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Research article

An exploratory study on STEM education through math trails with digital technology to promote mathematical literacy

Adi Nur Cahyono[1,*], Riza Arifudin[1], Rozak Ilham Aditya[2], Bagus Surya Maulana[1] and Zsolt Lavicza[3]

[1] Universitas Negeri Semarang, Indonesia
[2] Zandspace Company, Indonesia
[3] Johannes Kepler University Linz, Austria

* **Correspondence:** Email: adinurcahyono@mail.unnes.ac.id.

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Abstract: This study aims to investigate how the use of math trail activities and digital technology in STEM education can help to improve mathematical literacy. Exploratory design research involving teachers and eighth-grade students in a junior high school was conducted. A STEM Trails application was developed, several trails were designed, and students performed the activities. Participant observation, interviews, questionnaires, exams, and worksheets were used to collect data. Organization, annotation, data description, and statistical tests were carried out for data analysis. Based on the results of the analysis, an educational program was designed to provide students with valuable STEM experiences. This program was supported by GPS-based applications that serve as tools for students to develop mathematical literacy by solving STEM-related problems in the surrounding environment. As a result, the program promoted students' mathematical literacy. This study discovered a link between the program's instrumental approaches and the mathematical literacy developed throughout the instrumentation process. The findings of this study demonstrate that the integration of digital technology in STEM-based math trails can effectively enhance learners' mathematical literacy through contextualized and interactive learning experiences. It is recommended that future research should extend the implementation of STEM Trails to a wider range of learning environments and investigate its impact on students' skills and abilities in greater depth.

Keywords: STEM education, math trails, digital technology, mathematical literacy, exploratory

study

1. Introduction

In the context of a globalized world undergoing constant transformation, the capacity to access, comprehend, and utilize information in an intelligent manner is of pivotal importance. In particular, the ability of individuals to reason mathematically and to formulate, employ, and interpret mathematical principles to address problems in a multitude of real-world contexts is defined as mathematical literacy [1]. Mathematical literacy is explicitly taught in mathematics classes, but students are encouraged to apply the skills and concepts learned in this context to other subjects as well.

The integration of science, technology, engineering, and mathematics (STEM) into holistic learning activities has been demonstrated to facilitate the acquisition of 21st-century capabilities by students, as evidenced by several studies [2,3]. STEM education is an interdisciplinary approach to teaching and learning, whereby theoretical concepts are taught in conjunction with practical applications [4]. STEM disciplines offer numerous opportunities for students to engage in both challenging and exciting mathematical exploration and to make significant forays into other disciplines [5].

A multitude of resources present in our surrounding environment can serve as a source of inspiration for learning through a STEM-based approach. In numerous regions, particular sites and artifacts, including those pertaining to culture, offer avenues for acquiring contextual experience in the STEM domain. Such areas may be identified through direct engagement with local landmarks and other objects of significance. Landmarks are identifiable, fixed points within the landscape that continue to capture the public’s attention and foster a sense of familiarity. It is possible for places, streets, and entire regions to serve as landmarks. A multitude of landmarks and locations afford opportunities for the application of STEM concepts. Landmarks may be defined as points (e.g., tourist attractions), lines (e.g., roads), or areas (e.g., cities) [6].

Problems in STEM that are related to a specific place or object can be designed into tasks and linked to other tasks to form an exploratory path. In the field of mathematics, this concept, referred to as a *math trail* [7], provides a means of investigating mathematical principles in their natural environment. The advent of mobile applications with GPS features has enabled the creation of mathematical trails that can be conducted remotely, following technological advances [8–10]. Several projects have been undertaken with the objective of integrating mobile technology with the concept of mathematical trails [11–15].

The integration of mobile devices offers a valuable opportunity to incorporate practical learning elements, including engaging content, collaborative work, and authentic scenarios [16]. The use of digital tools is becoming increasingly prevalent in problem-solving processes, with digital simulations offering a means of investigating the effects of different systems or environmental variables (see [17–19]). Digital tools can enhance outdoor mathematical modeling by providing automated solution verification and guidance, improving students' problem-solving skills [20].

The advent of digital technologies has created opportunities to develop STEM education programs, including math trails, in innovative ways. These technologies include augmented reality/virtual reality, artificial intelligence, autonomy, and the Internet of Things [21]. Digital tools in STEM education enhance efficiency, make learning engaging, and increase student motivation, enabling the exploration of scientific concepts through innovative approaches [22]. This research project aims to address the research question of how STEM education, through math trail activities with digital technologies, can be designed to promote mathematical literacy.

2. Methods

This study employed an exploratory research design to address the research question. The objective of the research was to investigate the potential of STEM education programs, with a particular focus on mathematic trail activities utilizing digital technology, to enhance mathematical literacy. This approach engages researchers and practitioners (stakeholders) in addressing research and development, implementation, and dissemination [23–25]. The data produced by exploratory research is detailed, comprehensive, and valid, thereby enabling the formulation of well-founded hypotheses. A series of pilot studies was conducted with the objective of developing a learning environment that adheres to the concept of didactic situations in mathematics [26]. Additionally, a digital interactive instructional platform, designated as the STEM Trails App, was developed.

A field experiment was conducted with eighth-grade students in a junior high school in Indonesia learning mathematics on the topic of geometry. The initial mathematical literacy abilities of all eighth-grade classes in the school were found to be similar, and thus, for the purposes of this study, two classes were selected from the entire population as representative samples. One class had 31 students and was designated the experimental group, and the other had 30 students, designated the control group. The study was conducted in four phases: preliminary and three subsequent phases. The first phase was the prototype design, the second was the small-scale field experiment, and the third and fourth phases were the large-scale experiments. The researchers accompanied the students as participatory researchers, observing the activities during the program, taking notes, and collecting student portfolios. Subsequently, a debriefing session was held, and mathematical literacy tests were conducted before and after the intervention. The indicators used to measure mathematical literacy in this study refer to the framework developed by the OECD [1], namely the capacity to reason mathematically and to formulate, employ, and interpret mathematics to solve problems in a variety of real-world contexts, including concepts, procedures, facts, and tools to describe, explain, and predict phenomena. Data analysis started with the organization, annotation, and description of the data for qualitative analysis. Quantitative analysis was performed using data collected from students in an empirical field study.

3. Results

The study was initiated with an analytical phase and focus group discussions on the design of the activities and the platforms that support them. The discussions were attended by researchers from the university, representatives of the partner school, and programmers. The findings of this study were classified into three categories: STEM Trails platform, STEM Trails activities, and the impact of STEM Trails on mathematical literacy.

3.1. STEM trails platform

The platform developed for this study can be accessed at https://stemtrails.id. The platform is comprised of several sections, including a homepage, a news section that provides information and current updates, a trail section that displays publicly available STEM Trails, information about projects and teams, and a dashboard section (Figure 1). The platform categorizes users into three distinct groups: STEM Trails administrator, STEM trailblazers, and STEM trail walkers. The role of the STEM Trails administrator is to monitor the portal and to coordinate and grant access to STEM trailblazers and STEM trail walkers. The role of a STEM trailblazer is to devise STEM tasks and trails based on real-world items or events, which are then uploaded to the site. The platform is utilized by STEM trail walkers for the purpose of exploring trails and performing tasks along the designated or selected paths. Trail walkers may access tasks and paths directly or via the platform, depending on the configuration of the tasks and paths by the trailblazer.

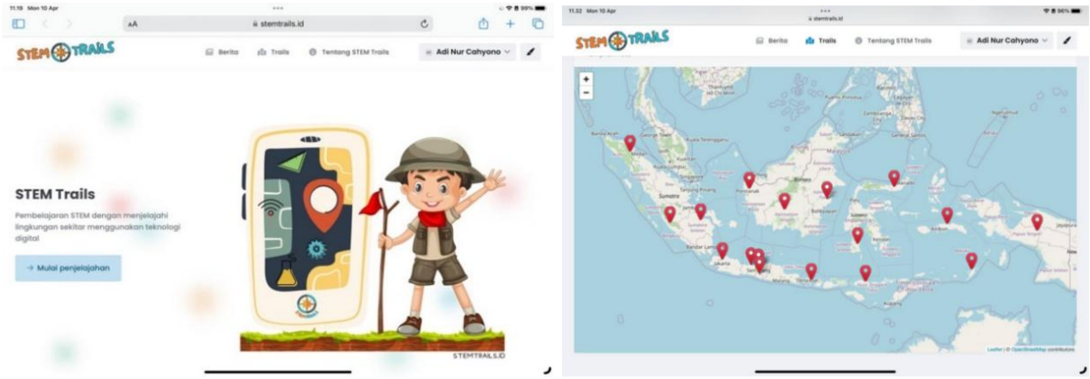

Figure 1. STEM Trails portal and some trail locations created by STEM trailblazers.

A STEM task comprises a title, a description that elucidates the nature of the object and the problem presented, a location indicated on a digital map or by GPS coordinates, a solution to the problem, an integrated STEM field, keywords, and a set of instructions or questions provided through a series of activities that the STEM trail walker must complete. A total of approximately four STEM tasks can be connected to create a STEM Trail (Figure 2). These tasks can be designed by the STEM trailblazer or by another person.

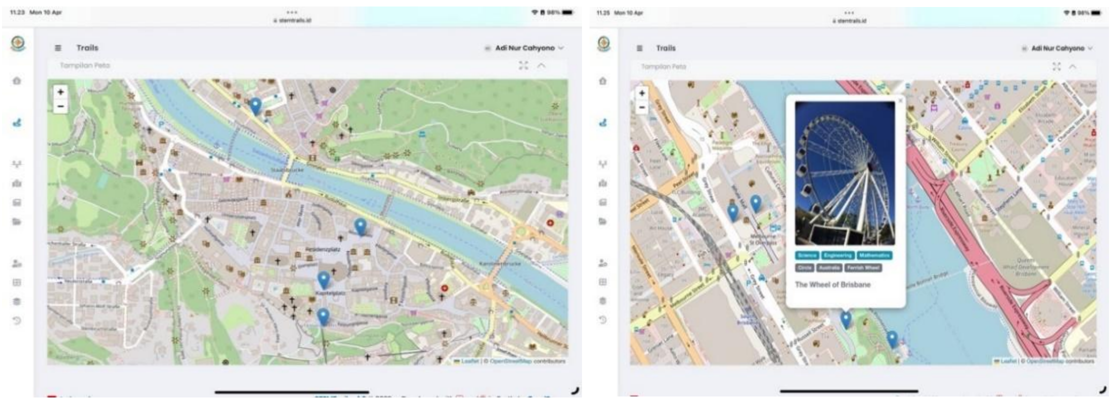

Figure 2. STEM trails and tasks.

3.2. STEM Trails activities

The STEM Trails activities begin with the trailblazers exploring the real world for objects or events that are related to science, technology, engineering, or mathematics, and integrating them into the curriculum. The trailblazers provide a description of the items, events, and design-related problems. The STEM trailblazers provide input for the site, linking their contributions with other activities, to create a comprehensive STEM Trail comprising approximately four tasks. Two categories of tasks and trails were devised: those that must be completed on-site and those that can be achieved without a physical visit to the site. The tasks and trails may be restricted to users with an account on the STEM Trails platform, or alternatively, they may be set up and accessed publicly without the need for login credentials.

In order to gain insight into the perceptions of those at the forefront of this field, we conducted interviews with key informants about the STEM Trails portal. One trailblazer posited that "the STEM Trails portal enables educators to prepare assignments for students through the use of ICT-based media, with a particular focus on digitally designed and interactive student worksheets". Another trailblazer posited that "the portal enables educators to disseminate tasks to other educators by organizing tasks and trails that can be accessed and utilized by other educators, even those in disparate locations". In terms of substance, trailblazers advanced the argument that "STEM Trails offers an opportunity to apply the concept of math trails not only to mathematics learning, but also to integrate across disciplines, particularly in STEM fields".

Figure 3 illustrates the way the trail walker progresses along the designated route and addresses the challenges that emerge. One example of a task is to describe the portal as "one of the key facilities for an institution". The site is utilized for security purposes. The gate is typically situated near the main entrance. It is necessary to surmount the height of the portal to permit vehicular access. A rope is attached to the end of the portal, enabling security personnel to swiftly close it by pulling it down. The question is thus posed as to which minimum length of rope is required to fulfill the purpose. Trail walkers are required to complete a series of tasks to successfully overcome this challenge. These include measuring the distance between the base of the portal and the support post, the height of the support bar, and the end of the portal to the point of projecting the end of the portal to the ground. Additionally, they must apply the principle of congruence to solve the challenge. These tasks and activities, facilitated by digital technology, pertain to mathematics, engineering, and science.

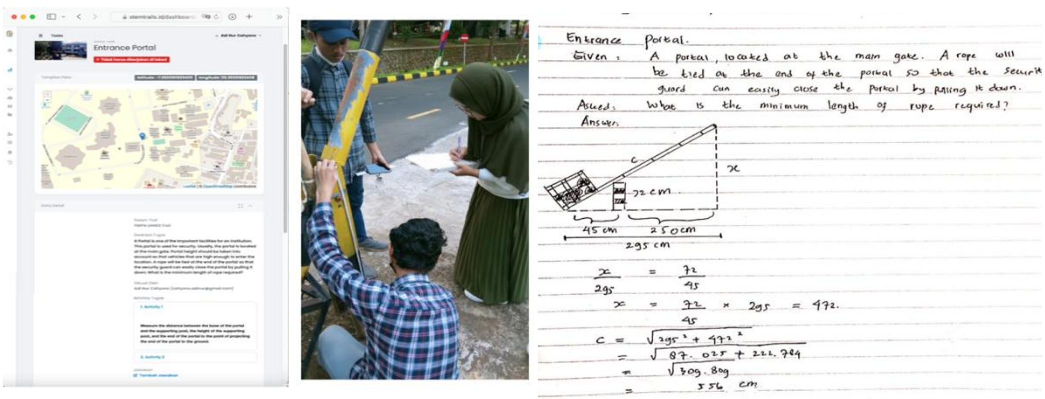

Figure 3. STEM trail walkers following a designated route, which incorporates a series of challenges that must be solved as they proceed.

Another example of a designed task is a task that integrates mathematics with science: 'How many fish can be kept in this fishpond?' (Figure 4). To answer this problem, students are invited to carry out several activities, namely: (1) The pond consists of several parts that resemble geometric objects. Calculate the area of each section and sum it up! (2) Divide the total area by the area of each fish to get the number of fish that can be kept in the pond. Note: One fish needs a place of about 900 cm^2.

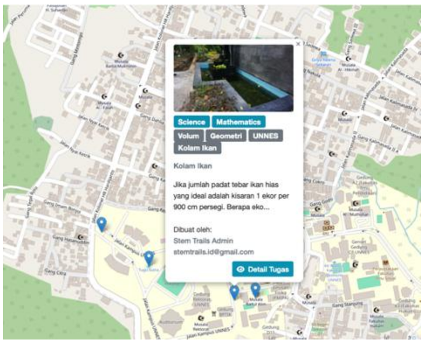

Figure 4. Task about fish in a pond.

Those undertaking the STEM Trail have the option of accessing either publicly broadcast or closed paths; the latter can only be accessed by inputting a specific code. Once a path has been selected for exploration, the platform displays a map with numerous location pins for the completion of route-based tasks. Trail walkers are required to follow the map displayed on the platform to complete the assigned tasks. Upon arrival at the designated location, the trail walker presses the corresponding pin, which then displays the pertinent assignment related to the object or event at that site. If the selected tasks and trails do not require a physical visit to the area, they can be accessed remotely. It is incumbent upon the trail walker to collect the data and information necessary to address the issue in question, as this is set forth in the job description for the tasks and paths that must be performed on-site. Nevertheless, trail walkers are provided with information and data pertaining to projects and routes that do not require their physical presence at the venue, as outlined in the task descriptions.

The trailblazer provides a series of questions and clues to be solved by the trail walkers to overcome a given challenge. Once the issue has been resolved and the solution entered on the student's worksheet, the results are automatically uploaded to the website, accompanied by feedback. The trail walker can evaluate the task at hand before proceeding to the subsequent item until all tasks along the path have been completed and the assigned challenge has been fulfilled. Upon completion of the activity by the trail walkers, who must log into the platform to submit their results, the trailblazer is able to view the outcome of their efforts.

The experimental and control groups, which were employed for the field experiments, received instructions from the same teacher on the same topic and subject matter, but with different interventions. In the experimental class, the mathematics teaching and learning processes were conducted in accordance with the STEM Trails program. The students in the control group received regular instruction in mathematics. In the STEM Trails program, students were assigned to groups of between five and six members. The activity was conducted during the regular school day, with each session lasting approximately two and a half hours. At the outset, the teacher provided a brief explanation of the rules and objectives.

Subsequently, the groups commenced exploration from disparate task locations. As the groups traversed the trail, the researchers and teachers observed and supervised the students' activities, but were not expected to aid, as all the necessary information was available on the app. With the assistance of the digital platform, both groups were able to navigate the planned route, locate task locations, solve problems at these sites, and subsequently proceed to the subsequent tasks. The findings demonstrate that the activities were conducted in an efficacious manner, the portal and application were efficacious and functional, and the rules and objectives of the program were clearly delineated and comprehensible.

The results of the questionnaire given to the students showed that 96.7% of the students were interested in participating in the STEM Trails activities, while the others abstained. In detailing the reasons for their interest (with the opportunity to mention more than one reason), it was found that enjoying outdoor activities (or similar sentences) was mentioned 25 times; “this activity is important to do” was mentioned 14 times, “knowing the relationship between scientific fields” (each mentioning the disciplines involved in this activity based on the tasks they encountered) was mentioned 10 times, “the opportunity to work together and do activities with friends” was mentioned 9 times, and “the tasks in the trail were challenging” was mentioned 7 times. There were also two negative responses, namely tiredness and difficulty in doing the tasks, but these were accompanied by positive answers such as “tiring but challenging” and “difficult but can be solved by working together with group mates”.

3.3. Impact of STEM Trails on mathematical literacy

The program was conducted as planned and offered opportunities for students to experience and learn mathematics by performing mathematical activities. However, it is unclear whether the students' learning experiences in the program affected their mathematical literacy. To answer this question, an individual paper-and-pencil post-test was administered to the students after they received the intervention. The test was administered to students in both experimental and control classes. Like the pre-test, the post-test was used to measure students' performance in mathematics, especially their ability and skills to understand and apply mathematics to solve problems. The pre-test and post-test results on mathematical literacy in the experimental and control groups are presented in Table 1.

Table 1. Test results on mathematical literacy in the experimental and control groups.

	Experimental group (n = 31)		**Control group (n = 30)**	
	Pre-test	Post-test	Pre-test	Post-test
Mean	77.7	88.4	77.5	81.9
Std. dev.	7.9	6.4	6.7	6.0
Max.	92.0	96.0	88.0	92.0
Min.	60.0	72.0	60.0	60.0

A statistical comparison of student scores between the experimental and control classes was conducted to determine the effect of the intervention on the students' mathematical literacy (Figure 5).

The t-test for independent samples revealed a significant difference. Levene's test for equality of variance was 0.850 > 0.05, which means that the data variance between the experimental and control classes was homogeneous. The two-sided p-value was <0.001, which means that there was a difference in the average mathematical literacy of students in the experimental and control classes. The results showed that the mean acquisition of mathematical literacy of the 31 students in the experimental group (90.32) was significantly higher (Cohen's d = 1.847197) than that of the 30 students in the control group (77.60). This means that the students in the experimental group outperformed those in the control group. In other words, the STEM Trails program intervention improved the mathematical literacy of the students.

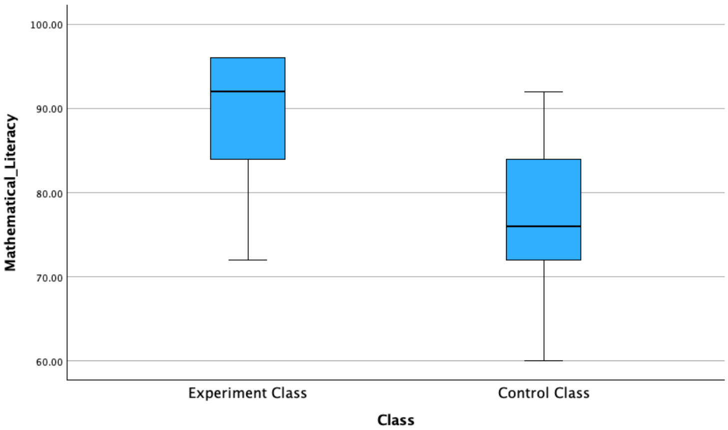

Figure 5. Comparison of students' mathematical literacy in experimental and control classes.

The results show that the STEM Trails project developed a strategy to integrate science, technology, engineering, and math into learning activities. This will assist students in acquiring 21st-century skills [2,3]. This strategy applies an interdisciplinary approach to teaching and learning, wherein theoretical concepts are taught alongside practical applications, referring to the STEM education concept of Holmlund [4]. This strategy has successfully provided many opportunities for students to engage in challenging and mathematical explorations and has made significant progress in integrating other disciplines. This is in line with the findings of Griffiths and Lavicza et al., concerning the integration of arts in this project [5,19].

The results also show that many resources in the environment can be used as inspiration for learning through a STEM approach. Specific sites and artifacts, including those related to culture, provide opportunities to contextually gain experience in STEM. Some landmarks, which can be points (such as tourist attractions), lines (such as roads), or areas (such as cities) [6], can be designed for STEM Trail tasks. This concept refers to the idea of math trails, which, according to Shoaf et al., are mathematical paths that can be traced to explore mathematics in the surrounding environment [7]. The integration of trails with the use of digital technology is based on previous research developments [8,10–13,27,28].

The incorporation of digital tools in this study has facilitated the integration of practical learning elements, including engaging content, collaborative working, and authentic scenarios, as previously discussed in the literature [16]. The utilization of digital tools has been employed in the problem-solving process, with digital simulations providing a means of investigating the effects of disparate systems or environmental variables, as referenced in several sources that form the basis of this study [17–19]. Furthermore, this study has demonstrated that digital tools can facilitate the enhancement of outdoor mathematical modeling through the provision of automatic solution verification and guidance, thereby facilitating the improvement of students' problem-solving abilities. This finding is consistent with the results of previous research [20]. This study has yielded innovative and efficient STEM education programs that are engaging and motivating for students, facilitating the exploration of scientific concepts through novel approaches, as previously documented [22].

This project has successfully optimized digital tools to provide opportunities to integrate practical learning elements, such as engaging content, collaborative work, and authentic scenarios; the project is in line with technological developments in the Industrial Revolution 4.0 era, with the characteristics mentioned by several researchers [16–19,21]. The STEM Trails program implemented in this project ran smoothly. The portal and app worked well, and the rules and objectives of the program proved to be understandable. The program offers opportunities for students to experience and learn mathematics through mathematical activities. The results showed that students' learning experiences in the program improved their mathematical literacy. This implies that interventions using the STEM Trails program can improve students' mathematical literacy.

4. Conclusions

The results show that the system for STEM education through math trails using digital technology was successfully designed and offered meaningful activities for students to gain mathematical literacy experience. A GPS-based application was developed to support students in implementing outdoor activities to solve problems related to STEM fields. Further research is needed to enhance the development and implementation of this program. The development will add more features through the rapid growth of technology, by adjusting to the expected competencies of STEM learning. Further, expanding its implementation is essential for studying not only other topics in STEM but also its performance in other places with different characteristics.

Students' mathematical literacy can be effectively improved through contextualized and interactive learning experiences, as demonstrated by the findings of this study, which demonstrate that the incorporation of digital technology into STEM-based math trails can effectively boost mathematical literacy. It is suggested that future research should investigate the influence of STEM Trails on students' skills and abilities in more depth, as well as extend the application of STEM Trails to a wider variety of learning situations.

Author contributions

Adi Nur Cahyono: Conceptualization, Data curation, Formal Analysis, Methodology, Writing – original draft, Funding acquisition, and Project administration; Riza Arifudin: Investigation, Resources, Validation, Visualization, Writing – review & editing; Rozak Ilham Aditya: Resources, Software, Visualization, and Writing – review & editing; Bagus Surya Maulana: Project administration, Resources, and Data curation. Zsolt Lavicza: Supervision and Writing – review & editing. All authors have read and approved the final version of the manuscript for publication.

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Conflict of interest

There is no conflict of interest in the research and writing of this article.

Ethics declaration

This research was conducted according to the relevant ethical standards.

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Author's biography

Adi Nur Cahyono is an Associate Professor of Mathematics Education at the Faculty of Mathematics and Natural Sciences, Universitas Negeri Semarang (UNNES), Indonesia. He received his doctoral degree (Dr.rer.nat.) from J.W.v. Goethe-Universität Frankfurt am Main, Germany, in the specialty of Didactics of Mathematics for his work on the MathCityMap Indonesia. He teaches, researches, and supervises undergraduate, master's, and doctoral students in teaching & learning geometry, mathematical modelling, and the uses of ICT in mathematics education. He is the founder and leader of the Centre for Research on Math Trails with Digital Technology (mathtrailslab.id).

Riza Arifudin is a lecturer in Computer Science at Universitas Negeri Semarang. He holds a master's degree in computer science from Universitas Gadjah Mada. In addition to teaching, he is actively engaged in research in the fields of education and artificial intelligence systems, focusing on developing innovations and technological solutions to support modern learning. He is also an author, having written several books in his areas of expertise.

Rozak Ilham Aditya is an Informatics Engineering graduate from the Faculty of Mathematics and Natural Sciences, Universitas Negeri Semarang (UNNES), Indonesia. He is currently working as a programmer and data scientist at Universitas Negeri Semarang, specializing in Full-Stack Web Development and data analysis. He is also a freelance programmer and the founder of Zandspace, a software house based in Semarang, Indonesia, focusing on innovative software and system development.

Bagus Surya Maulana is a Mathematics Teacher at Semarang Multinational School, Semarang, Indonesia. He received his bachelor's degree in mathematics education from Universitas Negeri Semarang in International Class and graduated in 2024. During his college years, he was active as a Lecturer Assistant and Laboratory Assistant in lecture activities. He is currently doing his master's degree through Fast Track Program at Universitas Negeri Semarang, Mathematics Education Study Program. He also received a Merit-based Scholarship from Bank Indonesia in 2023. Now, he teaches Mathematics at an International School with Cambridge Curriculum.

Zsolt Lavicza has worked on several research projects examining technology and mathematics teaching in classroom environments in Michigan and Cambridge. In addition, Zsolt has greatly contributed to the development of the GeoGebra community and participated in developing research projects on GeoGebra and related technologies worldwide. Currently, Zsolt is a Professor in STEM Education Research Methods at Johannes Kepler University's Linz School of Education. From JKU he is working on numerous research projects worldwide related to technology integration into schools; leading the doctoral programme in STEM Education; teaching educational research methods worldwide; and coordinates research projects within the International GeoGebra Institute.