inquiry-based instruction in real and virtual laboratory environments: Prospective science teachers' attitudes. *International Journal of Curriculum and Instruction*, *12*(2), 600–617.

Nais, M. K., Sugiyarto, K. H., & Ikhsan, J. (2018). The profile of students' self-efficacy using virtual chem-lab in hybrid learning. *Journal of Physics: Conference Series*, *1097*(1), Article 012060. DOI: 10.1088/1742-6596/1097/1/012060

Nicol, C. B., Gakuba, E., & Habinshuti, G. (2022). Students' opinions, views, and perceptions of science laboratory learning: A systematic review of the literature. *Eurasia Journal of Mathematics, Science and Technology Education*, *18*(3), Article em2087. DOI: 10.29333/ejmste/11793

OECD (2016). *PISA 2015 Results (Volume I): Excellence and equity in education*. OECD Publishing.

Ojomoh, V. K. (2024). Effect of the virtual laboratory on the self-efficacy of students in thermal physics undergraduate course. *International Research Journal of Modernization in Engineering Technology and Science*, *6*(8), 1807–1812. DOI: 10.56726/IRJMETS60984

Osborne, J., Simon, S., & Collins, S. (2003). Attitudes towards science: A review of the literature and its implications. *International Journal of Science Education*, *25*(9), 1049–1079. DOI: 10.1080/0950069032000032199

Oymak, O., & Ogan-Bekiroglu, F. (2017). Comparison of students' learning and attitudes in technology supported and laboratory-based environments. *The Eurasia Proceedings of Educational and Social Sciences*, *6*, 109–113.

Oymak, O., & Ogan-Bekiroglu, F. (2021). Comparison of students' learning and attitudes in physical versus virtual manipulatives using inquiry-based instruction. *IAFOR Journal of Education: Technology in Education*, *9*(4), 23–42.

Potkonjak, V., Gardner, M., Callaghan, V., Mattila, P., Guetl, C., Petrović, V. M., & Jovanović, K. (2016). Virtual laboratories for education in science, technology, and engineering: A review. *Computers & Education*, *95*(4), 309–327. DOI: 10.1016/j.compedu.2016.02.002

📖 Priest, S. J., Pyke, S. M., & Williamson, N. M. (2014). Student perceptions of chemistry experiments with different technological interfaces: A comparative study. *Journal of Chemical Education*, *91*(11), 1787–1795. DOI: 10.1021/ed400835h

📖 Pyatt, K., & Sims, R. (2012). Virtual and physical experimentation in inquiry-based science labs: Attitudes, performance and access. *Journal of Science Education and Technology*, *21*(1), 133–147. DOI: 10.1007/s10956-011-9291-6

📖 Ratamun, M. M., & Osman, K. (2018). The effectiveness comparison of virtual laboratory and physical laboratory in nurturing students' attitude towards chemistry. *Creative Education*, *9*(9), 1411–1425. DOI: 10.4236/ce.2018.99105

📖 Rutjens, B. T., Heine, S. J., Sutton, R. M., & van Harreveld, F. (2018). Attitudes towards science. In J. M. Olson (Ed.), *Advances in experimental social psychology* (pp. 125–165). Elsevier Academic Press. DOI: 10.1016/bs.aesp.2017.08.001

📖 Santos, M. L., & Prudente, M. (2022). Effectiveness of virtual laboratories in science education: A meta-analysis. *International Journal of Information and Education Technology*, *12*(2), 150–156. DOI: 10.18178/ijiet.2022.12.2.1598

📖 Sari Ay, O., & Yilmaz, S. (2015). Effects of virtual experiments-oriented science instruction on students' achievement and attitude. *Elementary Education Online*, *14*(2), 609–620. DOI: 10.17051/io.2015.25820

📖 Son, J. Y. (2016). Comparing physical, virtual, and hybrid flipped labs for general education biology. *Online Learning*, *20*(3), 228–243.

📖 Swastika, S., Gupta, S., & Abuhasan, W. (2024). Role of virtual lab in inculcating scientific attitude & self-efficacy: Meta analysis. *Library Progress International*, *44*(3), 161–171. DOI: 10.48165/bapas.2024.44.2.1

📖 Syahwin, S., Hardianti, T., & Fitriana, S. (2022). The effect of guided inquiry learning by virtual laboratory assistance in physics learning in Indonesian senior high schools: A meta-analysis. *International Journal of Instruction*, *15*(4), 101–114. DOI: 10.29333/iji.2022.1546a

📖 Ševkušić, S. i Kartal, V. (2017). Postignuća učenika iz prirodnih nauka – glavni nalazi, trendovi i nastavni program [Student achievement in science: Main results, trends, and curriculum]. U M. Marušić Jablanović, N. Gutvajn i I. Jakšić (ur.), *TIMSS 2015 – rezultati međunarodnog istraživanja postignuća učenika 4. razreda osnovne škole iz matematike i prirodnih nauka* (str. 51–65). Institut za pedagoška istraživanja.

📖 Taber, K. S. (2013). Revisiting the chemistry triplet: drawing upon the nature of chemical knowledge and the psychology of learning to inform chemistry education. *Chemistry Education Research and Practice*, *14*(2), 156–168. DOI: 10.1039/C3RP00012E

📖 Taramopoulos, A., Psillos, D., & Hatzikraniotis, E. (2012). Teaching electric circuits by guided inquiry in virtual and real laboratory environments. In A. Jimoyiannis (Ed.), *Research on e-learning and ICT in education* (pp. 211–224). Springer Nature. DOI: 10.1007/978-1-4614-1083-6_16

📖 Tas, Y., & Cakir, B. (2014). An investigation of science active learning strategy use in relation to motivational beliefs. *Mevlana International Journal of Education*, *4*(1), 55–66. DOI: 10.13054/mije.13.55.4.1

📖 Tekbiyik, A., & Ercan, O. (2015). Effects of the physical laboratory versus the virtual laboratory in teaching simple electric circuits on conceptual achievement and attitudes towards the subject. *International Journal of Progressive Education*, *11*(3), 77–89.

📖 Tsai, C. C., Ho, H. N. J., Liang, J. C., & Lin, H. M. (2011). Scientific epistemic beliefs, conceptions of learning science and self-efficacy of learning science among high school students. *Learning and Instruction*, *21*(6), 757–769. DOI: 10.1016/j.learninstruc.2011.05.002

📖 Tsihouridis, C., Vavougios, D., Batsila, M., & Ioannidis, G. S. (2019). The timeless controversy between virtual and real laboratories in science education – "And the winner is…". In: M. E. Auer, & T. Tsiatsos, (Eds.), *The challenges of the digital transformation in education: Proceedings of the 21st International conference on interactive collaborative learning (ICL2018)* (pp. 620–631). Springer Nature. DOI: 10.1007/978-3-030-11935-5_59

Waziri, K., & Belel, U. F. (2023). Comparative effect of virtual laboratory and physical laboratory practicals on the academic achievement and the attitude of biology students in senior secondary school, Adamawa state, Nigeria. *International Journal of Education and Social Science Research*, *6*(4), 102–113.

Winkelmann, K., Keeney-Kennicutt, W., Fowler, D., & Macik, M. (2017). Development, implementation, and assessment of general chemistry lab experiments performed in the virtual world of second life. *Journal of Chemical Education*, *94*(7), 849–858. DOI: 10.1021/acs.jchemed.6b00733

SUPPLEMENT 1. Characteristics of the studies included in the meta-analysis

Study	Geographical Location	Education Level	Natural Science Subject	Sample Size	Intervention Duration (Weeks)	Virtual Laboratory Design	Work Mode	Experimental Work Approach	Evaluation Mode	Likert Scale Type
Achimugu et al. (2023a)	Africa	Secondary school	Physics	88	4	2D	Individual	Guided inquiry	Before and after the intervention	Four-point
Achimugu et al. (2023b)	Africa	Secondary school	Physics	176	4	2D	Individual	Guided inquiry	Before and after the intervention	Four-point
Agaboola & Haruna (2017)	Africa	Secondary school	Natural Sciences	62	4	2D	Group	Guided inquiry	Before and after the intervention	Five-point
Akhigbe & Ad-eyemi (2020)	Africa	Secondary school	Biology	100	10	2D	Individual	Guided inquiry	Before and after the intervention	Five-point
Akpan & Stray-er (2010)	North America	Secondary school	Biology	35	1	2D	Group	Guided inquiry	Before and after the intervention	Four-point
Alkan & Kocak (2015)	Europe	University	Chemistry	31	1	2D	Individual	Guided inquiry	Before and after the intervention	Five-point
Bayrak et al. (2007)	Europe	Secondary school	Physics	28	4	3D	Individual	Guided inquiry	After the intervention	Five-point
Gambari et al. (2013)	Africa	Secondary school	Physics	56	4	2D	Individual	Guided inquiry	Before and after the intervention	Four-point
Husnaini & Chen (2019)	Asia	Secondary school	Physics	68	1	2D	Group	Open inquiry	Before and after the intervention	Five-point
Kapici et al. (2018)	Europe	University	Chemistry	52	4	2D	Group	Open inquiry	After the intervention	Five-point
Kolil et al. (2020)	Asia	University	Chemistry	1225	1	3D	Group	Guided inquiry	Before and after the intervention	Four-point

Study	Geographical Location	Education Level	Natural Science Subject	Sample Size	Intervention Duration (Weeks)	Virtual Laboratory Design	Work Mode	Experimental Work Approach	Evaluation Mode	Likert Scale Type
Mihret et al. (2022)	Africa	University	Physics	47	16	2D	Individual	Open inquiry	Before and after the intervention	Five-point
Mutlu & Sesen (2020)	Europe	University	Chemistry	34	8	2D	Group	Open inquiry	Before and after the intervention	Five-point
Nais et al. (2018)	Asia	Secondary school	Chemistry	52	1	2D	Individual	Guided inquiry	After the intervention	Four-point
Ojomoh (2024)	Africa	University	Physics	120	5	2D	Individual	Guided inquiry	Before and after the intervention	Four-point
Oymak & Ogan-Bekiroglu (2017)	Europe	Secondary school	Physics	89	8	2D	Group	Open inquiry	After the intervention	Five-point
Oymak & Ogan-Bekiroglu (2021)	Europe	Secondary school	Physics	96	8	2D	Group	Open inquiry	Before and after the intervention	Five-point
Ratamun & Osman (2018)	Asia	Secondary school	Chemistry	147	3	2D	Group	Guided inquiry	Before and after the intervention	Four-point
Sari Ay & Yil-maz (2015)	Europe	Primary school	Physics	69	2	2D	Individual	Guided inquiry	Before and after the intervention	Five-point
Son et al. (2016)	North America	University	Biology	187	8	2D	Individual	Open inquiry	Before and after the intervention	Five-point
Tekbiyik & Ercan (2015)	Europe	Primary school	Physics	65	5	2D	Individual	Guided inquiry	Before and after the intervention	Five-point
Waziri & Belel (2023)	Africa	Secondary school	Biology	140	4	2D	Individual	Guided inquiry	Before and after the intervention	Five-point