Arduino Microcontroller Boards in Digital Learning for Science and STEM Education: A Bibliometric Analysis (2012-2022)

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Abstract

An approximate assessment of the community's magnitude from a Google search revealed that the term "Arduino" generated more than 77 million search results, while the combined search term "Arduino AND digital learning" yielded around 16 million hits. This study aims to analyze the role of Arduino microcontroller boards in digital learning environments for science and STEM Education from a bibliometric perspective in the last decade. A total of 842 articles were analyzed from the Scopus database from 2012 to 2022. The findings revealed that the year 2021 witnessed the highest volume of publications, with the United States emerging as the most prolific country, followed by India, Indonesia, Brazil, and China. Among the authors, Yasmin B. Kafai garnered the highest frequency of citations, with Calin Galeriu, S Kubínová, J Šlégr, and James P. Grinias also being prominently cited. The keyword "Arduino" exhibits connections with terms such as "android," "Bluetooth," "distance learning," "e-learning," "low-cost," "simulation," and "IoT." This emerging trend reveals the strong connection among Arduino hardware, e-learning websites, and digital tools to scaffold skills among students. This study presents valuable findings that can serve as a valuable resource for future research.

Introduction

Digital learning takes many forms in order to facilitate the teaching and learning activities using technology in an integrated way (Behera, 2013; Veletsianos, 2016). 3D-simulations, online collaborations, virtual meeting with other people, and remote mentoring from experts are examples of learning activities in the digital learning space (Blayone et al., 2017). Digital learning (d-learning) combines electronic learning (e-learning) and mobile learning (m-learning) together (Behera, 2013). Mobile learning allows learners to interact with their learning resources via mobile devices far away from their normal place of learning environments, which overlaps with a bigger scope of the e-learning universe (Aparicio et al., 2016). The readiness of mobile technology and e-learning platforms has acted as a catalyst for the era of digital learning (Gameil and Al-Abdullatif, 2023). Digital learning has many beneficial outcomes, one of which is the student's ability to work at his or her own pace (Kumar Basak et al., 2018).

Today, digital learning is gradually consuming the term, e-learning. Based on the learning theory of connectivism, decision-making is itself a learning process and learning is a network phenomenon influenced by technology and socialization (Siemens, 2007; Goldie, 2017). This theory not only recognizes the concepts of synchronous and asynchronous learning but also emphasizes hands-on learning activities in both physical and virtual environments (Chen et al., 2013). In today's educational landscape, digital learning (d-learning) under the umbrella of technology-enhanced learning has been merging into science and STEM pedagogy.

Despite the technological advancements, students may still perceive science and STEM disciplines challenging. This is reasonable due to the demanded requirements of specific literacy (e.g. digital literacy, STEM literacy, scientific literacy, etc.) that the students must develop or acquire during the learning process (Kelley and Knowles, 2016). Given that each student learns at a different pace, lesson designs should cater to their diverse needs (Le et al., 2021). This is where technology intervention becomes crucial. For instance, certain science experiments may pose safety hazards in a traditional classroom setting. By leveraging digital tools and virtual laboratory experiments, augmented reality can provide a safer learning environment.

Arduino, an open-source hardware and software initiative, has been producing microcontroller-based Arduino boards since 2005, fostering a community of users for collaboration and interaction. Microcontrollers are programmable microcomputers or single board computers designed for a specific purpose (Hintz & Tabak, 1992). The application domains of Arduino span in various areas, including system design, healthcare, smart agriculture, home automation, mining, education, and general-purpose applications (Kondaveeti et al., 2021). An Arduino board comprises a microcontroller, such as the Atmel ATmega328p or ATmega168. Arduino makes the procedure of working with microcontrollers engaging and offers huge benefits to teachers, students, and hobbyists.

Rationale of the Study

A full implementation of Arduino learning environments can help students and educators to be engaged with interdisciplinary contents in the current digital age. Therefore, it is necessary to overview the practices involving Arduino microcontroller boards in the d-learning environments for science and STEM education. The bibliometric analysis related to Arduino has been extensively explored and documented in previous studies. For an example, Soares et al. (2019) analyzed 59 articles from the Scopus database published between 2007 and 2016. The bibliometric analysis covered the use of Arduino boards in RFID (Radio Frequency Identification), an automatic identification technology without physical contact with the objects based on the emission of radio signals. In addition, López-Belmonte et al. (2020) identified 346 Arduino-related publications in the field of education from the Web of Science (WoS) database between 2010 and 2019. More broadly, Trento et al. (2020) also conducted a bibliometric analysis study from 440 Scopus articles on the application of Arduino-based systems for monitoring and measuring environmental data in the period 2015-2020. In a recent bibliometric study, the keyword Arduino often appeared in relation with Soft Robotics (Rusu et al., 2023) and Robot Education (Yang et al., 2020). However, to the best of our knowledge, there are no bibliometric studies that examine the use of Arduino microcontroller boards in the context of digital learning for Science and STEM Education.

Objectives of the Study

This study is intended to visualize how the topic develops. Conducting a bibliometric study is important because it offers an overview of the research being carried out regarding the use of Arduino boards in science and STEM education. The purpose of this study is to collect and analyze published articles related to the use of Arduino microcontroller boards in the d-learning environments for science and STEM education from the period 2012-2022. This objective is specified in the following research question:

RQ. How much research has been done on the implementation of the Arduino boards for science and STEM education in the context of digital learning from the Scopus database?

We define a set of mapping questions (MQs) that will help to answer the research question. The following MQs were formulated:

MQ1. What is the distribution of the relevant publications by year?
MQ2. What is the distribution of the relevant publications by country?
MQ3. What kind of structure emerges regarding the most cited authors?
MQ4. What kind of structure emerged regarding co-authors' analysis?
MQ5. What kind of structure appears in terms of frequently used keywords?

Method

Research Design

This study adopted the bibliometric method to provide descriptive results of previous studies related to Arduino, digital learning, and STEM education from Scopus database. A large amount of data from a scientific database was analyzed using simple statistics (Donthu et al., 2021). The overview revealed a pattern in publications, number of citations, authors, and types of articles, keywords, and countries. These emerging trends were interpreted, which might serve as take-away pointers for students and educators in the field of Science, Technology, Engineering, and Mathematics (STEM). We had conducted a search related to all research results on the topic from the Scopus database for the 2012–2022 timeframe. The year 2012 was chosen as it was the initiation of the industrial revolution 4.0 and digital transformation (Xu et al., 2021).

Inclusion Criteria (IC) & Exclusion Criteria (EC)

This study adopted the bibliometric Inclusion criteria emerged from research results as a guide in tracing the study results. The guiding criteria in tracing the research results reviewed had several inclusion criteria, including:

1. IC-1 = The screening was limited to the title, abstract, and keywords of the documents
2. IC-2 = The screening was limited to English documents only
3. IC-3 = The screening results must focus on implementing Arduino boards in Education
4. IC-4 = All papers using Arduino boards in relation to the characteristics of digital learning

Exclusion criteria are a guiding criterion for eliminating research results that are irrelevant to the purpose of this study. The criteria set out in this study include:

1. EC-1 = research results not relevant to the topic and non-English papers
2. EC-2 = research, not a review, meta-analysis, philosophy, or framework
3. EC-3 = full text of research results not related to Education
4. EC-4 = research results do not show the use of Arduino boards in d-learning environment

Data Analysis

A search for topic results using the keywords “Arduino” AND “chemistry” OR “physics” OR “biology” OR “engineering” OR “science” OR “STEM” on Scopus was accessed on October 6, 2022. The documents were sorted based on the Inclusion and Exclusion Criteria. The research methodology adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, ensuring a standardized and transparent approach to the review process. This methodology is widely recognized in scientific research for systematic reviews and meta-analyses.

The results of the search and sorting process are illustrated in Figure 1, which presumably outlines the steps taken to analyze the research findings. It is mentioned that the final dataset, comprising 1,122 articles initially identified from Scopus, was refined using inclusion and exclusion criteria, resulting in a selection of 842 articles for the subsequent analysis.

To further explore the gathered data, a CSV file containing the compiled information was used. VOSviewer version 1.6.19, a tool for bibliometric visualization, and descriptive content analysis were employed for a comprehensive examination of the dataset. Bibliometric analysis involves the quantitative analysis of scientific publications, including patterns of publication, citation, and co-authorship.

A linear regression analysis of the number of publications was conducted using Jamovi version 2.3.21. Linear regression analysis is a statistical method used to examine the relationship between variables. In this context, it appears that the analysis aimed to investigate trends or patterns in the number of publications over time or in relation to other factors.

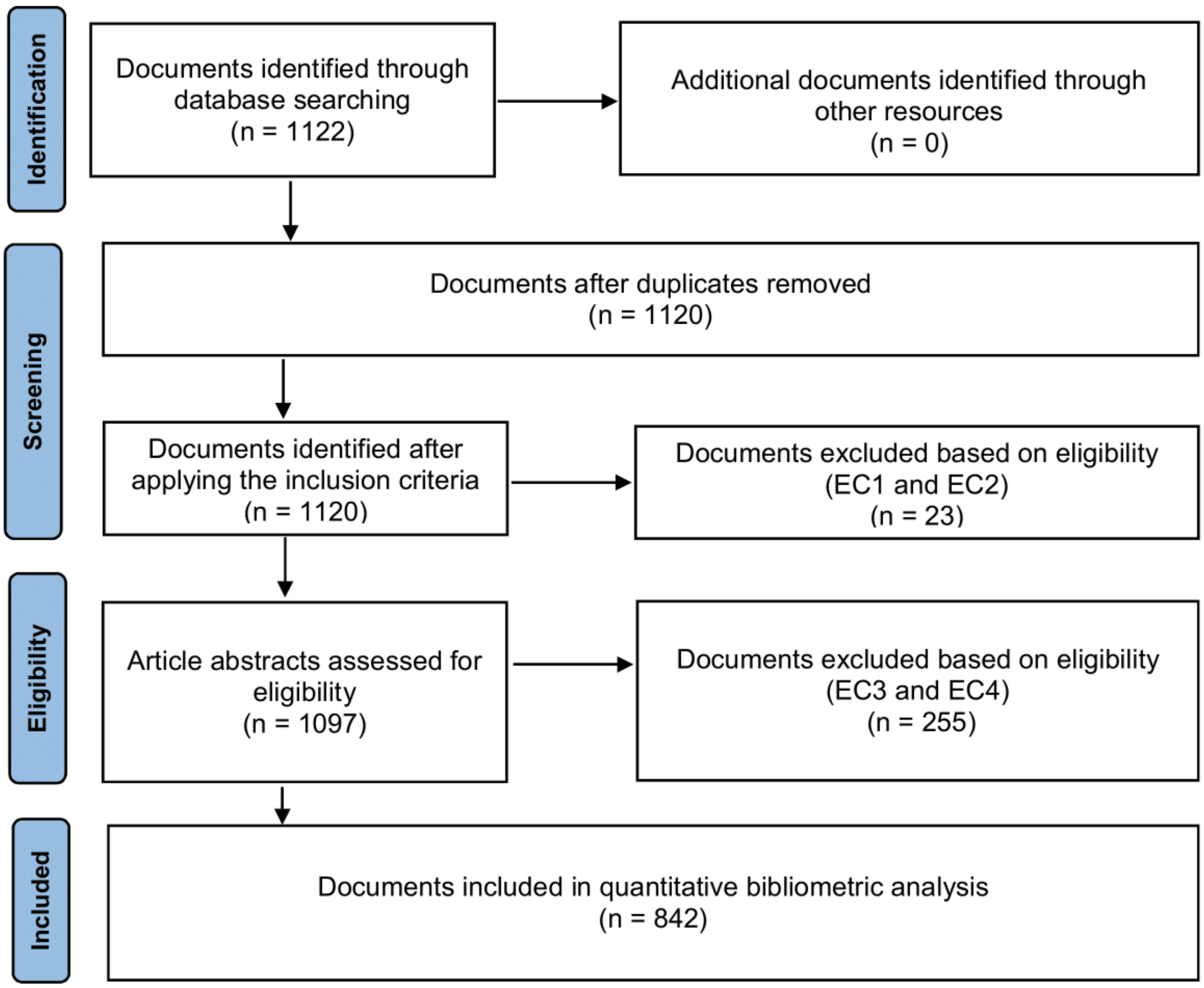

Figure 1. PRISMA flowchart of the analysis

Results and Discussion

MQ1. What is the distribution of the relevant publications by year?

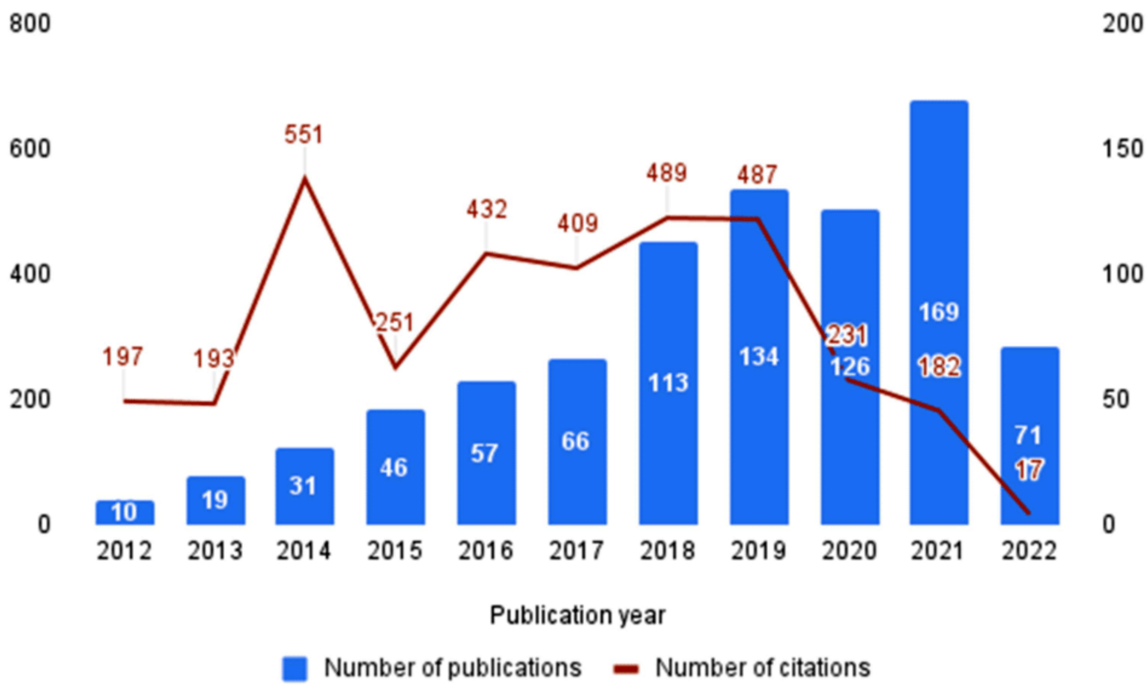

Figure 2. Distribution of relevant publications from 2012–2022

In 2008, Buechley et al. introduced a pioneering publication that marked the inception of utilizing LilyPad Arduino in the context of computational e-textiles. This work not only showcased the innovative integration of Arduino boards but also served as an example of their application in computer-based learning environments. The introduction of LilyPad Arduino, specifically designed for e-textile projects, demonstrated the potential for merging electronics with fabric, opening up new possibilities for interactive and tangible learning experiences. It has continued to captivate researchers, fostering a growing interest in the integration of Arduino in educational settings. The enduring appeal lies in the dynamic combination of hands-on experimentation and coding that Arduino platforms offer, promoting an engaging and effective approach to learning.

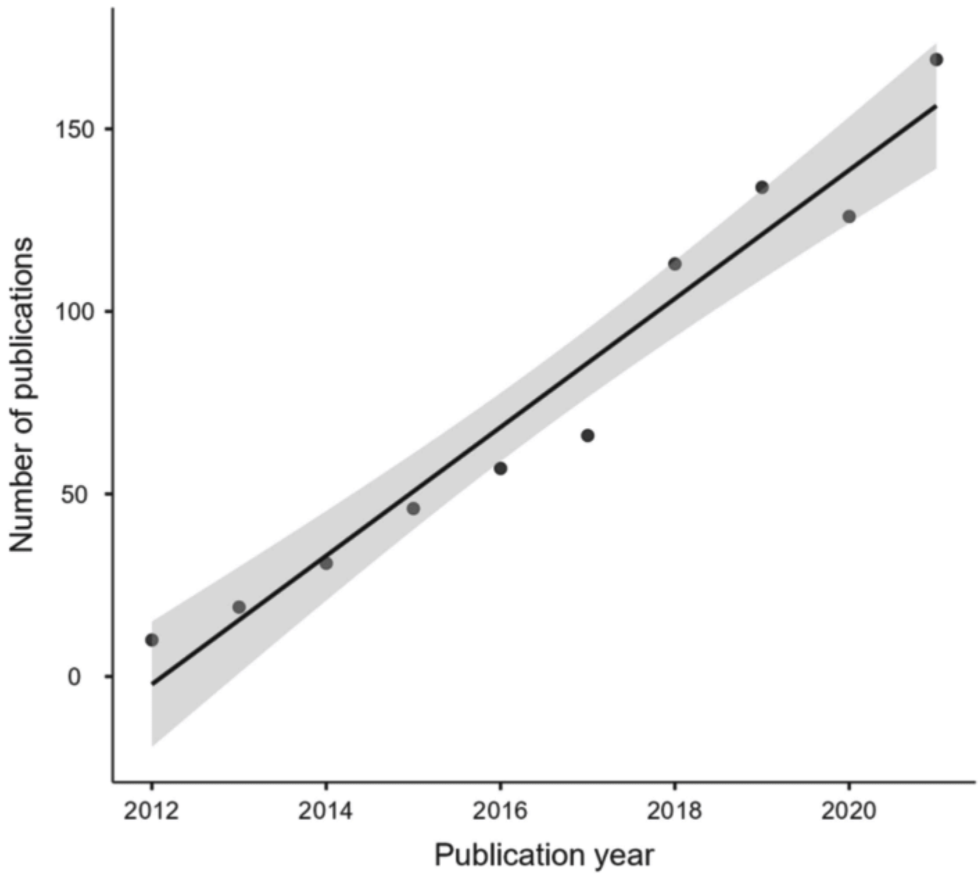

Figure 3. The linear regression analysis of publication counts from 2012–2021

The distribution of the emerging trend in the number of publications on this topic can be examined through a linear regression analysis (Donthu et al., 2021). In this analysis, the independent variable (year) is plotted on the x-axis, while the number of publications is plotted on the y-axis. The results are illustrated in Figure 3. The regression modeling was conducted to fit the year records from 2012 to 2021, excluding the publications in 2022 due to the incomplete access to the Scopus database. The equation derived from the analysis is y = 17.6x + 35426, with an R^2 value of 0.952. These findings indicate a strong linear trend in the number of publications, confirming the growing enthusiasm for research in this area.

Among the publications, 35.9% focused on research and development, prototyping, and curriculum development. Within this subset, topics such as remote monitoring applications/tools, computer-controlled prototypes, and the creation of interactive learning tools were covered. The remaining 64.1% of the 842 articles primarily concentrated on hands-on implementation, encompassing aspects such as learning to program Arduino boards, promoting STEM skills, understanding circuitry, and engaging in technological design. This trend suggests a large demand for the application of Arduino projects and prototyping.

MQ2. What is the distribution of the relevant publications by country?

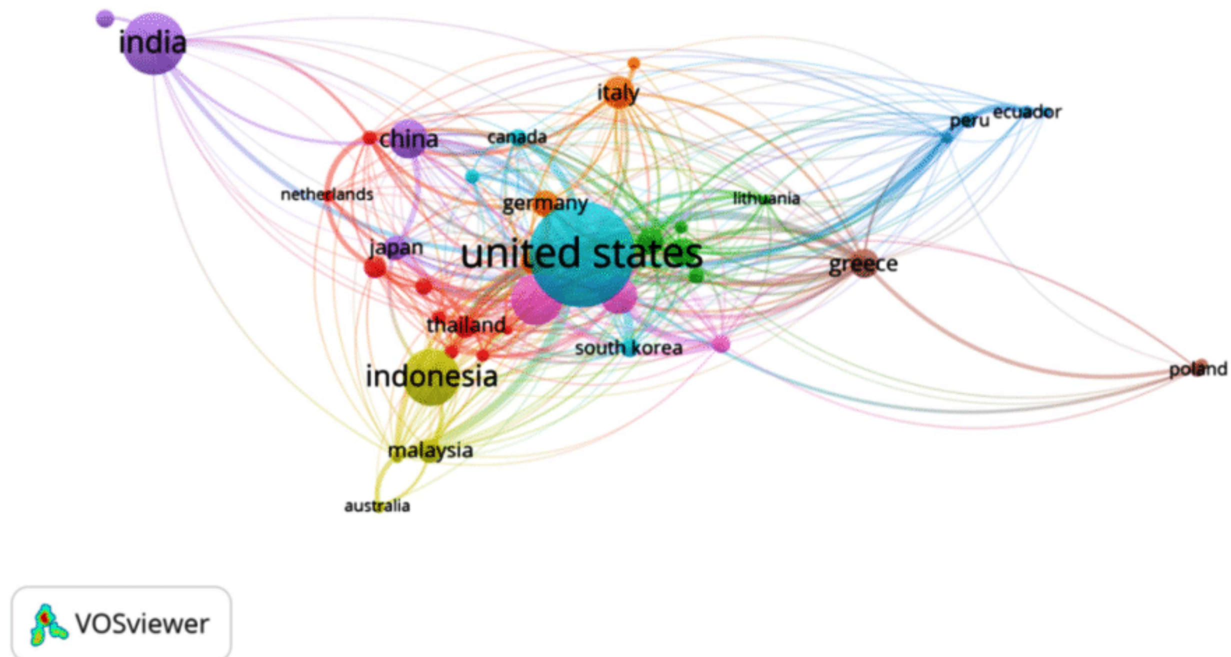

Figure 4. The visualization linkage of publications by countries

Figure 4 serves as a visual representation of bibliographic coupling, employing countries as the unit of analysis within the context of publications utilizing Arduino in digital learning environments for science and STEM education. The analysis, while insightful, is not without its limitations. Notably, a predetermined threshold of a minimum of 5 documents from a particular country was set, acting as a restricting factor in the study. Despite this constraint, the analysis successfully identified 40 countries, clustering them into 9 distinct groups based on bibliographic coupling.

Delving deeper into the content, the study brings attention to the geographical distribution of publications in the field of Arduino implementation for educational purposes. From 2012 to 2022, the United States emerged as the leading contributor, with the highest number of publications, underscoring its prominence in the integration of Arduino within digital learning environments. Following closely are India, Indonesia, Brazil, and China, comprising the top five countries with the most significant output in this thematic area. This pattern highlights a global acknowledgment of the "Do-It-Yourself" (DIY) and MAKER movement, as discussed by Chen and Wu (2017), signifying the relevance and widespread adoption of Arduino in science and STEM education beyond established educational hubs.

MQ3. What kind of structure emerges regarding the most cited author?

Figure 5. The visualization linkage regarding the most cited authors

The graphical representation in Figure 5 offers a comprehensive view of the most cited authors within the analyzed dataset. Employing a criteria of a minimum of 1 document and 1 citation per author, the network visualization reveals a complex web of scholarly connections. The graph comprises 16 distinct clusters, grouping together 269 authors whose works contribute significantly to the discourse on the subject. Each circle in the graph corresponds to an author, and the size of these circles is indicative of the extent of citation dominance, with larger circles denoting higher citation counts.

Within this intricate network, Yasmin B. Kafai stands out conspicuously with the most extensive circle size, signaling that she holds the distinction of being the author with the highest number of citations. This underscores the significant impact and influence of Yasmin B. Kafai's contributions to the field of Arduino in digital learning environments for science and STEM education. Additionally, notable circle sizes are observed for other authors such as Calin Galeriu, Kubínová, Šlégr, and Grinias, suggesting their prominence in terms of citation impact. The graph thus not only provides a visual representation of citation patterns but also serves as a valuable tool for identifying key figures whose work has resonated widely within the academic community in this specific domain.

Revealing the trend, the majority of the works by these authors revolve around the development and implementation of Arduino-based learning media or tools. These tools serve a twofold purpose. Firstly, they aim to assist students in visualizing abstract concepts through computer interfaces. Secondly, they facilitate the utilization of computer programming skills, circuitry, and technological design to effectively solve science problems. These findings imply the role of Arduino hardware and software in enhancing digital learning environments for science and STEM education.

MQ4. What kind of structure emerged regarding co-authors' analysis?

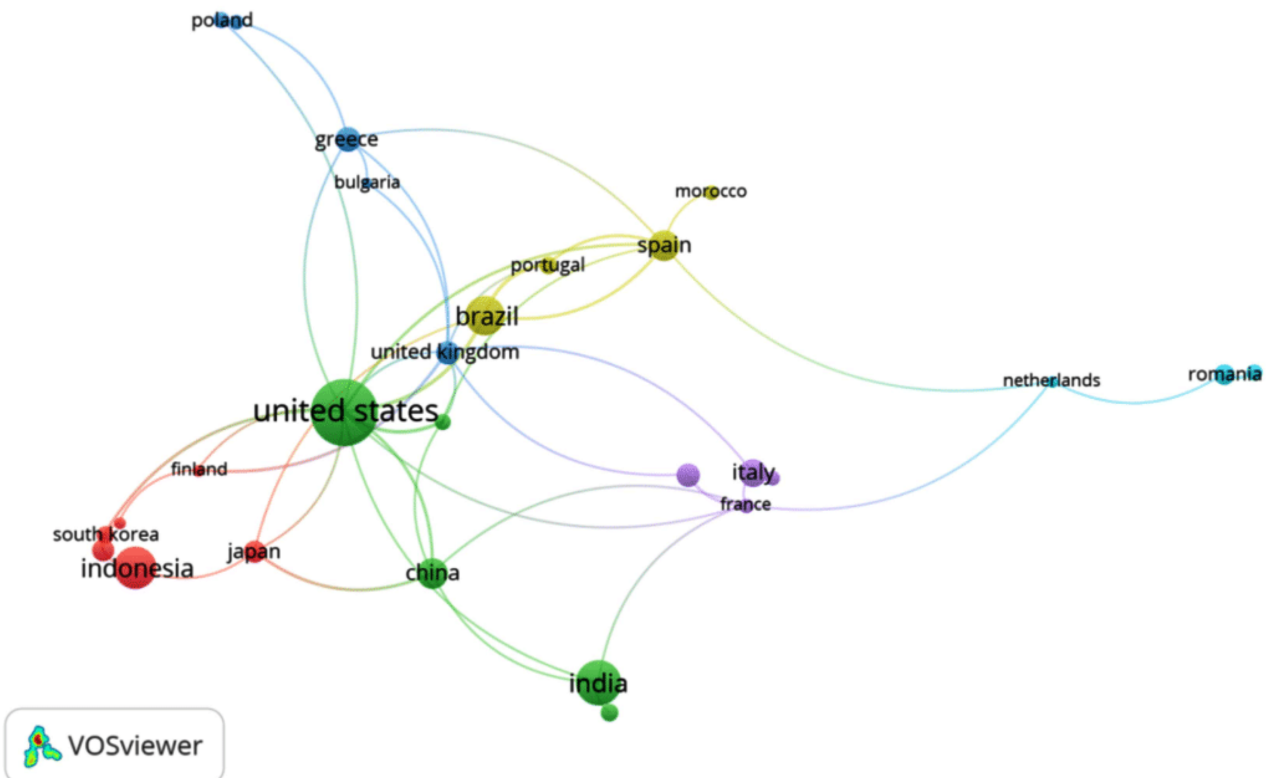

Figure 6. The visualization linkage regarding co-authors from several countries

Figure 6, with a minimum document requirement of 5 per country, offers a visual representation of country links based on co-authorship in publications related to the utilization of microcontroller boards like Arduino in science and STEM education. The lines connecting countries in the graph represent collaborative ties forged through co-authorship in shared articles. In total, the analysis identifies 27 countries, organizing them into 6 distinct clusters based on the strength of their co-authorship connections.

A notable finding in Figure 6 is the prominence of the United States and Spain, which exhibit the highest total link strength. This observation underscores the robust collaborative networks and co-authorship relationships established by researchers from these countries with their counterparts worldwide. The strength of these connections signifies the depth and breadth of international collaboration in advancing knowledge and practices related to microcontroller boards, emphasizing the global nature of research efforts in this field.

The analysis reflects a broader acknowledgment among countries of the growing importance of microcontroller boards, particularly in the realms of robotics and STEM education. As highlighted by Papavlasopoulou et al. (2017), the increasing recognition of the significance of prototyping and coding in science curricula across various educational levels, from elementary to higher education, is evident in the collaborative efforts reflected in Figure 6. This interconnectedness on a global scale signifies a collective endeavor to integrate cutting-edge technology into educational practices, fostering a collaborative approach to advancing STEM education worldwide.

MQ5. What kind of structure appears in terms of frequently used keywords?

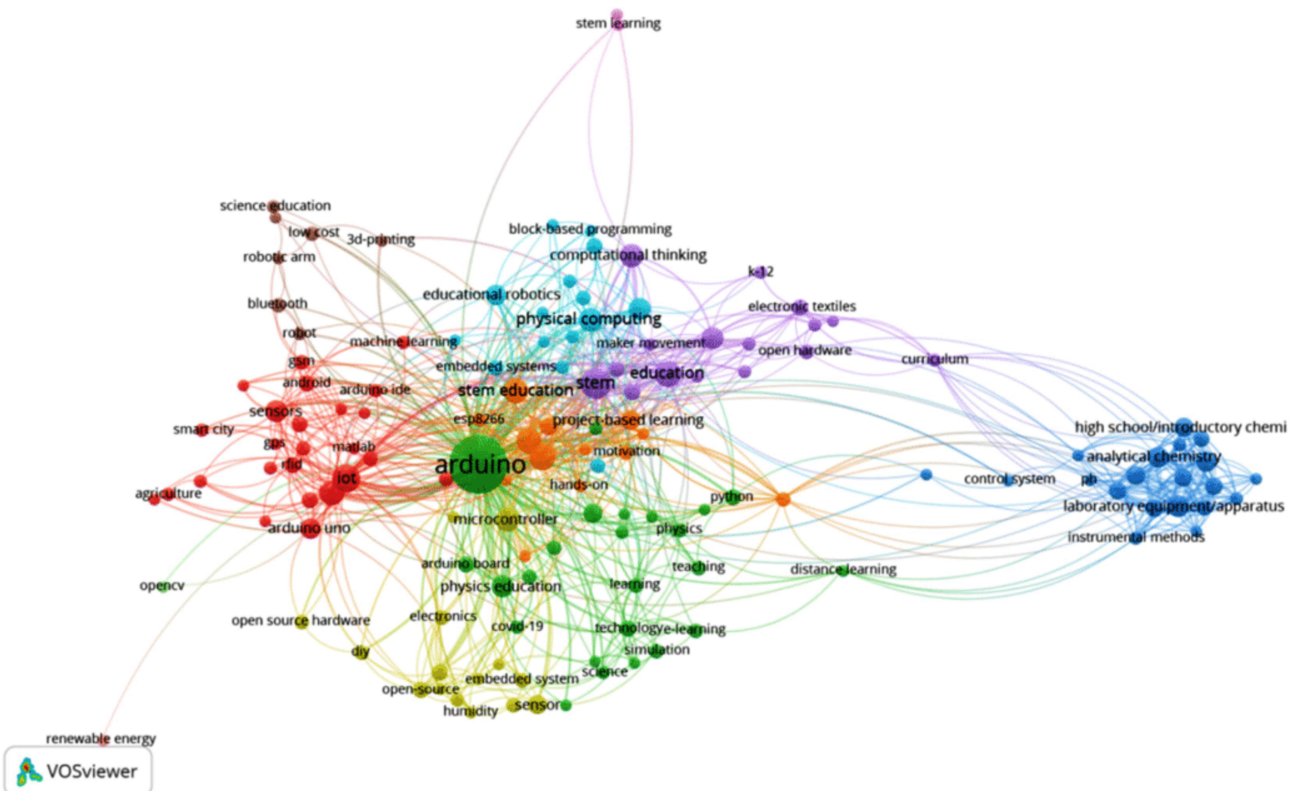

Figure 7. The overlay visualization related to the keyword co-occurrences

Figure 7 illustrates the most frequent co-occurrences based on author keywords, encompassing a total of 140 keywords organized into 11 clusters. Analyzing Figure 7 reveals that Arduino-related research occupies a central position between the clusters of mobile learning and e-learning. For instance, within the green cluster, keywords such as simulation, e-learning, and distance learning are connected to laboratory equipment/apparatus, high school chemistry, and control systems. The red cluster focuses on mobile learning aspects, featuring keywords like android, GSM, Bluetooth, and mobile robot. The purple cluster represents STEM education keywords, which are closely linked to programming, computational thinking, the maker movement, and project-based learning. These highlight the significance of the Arduino learning ecosystem within the context of this topic, showcasing its role in bridging mobile learning, e-learning, and STEM education domains. As a system, Arduino is flexible, practical and simple. Its user-friendly interface and immensely wide range of functions are traits advantageous in effective science education.

Conclusions

As students increasingly require problem-solving abilities and proficiency in technology, educators face ongoing challenges to improve their teaching and learning methods through digital learning environments, particularly in the fields of science and STEM education. These environments incorporate a diverse array of computer programming and robotics activities, both within and beyond the confines of traditional classrooms, using digital tools, mobile applications, and interactive multimedia. Within the year range 2012–2022, 1122 articles from Scopus database were extracted and sorted based on inclusion and exclusion criteria. As a result, there were 842 articles related to the role of Arduino in the digital learning environments for science and STEM education.

The user-friendly and widely available nature of Arduino boards makes them accessible to students, providing a straightforward avenue for learning coding and prototyping machines, even without prior electronics or programming experience. These adaptable microcontroller platforms enhance educational experiences by enabling hands-on experimentation, prototyping, and the realization of creative concepts. Through Arduino, students can develop coding skills while exploring STEM-related ideas (Science, Technology, Engineering, and Mathematics). Furthermore, students have the opportunity to share their code, create personal Arduino libraries, and actively contribute to the community, fostering collaborative learning and the exchange of knowledge and ideas.

In this study, we have found that the general practice of utilizing Arduino boards has been well-accepted in the field of STEM Education. Predominantly, 64.1% of the 842 articles concentrated on hands-on implementation to increase computational, creativity, problem solving, and coding skills. Based on the bibliometric analysis, it can be seen that the keyword “Arduino” was found strongly linked with several keywords, such as “e-learning”, “distance learning”, “android”, “low-cost”, “Bluetooth”, “IoT”, and “STEM”. We predicted that the number of publications related to these keywords will continue to grow in the future. Tinkering is effective in promoting STEM skills. Playfulness and ingenuity can fuel STEM learning, especially with electronics, circuitry, and robotics (Bevan et al., 2014).

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