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Araştırma Makalesi

ARDUINO IN TEACHING LABS: A BIBLIOMETRIC ANALYSIS

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Abstract

Arduino microcontroller boards are increasingly used in teaching laboratories as a technology that attracts attention with its superior features and ease of use. In this study, it is aimed to carry out a bibliometric analysis to examine the studies using Arduino in teaching laboratories and to assist researchers by predicting the direction of future studies. This study used bibliometric and content analysis. By scanning the WoS and Scopus databases 404 studies were reached and according to various exclusion criteria 215 of them were included in this study. Biblioshiny software was used for analysis, and the studies were also examined with content analysis based on technology-based learning. It is found that Arduino in Teaching Lab. (ATL) research has a high growth rate and the publications in this field mostly have two or more authors, the country with the most publications is the USA. In the studies, it was seen that the majority of the studies aimed at developing the laboratory setups/devices/equipment available on the market at a lower cost, and the majority of studies were carried out in the engineering laboratory with university students. It can be concluded that the use of Arduino in science laboratories is important in terms of eliminating concerns about laboratory costs, creating new opportunities in the learning process, and encouraging the acquisition of scientific process skills and a focus on STEM professions. This study focuses on the use of technologies like Arduino in education. The findings presented in this study can be considered as guiding principles for future research.

Keywords: Arduino, bibliometric analysis, science teaching, laboratory

ÖĞRETİM LABORATUVARLARINDA ARDUINO: BİR BİBLİYOMETRİK ANALİZ

Özet

Arduino mikrodenetleyici kartları, üstün özellikleri ve kullanım kolaylığıyla dikkat çeken bir teknoloji olarak, öğretim laboratuvarlarında giderek daha fazla kullanılmaktadır. Bu çalışmada, öğretim laboratuvarlarında Arduino kullanımına ilişkin çalışmaları incelemek ve araştırmacılara gelecekteki çalışmaların yönünü tahmin ederek yardımcı olmak amacıyla bibliyometrik bir analiz yapılması amaçlanmıştır. Bu çalışmada, bibliyometrik

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ve içerik analizleri kullanmıştır. WoS ve Scopus veritabanları taranarak 404 çalışmaya ulaşılmış ve çeşitli dışlama kriterlerine göre 215'i bu çalışmaya dahil edilmiştir. Analiz için Biblioshiny yazılımı kullanılmış ve çalışmalar ayrıca teknoloji tabanlı öğrenmeye dayalı içerik analizi ile de incelenmiştir. Çalışmanın bulgularına göre, öğretim laboratuvarlarında Arduino kullanımına yönelik araştırmalar yüksek bir büyüme oranına sahiptir. Bu alandaki yayınların çoğunun iki veya daha fazla yazarlı olduğu, en fazla yayının ise ABD kaynaklı olduğu belirlenmiştir. Çalışmaların büyük bölümünün, piyasada bulunan laboratuvar kurulumlarını, cihazlarını ve ekipmanlarını daha düşük maliyetle geliştirmeyi amaçladığı görülmüştür. Ayrıca bu çalışmaların çoğunun üniversite öğrencileriyle ve mühendislik laboratuvarları bağlamında yürütüldüğü tespit edilmiştir. Sonuç olarak, Arduino'nun bilim laboratuvarlarında kullanımı, hem laboratuvar maliyetlerine ilişkin sorunların azaltılması hem öğrenme sürecinde yeni fırsatlar sunması ve hem de bilimsel süreç becerilerinin kazanımı ve STEM mesleklerine olan yönelimi teşvik etmesi açısından önem taşımaktadır. Arduino gibi teknolojilerin eğitimde kullanımına odaklanan bu çalışmada elde edilen bulgular, gelecekte yapılacak araştırmalar için yol gösterici nitelikte değerlendirilebilir.

Anahtar Kelimeler: Arduino, bibliyometrik analiz, fen öğretimi, öğretim laboratuvarı

1. INTRODUCTION

Teaching laboratories are instructional environments specifically designed to support students' learning of scientific concepts through planned, hands-on activities conducted within the curriculum. Unlike research laboratories, whose primary purpose is to produce new scientific knowledge, teaching laboratories aim to help students apply theoretical knowledge, observe scientific phenomena, concretize abstract concepts, and develop scientific process skills. In science education, these laboratories have an essential role because they provide students with opportunities to relate the subjects covered in theoretical courses to practical applications. Different methods (open-ended experiments, closed-ended experiments, induction, deduction, etc.) can be used while teaching in laboratories, and students can actively participate in the process and work to find answers to the questions in their minds. Laboratory studies contribute to students' meaningful learning (Galloway and Bretz, 2015), play a role in their acquisition of scientific process skills (Kaleka and Nur, 2018; Setiani, Surasmi and Tresnaningsih, 2020), and increase their academic success (Greenbowe et al., 2007; Mohammed et al., 2020) and can influence career choices and encourage orientation towards professions in STEM fields (Odera et al., 2015; Sasson, 2021).

However, there are also some concerns and challenges about the teaching laboratory. The first is that educational institutions are required to make substantial investments. Considering the materials, equipment, and various chemicals to be used in the laboratory, as well as the teaching assistants who will work during the laboratory process, it is an important expectation the learning outcomes achieved at the end of the process should justify these costs (Hofstein and Lunetta, 2004). NRC's 2006, 2012, and 2018 reports (NRC 2006; 2012; 2018) also emphasized that teaching in the laboratory should "bring together realistic scientific practices and the use of technology" and support broader learning outcomes For this reason, there is a need for studies that focus on laboratory teaching processes and on improving the quality of these processes. It is undoubtedly important to evaluate the developments in technology in terms of improving the teaching in laboratory. At this point, Arduino microcontroller boards, developed within the scope of a project study (Arduino, 2022) in 2005, came to the fore with advantages such as ease of use and open-source code, among the important technological developments. Arduino cards can read many different inputs (such as light and heat detected by sensors) and convert them into an output (such as the lighting of an LED or the operation of a motor) (Arduino, 2022). Moreover, Arduino can reach more widespread use, as there is no need for high-level coding and programming knowledge while doing all this, and even block coding can now be used instead of text coding (Fidai, Capraro and Capraro, 2020). At the same time, its affordable cost (Grinias et al., 2016) is another important advantage of Arduino.

Thanks to these advantages, Arduino microcontroller boards find a place in various studies in research and teaching laboratories. In these studies, Arduino is combined with various sensors (sound, light, gas, etc.). For example, Ntourou, Kalagiannakis, and Psycharis (2021) taught 5th-grade students about concepts related to electricity, Kang, Yeo and Yoon (2019) gas reactions and pressure, Gomes et al. (2020) developed designs using Arduino microcontroller boards to teach calorimetry applications to visually impaired students. In Vidal, Bravo and Rengifo's (2022) study, engineering students performed various physics experiments (such as acceleration, force, thermal conductivity and resistance, gravity, inertia) using the Arduino kit. In another study, an Arduino-based laboratory system (named SolarInsight) was developed by Zachariadou, Yiasemides and Trougkakos (2012) to be used in experiments on photovoltaic cells for electrical engineering and physics students.

Bibliometric analysis is a literature scanning method that evaluates the authors, countries, citation numbers, years in which the studies were carried out, the institutions of the researchers, the journals in which the studies were published quantitatively, and the relationships between these factors qualitatively, of the articles examined in any research field (Aria and Cuccurullo, 2017). Bibliometric analysis studies, which have been carried out more widely recently, can provide syntheses for determining future research priorities and allow the identification of problems that need to be corrected in future studies. However, as stated by Greener (2022) bibliometric analysis should include analysis and meaning beyond just focusing on facts.

In this regard, it can be mentioned that there are a few bibliometric studies on the use of Arduino in studies in the field of education. According to Lopez-Belmonte et al. (2020), these studies started in 2010, and Arduino is used more frequently in performing experiments, computational thinking, and computer-based learning. Sulimro et al.’s (2023) bibliometric analysis study on Arduino-based systems in digital learning environments for science and STEM teaching shows that such studies reached the highest frequency in 2021, and mostly associated keywords were e-learning, distance learning, low cost, Bluetooth, IoT, and STEM. The study by Pabuccu-Akis (2024), in which the bibliometric analysis of studies on the use of Arduino in STEM activities was carried out, reveals that the use of Arduino in STEM activities has great potential in the future and that the most cited authors and studies in this field are in the USA, but Turkey is the most productive country. One of the most common uses of Arduino in education is laboratory applications. However, as far as we know, there is no bibliometric analysis study in this sense in literature.

In this study, both bibliometric analysis and content analysis were conducted to better understand the current situation regarding studies using Arduino in teaching laboratories

(ATL), to predict the direction of future studies, and to shed light on researchers who want to work in this field. In this context, the research questions that guide this study are as follows:

1. What is the bibliometric profile of research on ATL?

   a. Which countries and institutions are leading contributors to ATL research?
   b. Who are the most productive authors in ATL research?
   c. Which journals are the primary publication outlets for ATL research?
   d. Which publications are the most highly cited in ATL research?
   e. What are the most frequently used keywords and the main thematic structures in ATL research?

2. What are the educational and application-related characteristics of ATL research?

   a. What are the applied domains in ATL research?
   b. For what purpose was Arduino used in ATL research?
   c. Who are the students at ATL research?

2. METHOD

2.1. Dataset Retrieval and Preprocessing

PRISMA 2020 guideline (Page et al., 2021) was followed in the study. Accordingly, identification, screening, and inclusion stages were carried out to create the data set. A descriptive search was conducted on the Web of Science Core Collection and Scopus databases on November 4, 2025. When searching using the Boolean expression ("Arduino" AND {"teach*" OR "learn*" OR "educ*"} AND {"lab" OR "laboratory"}) for the title, keywords, and abstract sections, a total of 1124 results (395 results from WoS and 729 results from Scopus) were found. During the screening phase, these results were examined according to the inclusion and exclusion criteria.

Among the results, the earliest publication year was 2010, which was later than 2005, the year in which Arduino's emergence, so no additional time restriction was applied. By selecting the publication type as only articles, the number of publications in the data set decreased to 432 (170 documents from Wos and 262 documents from Scopus). Studies written in English were then selected. This criterion was applied because the study aimed to examine the internationally accessible literature on ATL and to ensure linguistic consistency in the bibliometric and content analyses, particularly in the analysis of titles, abstracts, keywords, purposes of Arduino use, application domains, and participant groups. By choosing only English as the publication language, 404 results (159 documents from WoS and 245 documents from Scopus) remained in the data set.

We then combined this dataset using R and eliminated duplicate documents, leaving us with 262 documents. A total of 47 publications (that are out of scope of this research, i.e., publications that focused on machine learning, e.g., aiming to develop a soil phosphorus test using a low-cost spectrophotometer and a machine learning technique by Mayrink et al.(2022), or publications on developing only a device without mentioning its use in education/training, e.g., the study for development of a dip coating equipment for the production of thin films by Castillo-Vilcatoma et al. (2022), or publications comparing Arduino with other microprocessors, e.g., study by Martinez, Nieves and Rua (2021) comparing Arduino with Raspberry Pi 3, etc.) were removed from the data set as a result of this detailed review. Thus, 215 publications constituted the data set of this study. During the screening and eligibility assessment stages, the retrieved publications were evaluated according to predefined inclusion and exclusion criteria, as presented in Table 1. Figure 1 shows the PRISMA guideline we followed while creating the dataset.

Table 1. Inclusion and exclusion criteria used in the preparation of the dataset

Criterion	Inclusion Criteria	Exclusion Criteria
Database	Publications indexed in the Web of Science Core Collection and Scopus databases	Publications not indexed in either Web of Science Core Collection or Scopus
Search terms	Publications retrieved using the Boolean expression: ("Arduino" AND {"teach*" OR "learn*" OR "educ*"} AND {"lab" OR "laboratory"})	Publications not matching the specified Boolean search expression
Document type	Research articles	Publications other than articles, such as conference papers, reviews, book chapters, editorials, and other document types
Publication language	Publications written in English	Publications written in languages other than English
Relevance to educational/laboratory use of Arduino	Publications examining Arduino in relation to teaching, learning, education, training, or instructional laboratory practices	Publications using Arduino without an educational or training context

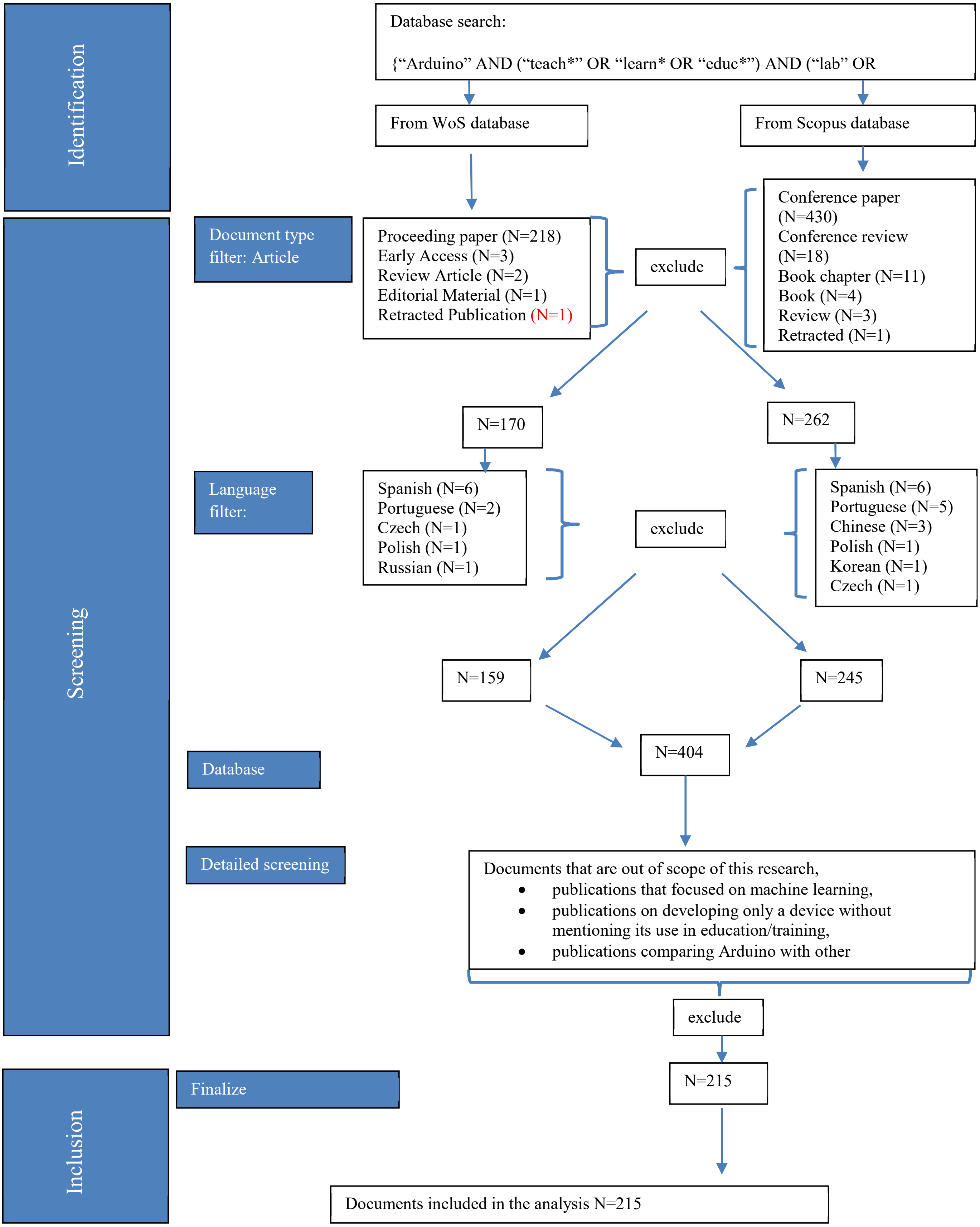


Figure 1.PRISMA guideline followed to obtain the data set

The studies that comprise the resulting data set were also subjected to a systematic review from Hsu et al. (2012) to answer research questions 7-9 with a more detailed examination. The review was conducted according to the technology-based learning model for the use of Arduino in the teaching laboratory, as shown in Figure 2. For this purpose, 215 studies that make up the data set were examined according to the following coding scheme:

- Domain: In which lab scope is the study carried out (chemistry, physics, biology, engineering, etc.)

- Objective: The purpose of use of Arduino in the study (deploying an experimental setup/device, regular distribution/device development, programming/coding teaching, beginning of remote laboratory application, disseminating its effectiveness on teaching by using a ready-made kit, etc.)

- Learners: Who are the learners/potential learners in the study (high school students, college students)

The content analysis was carried out separately by two researchers. First, the abstracts (full texts if necessary) of the studies constituting the data set were read and codes were created. Then, these codes were compared, and the reliability of the study was checked by calculating the inter coder agreement according to the Miles, Hubermann and Saldana (2014)'s criterion which states a consistency value of 0.70 is acceptable. The agreement percentages calculated for the domain, objective and learners were calculated as 0.99, 0.95 and 0.99, respectively.

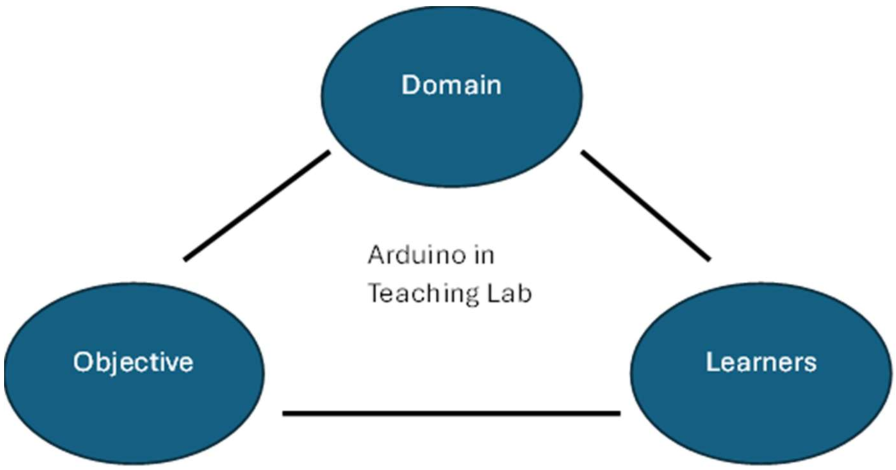


Figure 2. Technology-based learning model for using Arduino in teaching lab

3. FINDINGS

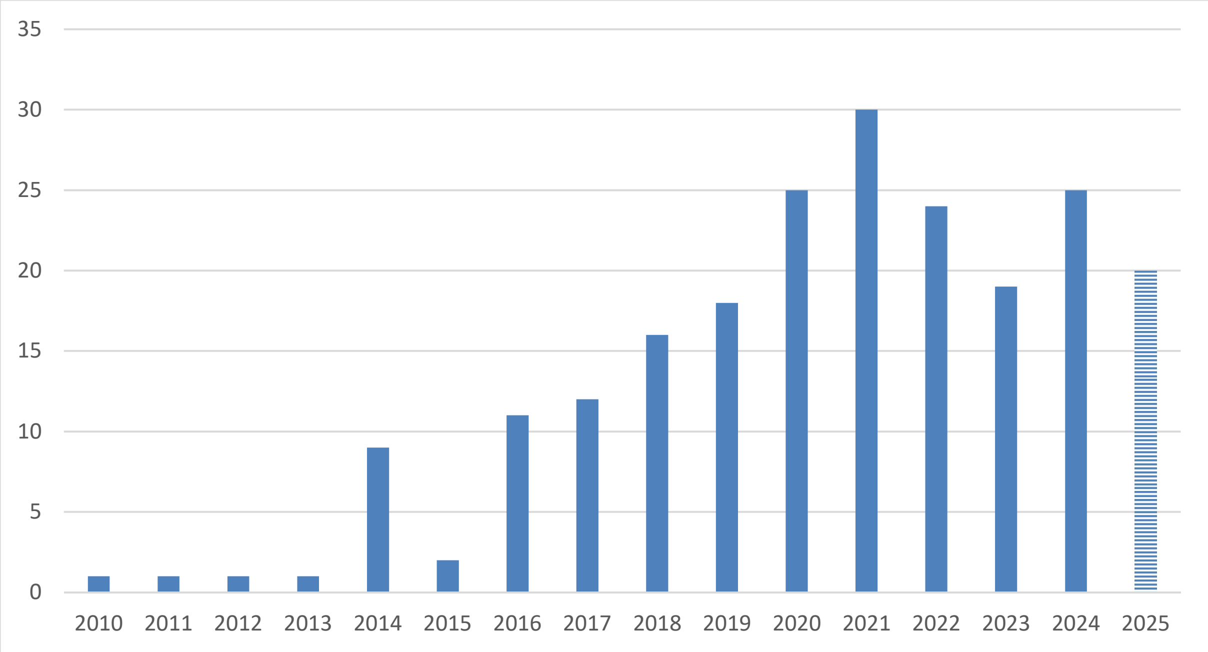
3.1. Overview of the dataset

Figure 3. Overview of analyzed studies

Figure 3 shows that the data set used in this bibliometric analysis study includes 215 studies from 98 sources. The average annual growth rate of studies is 22.11%, the average document age is 4.5, and the number of citations per document is 9.94. Accordingly, using Arduino in teaching laboratories is a relatively new study subject that attracts academic interest and has high growth potential. It is understood that the studies were largely conducted by multiple authors, and the average number of authors per study was 3.69.

3.2. Research productivity

The number of studies on using Arduino in teaching laboratories over the years is shown in Figure 4. It is seen that research was in a rapidly increasing trend between 2010, when the publications started, and 2021, and a tendency to partially decrease after 2021. It is thought that this situation may be related to the COVID-19 pandemic, which affected the whole world in 2020. The study conducted by Johnson et al. (2021) on the COVID-19 experience of academia confirms this thought. According to the results of the research, participants (362 academics) think that the biggest negative impact of COVID-19 on academic science is the disruptions in lab studies (71%). It should also be noted that the data set for this study was obtained in November 2025, and therefore, the values for 2025 should not be considered for whole year.



*It should be noted that the figure does not show all of the 2025 data. since the study was conducted in November 2025

Figure 4. Number of studies by years

3.3. Leading countries

As can be seen from Table 2, the country that produces the most publications on the subject is the USA (N = 93). Then come Spain (N=44) and Canada (N=22). Another important point is that although Germany is ranked 10th in the list regarding the number of publications, it is at the top of the list regarding the average number of citations per publications. In this case, it can be evaluated that the most effective publications were made in Germany. Moreover, while the first publications on ATL research in the USA were published in 2013, the first in Spain were in 2011 and Canada in 2010. In this case, it can be stated that Canada is the country where pioneering publications on ATL research were developed (the first publication was in 2010). The start date of publications in Italy, where Arduino was implemented as a project work (at Interaction Design Institute Ivrea), is 2014. In addition, although the publications in India started later than other countries (in 2020), it made a fast start and is ranked 6th on the list. In Figure 5, drawn using the Biblioshiny software, leading countries are shown in darker colors on the map.

Table 2. Leading countries

Country	TP	TC	AAC	Year of the first ever publication
USA	93	527	17.6	2013
Spain	44	237	12.5	2011
Canada	22	99	14.1	2010
Romania	22	90	9.0	2014
United Kingdom	22	61	15.2	2017
India	21	57	5.7	2020
Italy	21	24	2.7	2014
Brazil	20	36	4.0	2015
China	19	110	13.8	2016
Germany	16	122	30.5	2016

**TP: Total Production TC: Total Citations AAC: Average Article Citation*

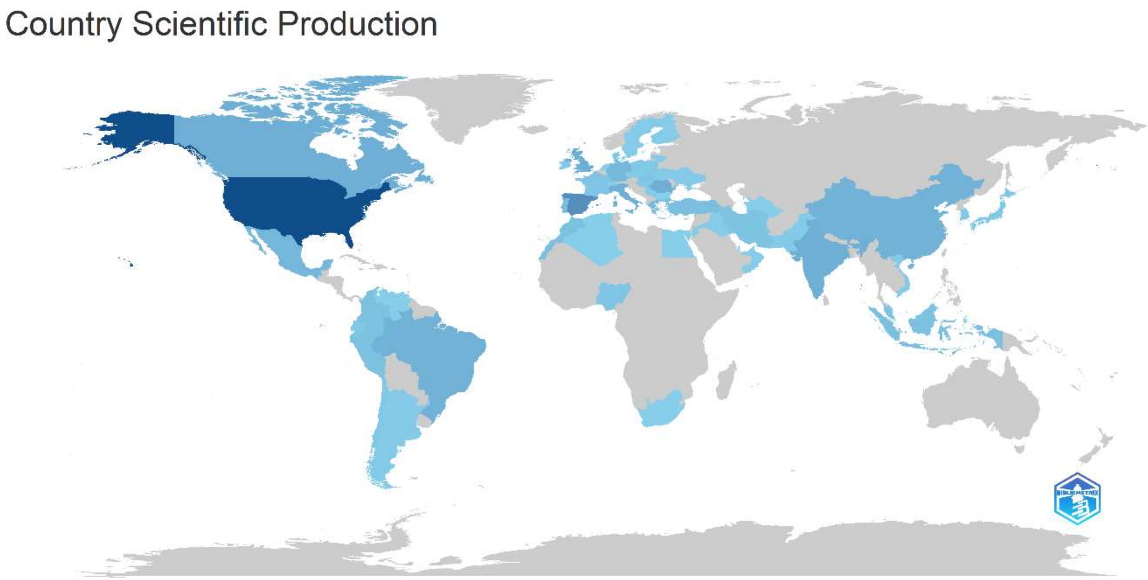


Figure 5. Leading countries

Cooperation networks between countries are seen in Figure 6. In this figure, collaborations between countries are shown in different colors and the lines become thicker as the number of collaborations increases. Accordingly, the USA and the UK are the countries that cooperate most among countries. USA has broadcast collaborations with Spain, Turkey, Italy and the United Kingdom, and the UK with Finland, Germany, India, Italy, Pakistan, Sweeden and Brunei.

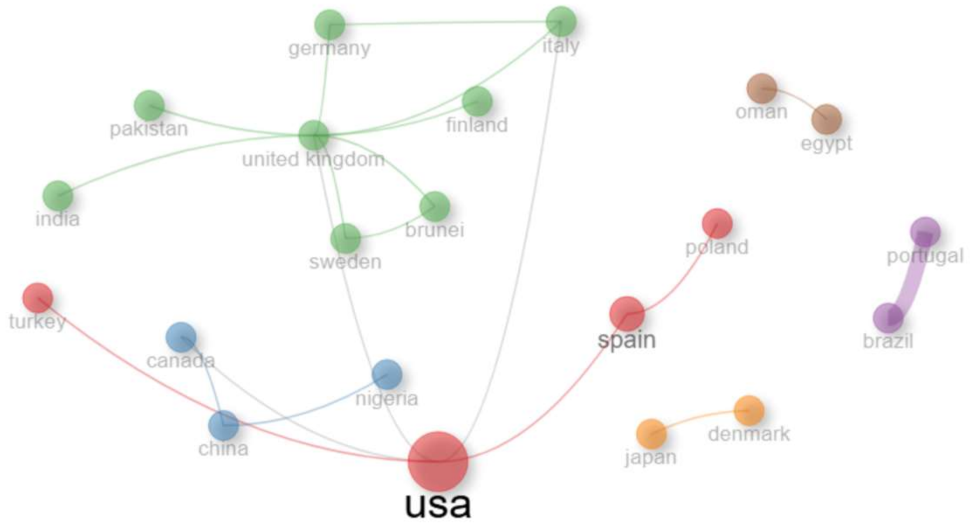


Figure 6. Country collaboration map

3.4. Most prolific authors

Lotka's Law (Lotka, 1926), which shows the frequency distribution of scientific productivity among authors, suggests that the number of authors with a given number of publications follows an inverse square distribution. It states that a small number of authors publish the majority of publications, and a large number of authors publish fewer publications. In this study, author productivity was also evaluated using Lotka's Law, and the finding is shown in Figure 7 (drawn with Biblioshiny software). As can be seen, the interest of authors in this field is mostly aligned with the real Lotka curve. Accordingly, 683 authors (93.1% of the authors) published only one publication. Forty-three authors (5.9% of the authors) have two publications, seven authors (1.0% of the authors) have three publications and only one author (0.1% of authors) has four publications.

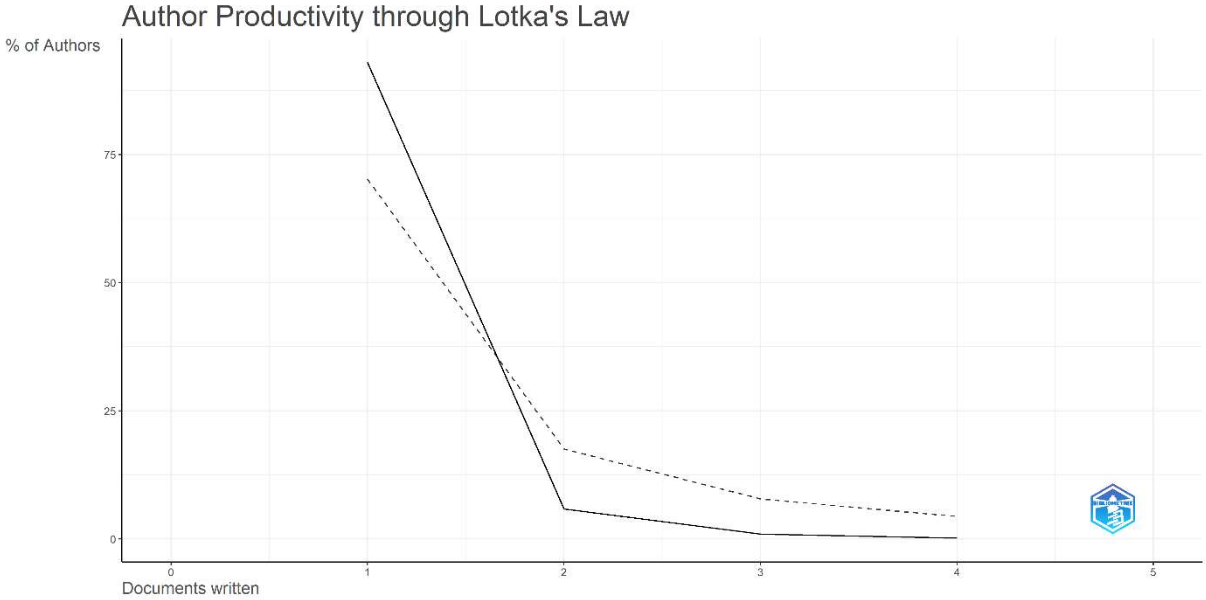


Figure 7. Author productivity according to Lotka's Law

Table 3 shows the most productive authors. This table is limited to eight authors because, among the 683 authors, only one has published four, seven have published three, and the number of authors who have published two is 43. Therefore, it was deemed appropriate to limit this table to eight. The most productive author among these is Calin Galleriu. Galleriu published the first of his four publications in 2013 while at Becker College (US), describing an Arduino-controlled photogate. The author stated that Arduino allows for the acquisition of such physics equipment at a low cost and is ideal for STEM projects. Other publications by the author, published in 2014, 2018, and 2023, demonstrate his work on developing and using Arduino-powered equipment used in physics laboratories at lower costs. The author generally published alone (three of the four publications). According to Table 3, the authors ranked with three publications, Ciganek, J., Drahos, P., Haffner, O., and Kucera, E., were found to have co-authored all their publications. These authors published all three of their publications consecutively in the same year (2020). The other author on the list (with three publications) is Sadegh-Cheri, M. This author published his publications intermittently (between 2019-2020-2022) as a single author each. Morais and Pinto, the other authors with three publications, published their publications as multi-authors. Figure 8 shows the distribution of publications by the most productive authors by year, with more articles indicated by the size of the circles. This author's productivity can be better understood when considering that only 29 of the total publications were single-authored, three of which were authored by Sadegh-Cheri. It is noteworthy that four of the eight most productive authors were co-authors on the same publications.

Table 3. Most prolific authors

Author	# of publications	Institution	Country	h-index
Galeriu, C	4	Mark Twain Internatioal School	Romania	5
Ciganek, J	3	Slovak University of Technology in Bratislava	Slovakia	6
Drahos, P	3	Slovak University of Technology in Bratislava	Slovakia	7
Haffner, O	3	Slovak University of Technology in Bratislava	Slovakia	8
Kucera, E.	3	Slovak University of Technology in Bratislava	Slovakia	9
Morais, C	3	Faculty of Sciences, University of Porto	Portugal	9
Pinto, C	3	Technical University of Munich	Germany	47
Sadegh-Cheri, M	3	Graduate University of Advanced Technology	Iran	8

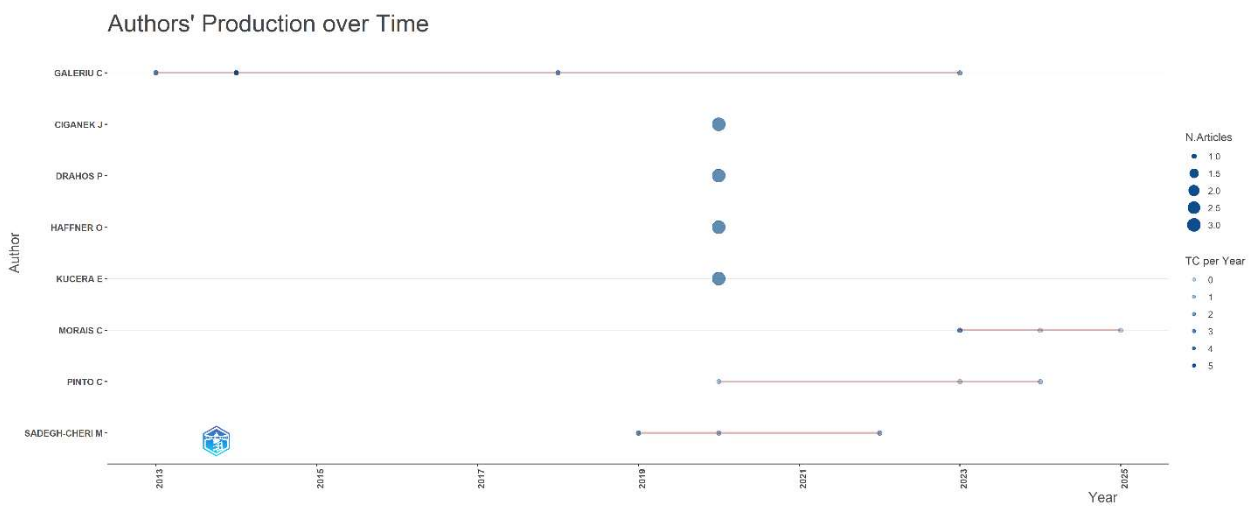


Figure 8. Most productive authors' production over time

It's noteworthy that some of the most productive authors' countries (namely Romania and Germany) are not at the top of the list of leading countries, and some (Slovakia, Portugal, and Iran) are not even listed (in the top 10). To understand why, the dataset were carefully reexamined. It is found that two of the four publications of Galeriu, the most productive author, were from the US (the top 10), while the other two were from Romania. It is also found that there are seven authors from Slovakia in the dataset: four of them have three publications each, two have two publications each, and one has one publication (a total of three publications from Slovakia, most of which are co-authors of the same publications). Similarly, in Iran, the country of the other author on the most productive author list, one of the six authors (the author on the most productive author list, Sadegh-Cheri M.) has three publications, and the other five authors have one publication. In contrast, in the United States, which ranks first on the list of leading countries, each of the 96 authors who published 93 articles (in the ATL survey that forms the dataset for this study) was found to have only one publication. According to the author collaboration network shown in Figure 9, collaboration is strongest among the authors with the most publications on the topic (Cigarek, Drahos, Haffner, and Kucera). However, five smaller and larger collaboration clusters stand out.

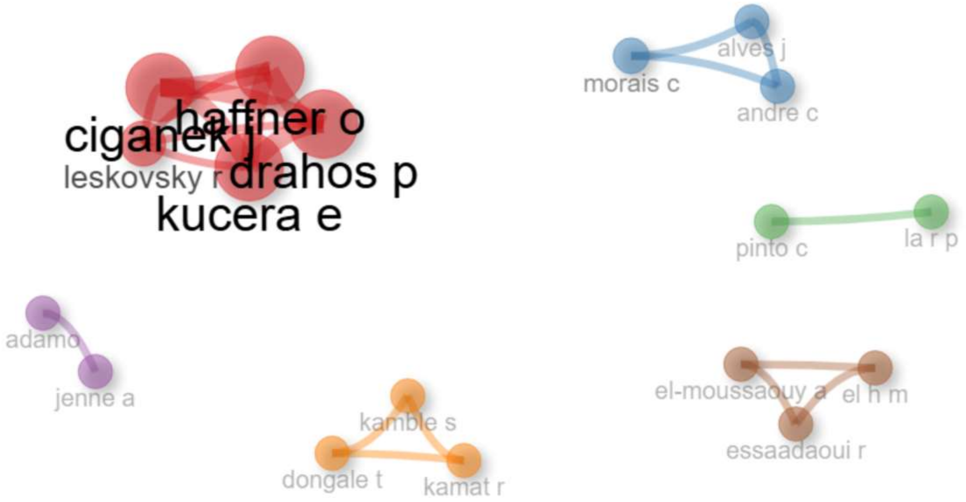


Figure 9. Collaboration between authors

3.5. Leading institutions

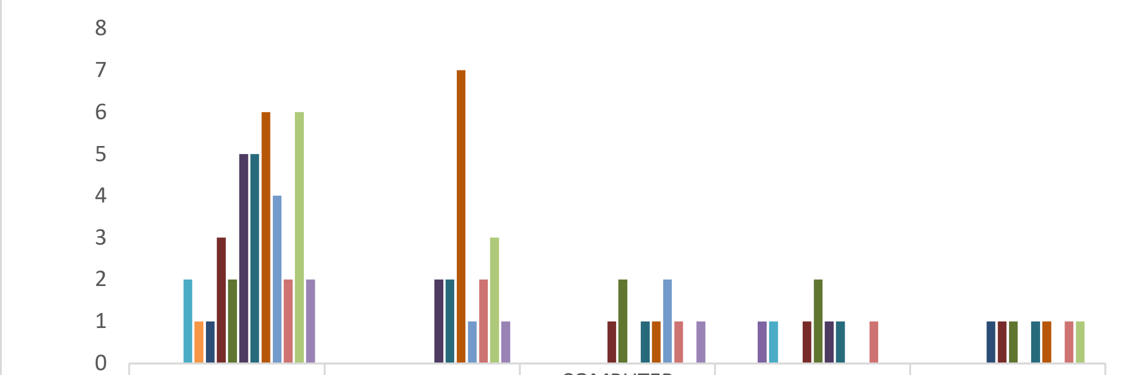
A list of leading institutions publishing in ATL research can be seen in Table 4. This list and its institutions appear to be consistent with the list of most productive countries. However, it is noteworthy that no institution from Canada, which was the country where the first publications in ATL research were published and topped the list of most productive countries, is included in this list. It is also noteworthy that Morocco and Peru, which are neither among the countries with the most productive authors nor among the countries with the most publications, are included in this list. This striking finding is likely because researchers at these research institutions are based in different countries for research/education and/or collaborate with research institutions from different countries.

Table 4. Leading institutions

Institution	# of publications (% of total publications)	Institution's location	Institution's productivity by years
University of Bucharest	10 (%1.81)	Bucharest, Romain	2019 (N=8) 2020 (N=2)
University of Michigan	10 (%1.81)	Ann Arbor, MI, USA	2016 (N=5) 2021(N=5)
Sultan Moulay Slimane University of Beni Mellal	7 (%1.27)	Beni Mellal, Morocco	2016 (N=2) 2019 (N=3) 2022 (N=2)
Univ Tubingen	7 (%1.27)	Tubingen, Germany	2017 (N=7)
Kerman Grad Univ Adv Technol	6 (%1.09)	Kerman, Iran	2019 (N=2) 2020 (N=2) 2022 (N=2)
Slovak Univ Technol Bratislava	6 (%1.09)	Bratislava, Slovakia	2020 (N=6)
Univ Nacl Ingn	6 (%1.09)	Lima, Peru	2021 (N=2) 2022 (N=4)
Univ Politecn Madrid	6 (%1.09)	Madrid, Spain	2011 (N=2) 2018 (N=4)

3.6. Most influential journals

The journals with the most publications on ATL research are shown in Figure 10. These journals also account for over one-third (37.7%) of the total publications in the analyzed dataset (N=215). Specifically, when evaluated in terms of both the number of publications and the frequency of publication dates, Journal of Chemical Education appears to be the most influential journal. Sadegh-Cheri, one of the most prolific authors, has published three of his publications in Journal of Chemical Education, while Morais has published two of his three publications in this journal. However, Galeriu, the most prolific author, has published three of his four publications in the fourth most influential journal, Physics Teacher.



	JOURNAL OF CHEMICAL EDUCATION	PHYSICS EDUCATION	COMPUTER APPLICATIONS IN ENGINEERING EDUCATION	PHYSICS TEACHER	AMERICAN JOURNAL OF PHYSICS
2010	0	0	0	0	0
2011	0	0	0	0	0
2012	0	0	0	0	0
2013	0	0	0	1	0
2014	2	0	0	1	0
2015	1	0	0	0	0
2016	1	0	0	0	1
2017	3	0	1	1	1
2018	2	0	2	2	1
2019	5	2	0	1	0
2020	5	2	1	1	1
2021	6	7	1	0	1
2022	4	1	2	0	0
2023	2	2	1	1	1
2024	6	3	0	0	1
2025	2	1	1	0	0

Figure 10. Number of publications by year

Bradford's law describes the distribution of scientific literature across journals. Accordingly, a small number of journals within a given field account for the majority of research output, while a larger number of journals accounts for a smaller proportion (Bradford, 1985). Figure 11 (drawn with Biblioshiny) shows the main sources of ATL research according to Bradford's law. Accordingly, Journal of Chemical Education (local H-index: 14, total citations: 657), Physics Education (local H-index = 4, total citations: 65), Computer Applications in Engineering Education (local H-index = 6, local citations = 117), and Physics Teacher (local H-index = 6, local citations = 147) are the main sources of ATL research.

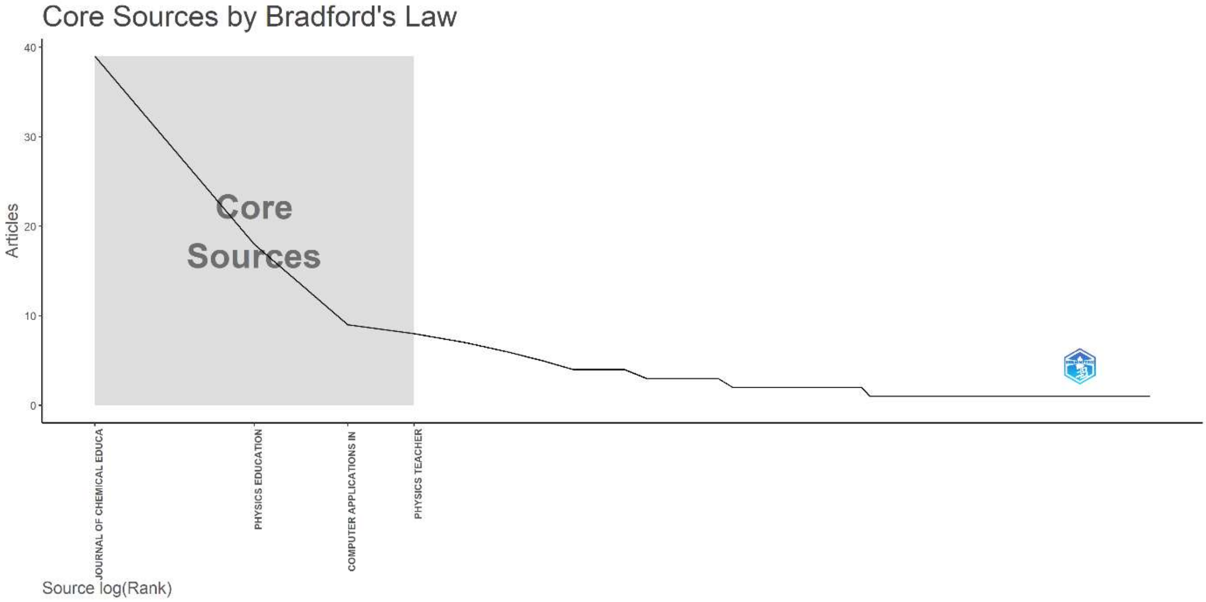


Figure 11. Basic sources of ATL research

3.7. Most cited publications

Table 5 lists the five most cited publications related to ATL research. The most cited study is Chagas et al. (2017), which describes a design incorporating Arduino-based optical and thermal cameras for use in neurogenetic studies. The researchers noted that this design is used both as a medical diagnostic tool and as a teaching material in neurogenetics courses offered at various African universities. Interestingly, Chagas et al.'s (2017) study appears to have received only one citation from the publications comprising this study's dataset. However, the second-placed study by Grinias et al. (2016) received 15 citations, and the fourth-placed study by Kubinova and Slegr (2015) also received 15 citations. A common feature of both studies is that they were published in the Journal of Chemical Education, which ranks first on the list of most influential journals.

Table 5. Most popular publications

Title	Author/s	Journal	PY	GC	LC
The (sic)100 lab: A 3D-printable open-source platform for fluorescence microscopy, optogenetics, and accurate temperature control during behaviour of zebrafish, Drosophila, and Caenorhabditis elegans	Chagas, A.M., Prieto-Godino,L.L., Arrenberg, A.B., Baden, T.	PLOS BIOLOGY	2017	114	1
An Inexpensive, Open-Source USB Arduino Data Acquisition Device for Chemical Instrumentation	Grinias, J.P., Whitfield, J.T., Guetschow, E.D., Kennedy, R.T.	JOURNAL OF CHEMICAL EDUCATION	2016	93	15
Arduino-A1: Low-Cost Educational Mobile Robot Based on Android and Arduino	López-Rodríguez, F.M., Cuesta, F.	J INTELL ROBOT SYST	2016	75	1
ChemDuino: Adapting Arduino for Low-Cost Chemical Measurements in Lecture and Laboratory	Kubinova, S., Slegr, J.	JOURNAL OF CHEMICAL EDUCATION	2015	72	15
Theorizing the nexus of STEAM practice	Peppler, K., Wohlwend, K.	ARTS EDUCATION POLICY REVIEW	2017	64	0

*PC: Publication year GC: Global Citation LC: Local Citation

3.8. Most frequently used keywords

Figure 12 shows a word cloud where the font size of the word is an indicator of the word's frequency of use. The cloud is plotted with the most frequently used keywords. Accordingly, Arduino, applied learning/manipulatives, laboratory equipment/devices, postgraduate studies, computer-based learning, laboratory training, and analytical chemistry were used as keywords in most studies. An examination of the frequency distribution of words over time (shown in Figure 13) reveals that the word "Arduino" has seen an accelerated increase since 2015. Additionally, "applied learning" and "laboratory equipment" have been the most frequently used keywords, particularly in recent years.

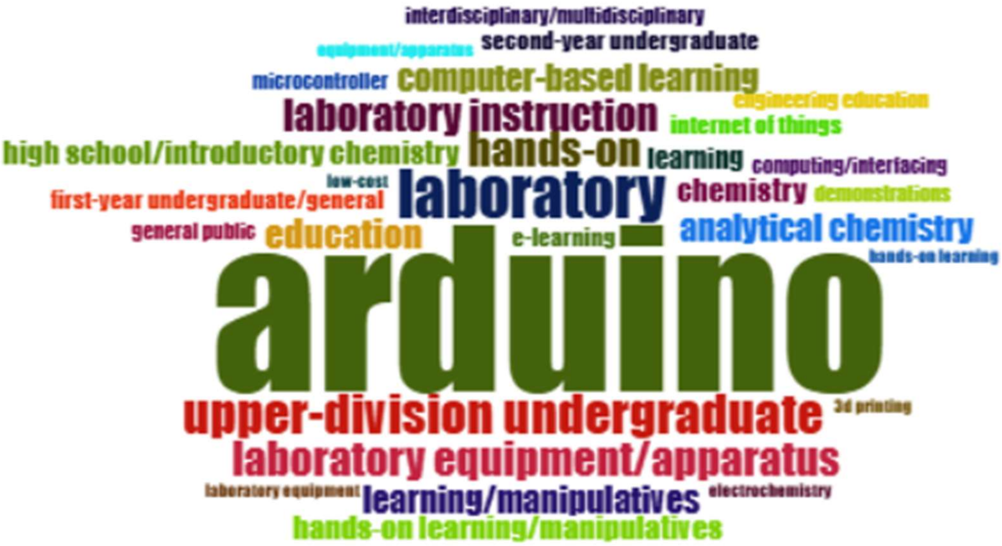


Figure 12. Word cloud of most frequently used author keywords

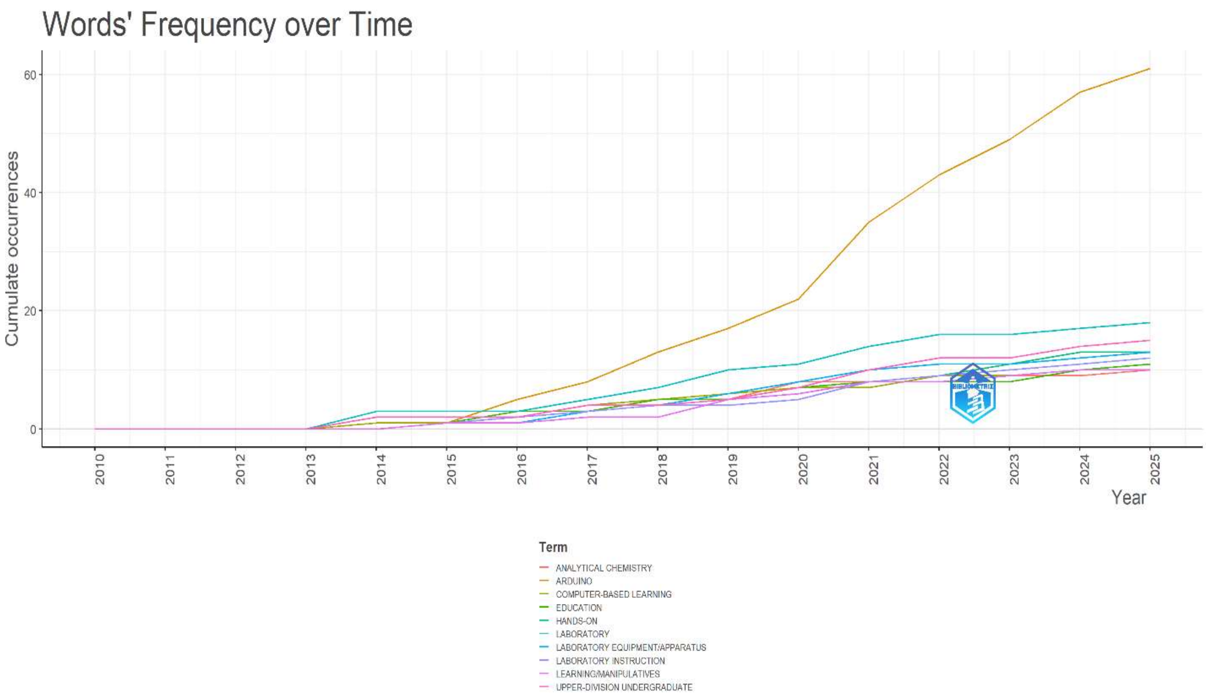


Figure 13. Frequency distribution of author keywords over time

The trend topic map shown in Figure 14 was created by focusing on the three most frequently occurring keywords for each year, appearing at least five times. Accordingly, the keyword "engineering education" was one of the three most frequently occurring keywords each year between 2017 and 2024. Similarly, "curricula", an author keyword that managed to become a trending topic between 2016 and 2023, appears to be the second longest trending keyword. Furthermore, for 2024, the last full year in this study's dataset, the trending topics were "engineering education," "remote lab," "design," "low-cost," "3D printing," and "chemistry."

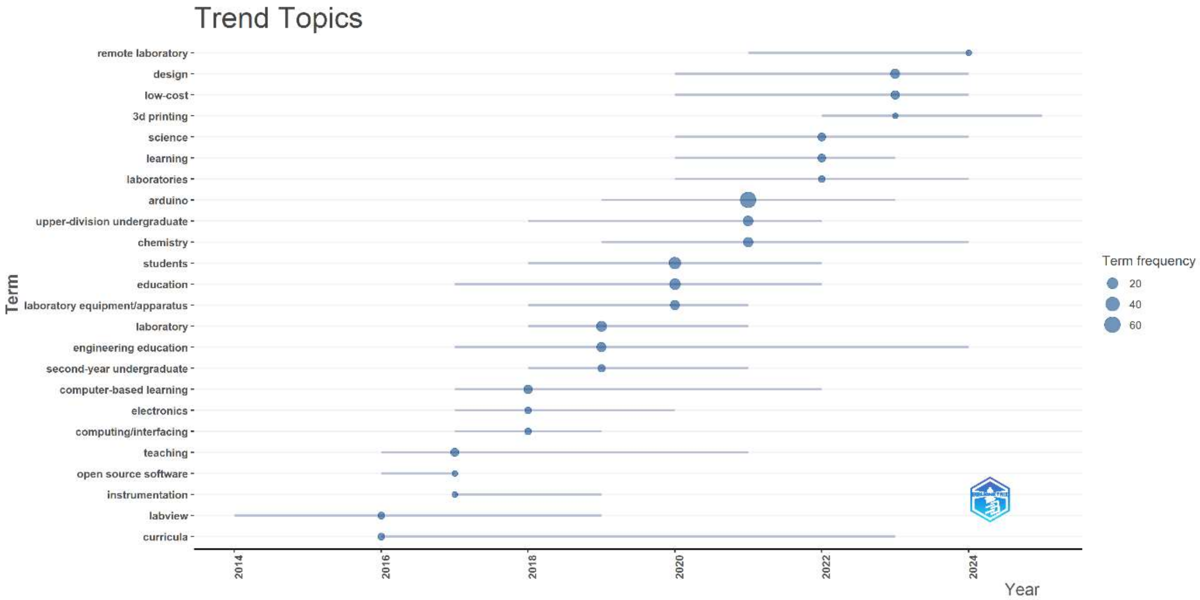


Figure 14. Trend topics (by using author keywords)

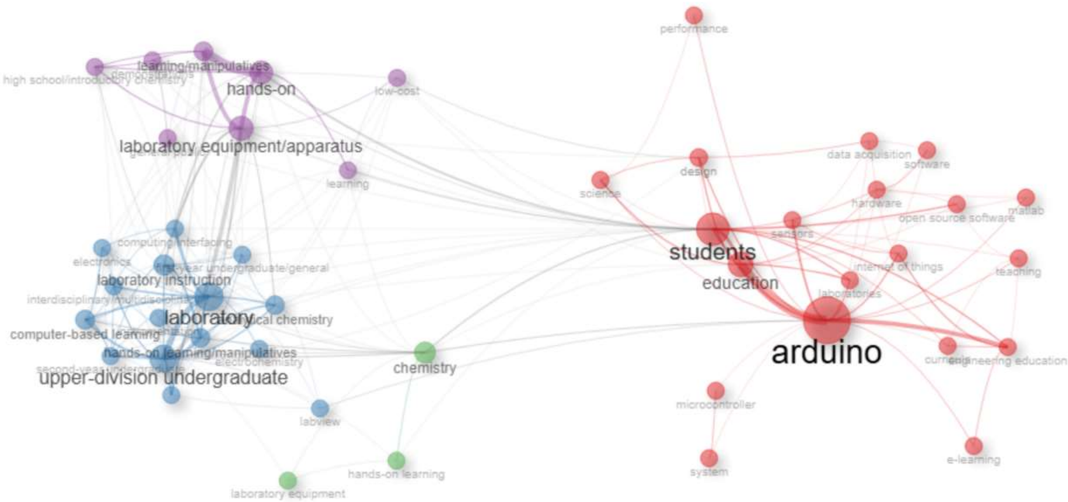


Figure 15. Co-occurrence network

When the co-occurrence network in Figure 15 is examined, it is seen that the co-occurring keywords are grouped into four islands. The words "low-cost", "learning" and "chemistry" stand out as the keywords that provide connections between these four islands.

3.9. Domains in ATL research

It is seen from Figure 16 that most of the research was carried out in the engineering laboratory (N = 81). This is followed by research in the physics lab (N=54) and chemistry lab (N=43). Interestingly, the number of research conducted in the biology laboratory (N=3) is quite limited compared to others/unspecified (e.g. control systems lab., process control lab. etc.).

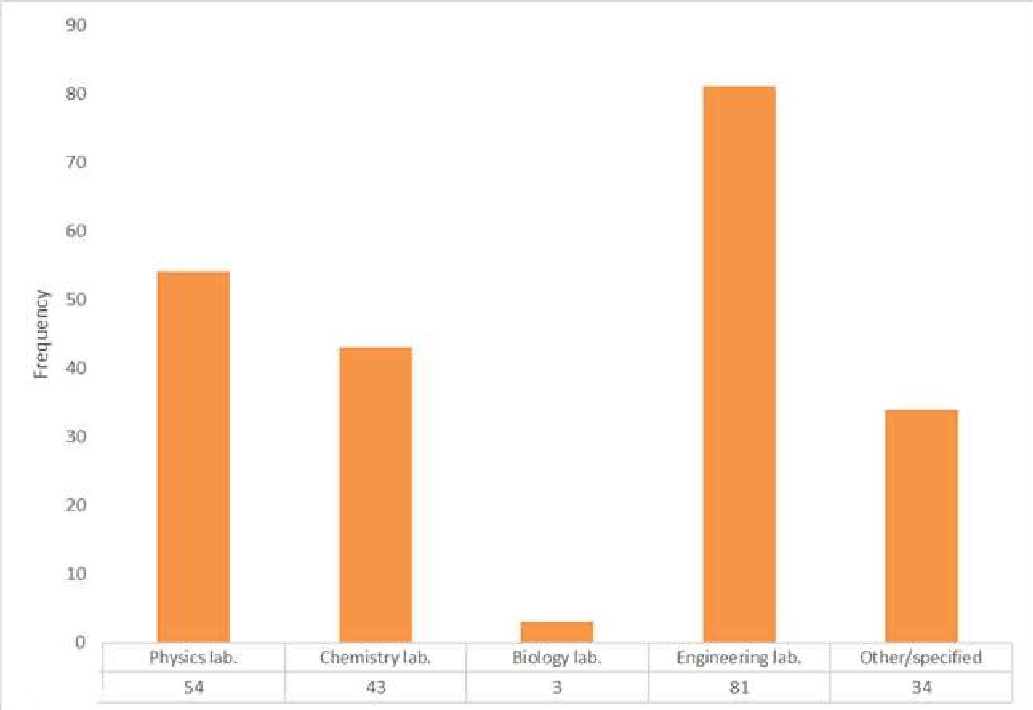


Figure 16. Domains in ATL research

3.10. Objectives of using Arduino in ATL research

The studies determined that the majority of the Arduino's purpose of use (57.7% of all studies in the data set) was to develop laboratory devices/mechanisms. For example, the study of Qutieshat, Aouididi and Arfaoui (2019), in which they describe the construction of a simple and low-cost Arduino-based pH sensor that can be used by visually impaired students, or the study of Zachariadou, Yiasemides and Trougkakos (2012), in which they describe the development and application of a device called SolarInsight to explain the basic principles of photovoltaic cells, were evaluated in this context. It is followed by the aim of teaching programming/coding/electronics to students. For example, the study of Tselegkaridis, Sapounidis and Papakostas (2024), who used Arduino to teach circuits and coding, was evaluated in this context. The fewest studies examine the effect of Arduino use on various learning parameters, e.g. acquisition of declarative knowledge, creating interest to physics, integrating STEM activities (see Figure 17).

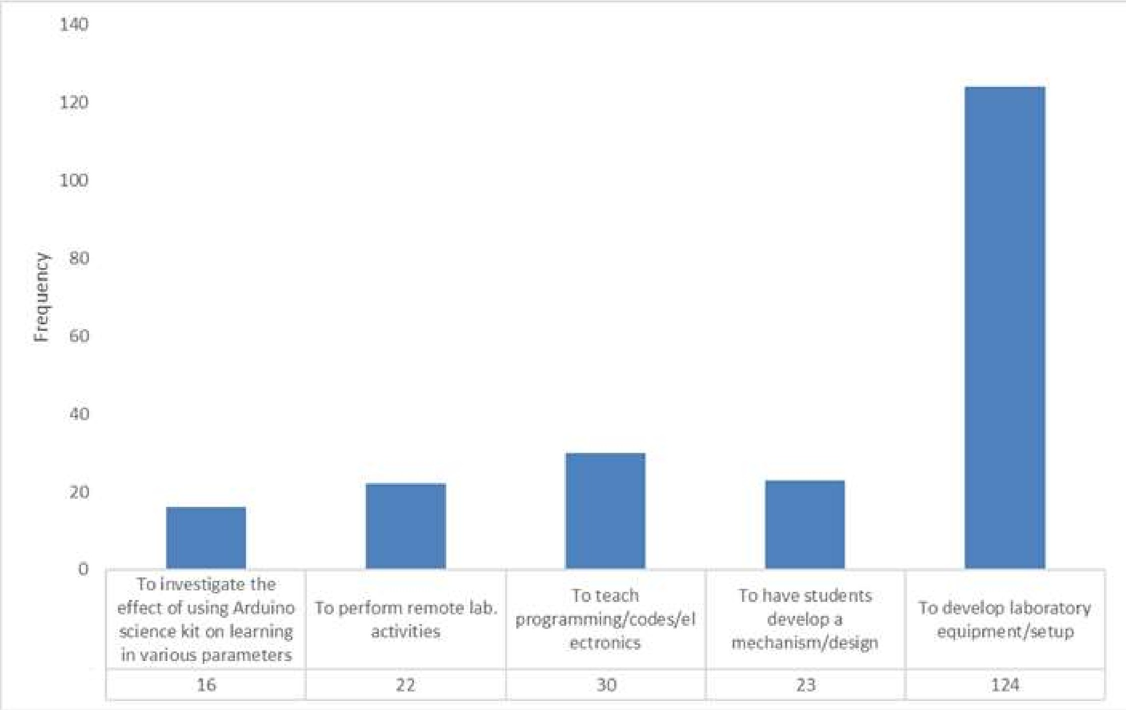


Figure 17. The objective of using Arduino in ATL research

3.11. Learners in ATL research

It is seen from Figure 18 that the largest student group in the studies is university/college students (68.8%). The least number of studies was conducted on secondary school students (2.33%).

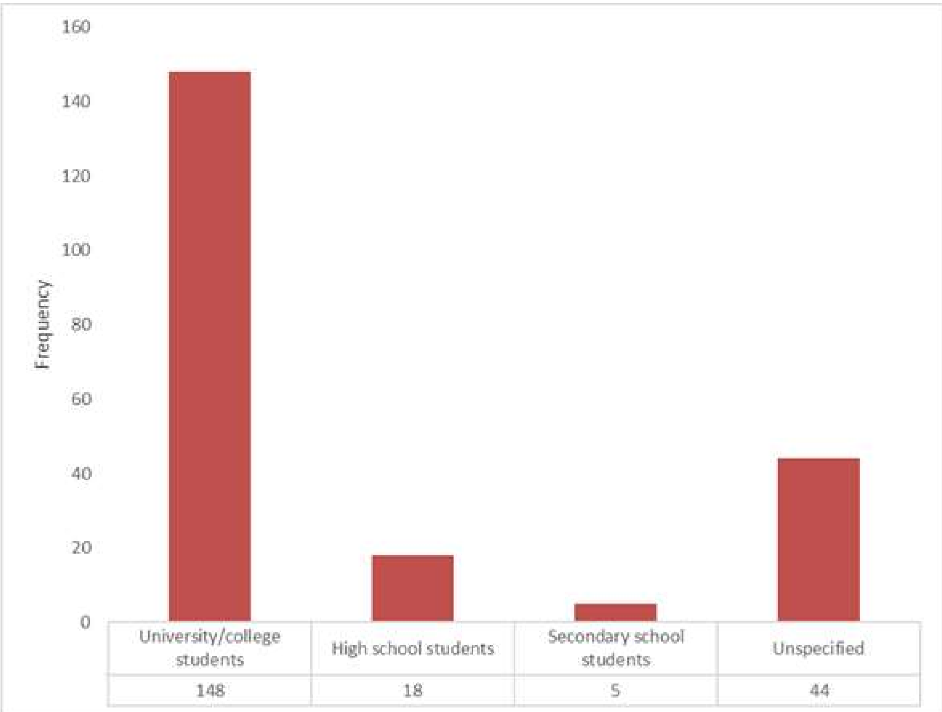


Figure 18. Learners in ATL research

4. CONCLUSION

Arduino, which emerged as a project (Arduino, n.d.) in Italy in 2005 as an alternative to the fact that existing microcontroller cards were difficult and complex and could only be used by engineers, has a simple-to-use structure and appeals to people from all walks of life. There is no need for advanced-level electronics or coding knowledge to use Arduino. Moreover, its open-source code contributes to its widespread use (Arduino, n.d.). In this way, it is possible to develop new projects easily. Although laboratories are seen as an indisputable necessity by scientists in the teaching process, especially the high costs (for both consumables and equipment/hardware) are seen as a reason to question the place of laboratory use in the teaching process, and studies on this subject are encouraged (Hofstein and Lunetta, 2004; Bretz, 2019). At this point, Arduino seems to offer an important opportunity. Because with Arduino, it is possible to design devices and equipment that can be used in the laboratory and the teaching process at lower costs. In this study, it is decided to carry out this bibliometric analysis study to contribute to other researchers by examining the studies in literature. Bibliometric analysis enables studies in literature to be examined systematically and sheds light on how researchers can conduct better research by enabling them to see the studies, trends, and deficiencies in the field (Aria and Cuccurullo, 2017).

From the findings of this study, it is understood that studies on Arduino in teaching laboratories (ATL research) started with a study published by a researcher from Canada in 2010. In this publication (Michal, 2010), which came five years after the emergence of Arduino as a project, the subject is the development of a spectrophotometer that can perform nuclear magnetic resonance (NMR) measurements in the Earth's magnetic field using Arduino microcontroller boards. The study, which mentions that this spectrophotometer was developed at a very low cost (approximately $200) and has an advantageous use due to its easy portability, was published in the journal Measurement Science and Technology. Although it is a pioneer publication, Michal's (2010) study is not the most cited publication. The reason why it is not at the top of the list may be the source of the publication. Because this journal is not among the influential journals in the field, it is even included only once in the data set.

Lopez-Belmonte et al. (2020), who examined the publications on using Arduino in education, also stated that the publications started in 2010 and were mostly related to physical experiments, computational thinking, and computer-based learning. It is observed that the number of publications on ATL research increased rapidly until 2020 and remained at a certain amount after that. However, it should be considered that the data for this study was obtained in November 2025. It is thought that the pause after 2020 may be related to COVID-19. The pandemic has forced the transition from face-to-face education to compulsory distance education for a year (in some countries, a second year). It is thought that this situation may cause the work to be interrupted. It should be remembered that due to the compulsory distance education of students during the pandemic, the data collection processes of researchers were also disrupted and therefore the trend slowed down. The findings of the study conducted by Johnson et al. (2021), in which academics stated that the most important problem experienced during the pandemic was the disruptions in the data collection process, also support our belief.

Many schools and universities have tried to somehow transform their laboratory processes into distance learning during the pandemic. As can be seen from Kelley's (2021) review of studies examining how laboratory practices were carried out during the COVID-19, students were mostly asked to watch pre-recorded experiment videos or perform experiments that could be done at home. However, it seems that the pandemic also reveals the need for such studies and laboratory applications that can be managed remotely. In their bibliometric analysis study published in 2016 by Heradio et al. (2016), in which they examined studies on remote and virtual labs, they stated that these studies were on an increasing trend. As a result of this study, by examining the studies that constitute the data set qualitatively, it was revealed that one of the purposes of using Arduino in the laboratory (third place) is to perform lab activities remotely. For example, in the study of Cvjetkovic and Stankovic (2017), it is explained how Arduino can be used to remotely operate the laboratory and three examples are presented for physics and engineering laboratories (remote use of various sensors and actuators, remote investigation of linear analog systems of the 1^{st} to 5^{th} order, and remote measurement of voltage/current characteristics of solar panels). Another study conducted by Furlong and Pegg (2023) investigated the design and operation of heat exchanger platforms that can be operated remotely or in person. A design that included flow measurement and control, flow reversal, and temperature measurement was implemented for the heat exchanger and this design was used to perform lab activities remotely during COVID-19. Following the COVID-19 pandemic, the same design was used face-to-face by students. As a result, it was understood that there was no difference between student performances (examined as conceptual knowledge) for both face-to-face and remote use of the design. The researchers emphasized that remote access can easily be used in situations such as space constraints and health problems and also enables more efficient operation (with good scheduling, even when the lab is not open) during non-compulsory times. As a result of the trend topic analysis carried out with the author keywords, the keywords "engineering education", "remote lab", "design", "low-cost", "3d-printing" and "chemistry" appeared to be the trend topics of the year 2024 (the last full year within the data set of this study).

It is understood that the ATL studies examined in this study were largely conducted by multiple authors (average number of authors: 3.69). Only 29 of the 215 documents are single-authored studies. Although the USA produced the largest number of publications on ATL research (N=93), It is noteworthy that Germany is at the top of the list in the evaluation made by considering the number of citations per article. The University of Michigan, which ranks first on the list of the most effective institutions, and the University of Tubingen, which ranks second, confirm these findings.

When a detailed examination was conducted, it was seen that there was no harmony between the most productive authors and the leading countries. While the United States, the country with the most publications, doesn't rank high on the list of countries with the most profilic authors, the only author with four publications in this field is from Romania. However, the researcher's career reveals that two of his publications on this topic occurred while he was in the United States (at Becker College, presumably as a visiting scholar) and two while working at an institute in his country (Mark Twain Int.Sch). Slovak authors, who rank second on the list of most productive authors and have a total of three publications, are co-authors on all three. This means that if each had published separately, there would have been 12 publications, and the number of publications in Slovakia would have increased from 3 to 15. Therefore, while it's natural to expect the list of most productive authors and leading countries to be consistent, it's important to consider that the number of published authors and the number of publications they have on the topic are also important.

The most cited publication is Chagas et al. (2017), in which a design with Arduino-based optical and thermal cameras was developed for use in neurogenetic studies, and this design was used both for medical diagnoses and as teaching material in neurogenetic courses held in various African universities. Interestingly, although this study has the highest global citation, the number of local citations is extremely low (1 citation). This may be because the journal in which the publication was published, Plos Biology, is not among the influential journals in ATL research. This journal is included only once in the data set. Another interesting finding is that none of the authors of the most cited studies are among the most productive authors. However, this is understandable, considering that the publications of the most productive authors were in the last years. In addition, two of the five most cited publications were published in the Journal of Chemical Education, considered the most influential journal on ATL research (evaluated in terms of number of publications). Moreover, these publications have the highest local citation numbers. Therefore, it should be stated that in addition to making a pioneering publication in the field and being the most productive author, choosing the journal in which the publication is made is also critical for researchers.

The second most cited publication is the study by Grinias et al. (2016), which describes the development of an open-source USB data acquisition device built using Arduino Uno and its use in a research laboratory for gas chromatography and capillary electrophoresis-UV separation. Although the number of global citations of this work is the second in the list, it can be said that this work is a good reference for ATL researchers when the number of local citations is taken into account. This is possibly due to the fact that this work touches on the basic points that will be essential for almost all ATL research (collection of various data via a USB using Arduino, processing of data using Python). The third most cited study was published in the Journal of Intelligent Robot Systems in 2016 by López-Rodríguez, F.M., and Cuesta, F. This study, which describes the development and educational use of a low-cost Android and Arduino-based mobile robot, has only one local citation. The fourth most cited publication by Kubinova and Slegr (2015) describe a device (ChemDuino) that was developed using Arduino, both as a demonstration measurement device, as a computer interface, and as a basis for students to make measurements. This study, like the study by Grinias, Whitfield, Guetschow, and Kennedy, ranks first in terms of local citations. It's important to note that the journal in which both highly cited studies were published (Journal of Chemical Education) is ranked first on the list of most influential journals. Therefore, it's important to emphasize that the publication location is a key factor in the study's increased citation count.

In this study, ATL research was also examined in terms of the domains where the studies were carried out, the objective of using Arduino in the study, and learners/potential learners in the study. The studies were mostly carried out in the engineering laboratory (N = 81), followed by the physics laboratory (N = 54) and chemistry laboratory (N = 43), and Arduino was mostly used (57.7% of all studies in the data set) to develop laboratory devices/equipment. It was found that the learners in the majority of the studies were university/college students (68.8%). It is seen that the word cloud drawn with the keywords of the studies is also compatible with these findings, and the most preferred keywords are "hands-on learning," "laboratory equipment," and "upper division undergraduate." In such studies (using Arduino while developing an experimental setup with university students), it is often mentioned that the equipment/devices required for laboratory studies are costly and that this cost can be reduced considerably with Arduino. For example, Guzman-Fernandez et al. (2021) stated in their study that they described the development and application of a low-cost Arduino-based experimental equipment (capable of measuring temperature, mixing, and pH) to collect experimental data and that they were able to reduce the cost from approximately $600 to around $75. Moreover, researchers encourage teachers and students by emphasizing that such developments do not require advanced programming and coding knowledge and pointing out the advantages of Arduino being open source. Similarly, Mercer and Leech (2017) stated that they were able to develop a magnetic stirrer that could be used in laboratory studies at the cost of only $40, and Kubinova and Slegr (2015) stated that many data acquisition devices needed in the chemistry laboratory could be developed at low-cost thanks to Arduino.

In this study, it was seen that 4 of the 5 authors who were determined as the most prolific authors and who had above average publications (3 publications) worked together and used Arduino to teach programming/coding/electronics in their publications, while the other most prolific author used Arduino to develop laboratory setup/equipment in his work.

Arduino kits were used in some studies, and their effects on various learning parameters were examined. For example, Cakır and Guven (2019) enabled secondary school students to model the contraction and relaxation movements of the heart using an Arduino kit on the circulatory system, and based on the results of the study, they stated that such a teaching practice was effective in developing students' positive attitudes towards technology, improving their computing skills and increasing their academic success on the subject. Chaudry (2020) states that using Arduino Uno increases students' interest in physics and encourages them to learn basic physics topics and their applications in daily life and that students define these applications as fun, creative, and completely new experiences. However, it is understood that the amount of these studies is small (they constitute 7.44% of the examined data set), and further studies in this direction will contribute to the literature.

Another purpose of using Arduino in studies is for students to create and use an experimental setup using Arduino. For example, in McClain's (2014) study, university students developed a photometer using basic electronic components and Arduino and used it to measure the chromium concentration in an unknown water sample. In another study, Lossjew and Bernholt (2024) encouraged pre service chemistry teachers to build a system (using Arduino) that could measure the gas pressure released as a result of chemical reactions, thus aiming to develop both their content and epistemic knowledge. As stated in the results of these studies, students developed research skills and problem-solving skills beyond using an existing design in this process. Because in this way, students have to not only learn how to use the existing design/setup and evaluate its outputs, but also examine and learn how this data is created. Therefore, it is possible to contribute to students' design, research and problem-solving skills in addition to improving content knowledge by using Arduino in teaching laboratories.

Another important issue regarding ATL studies is the usefulness of Arduino for remote lab applications. This may be an advantage, especially if there is a mandatory (and emergency) transition to distance education, such as a pandemic. However, remote lab applications can also be used for more efficient use of equipment and to provide a more flexible study schedule to students who will perform experiments.

From an educational perspective, the significance of Arduino-based teaching laboratories should not be reduced to the affordability or technical functionality of the devices developed. Although reducing the cost of laboratory equipment is an important contribution, the educational value of these environments depends primarily on how Arduino-supported activities are integrated into teaching and learning processes. Effective laboratory experiences are expected to support conceptual understanding, scientific reasoning, practical skills, engagement with the complexity of empirical work, collaboration, and students' interest in science (Hofstein & Lunetta, 2004; National Research Council, 2006). Therefore, the growing body of ATL research should be evaluated not only in terms of the devices produced, but also in terms of the learning opportunities these devices create for students.

The findings of this study indicate that Arduino has most frequently been used to develop laboratory devices and experimental equipment, particularly in engineering, physics, and chemistry laboratories. This finding suggests that Arduino has considerable potential to transform students from passive users of ready-made laboratory instruments into active designers, builders, and evaluators of experimental systems. When students construct an Arduino-based experimental setup, calibrate sensors, collect data, identify sources of measurement error, analyse results, and revise their designs, they engage in practices that are central to contemporary science and engineering education. These practices include planning and conducting investigations, analysing and interpreting data, designing solutions, engaging in evidence-based reasoning, and communicating findings (National Research Council, 2012). In this respect, Arduino-based laboratory activities may provide an appropriate context for integrating scientific inquiry with engineering design and computational thinking.

However, the educational potential of Arduino should not be assumed to emerge automatically from the availability of low-cost technology. Educational research on inquiry-based science teaching indicates that student learning is strongly influenced by the quality of instructional guidance provided during inquiry activities (Furtak et al., 2012). Thus, Arduino-based laboratory implementations should include appropriately structured tasks, teacher scaffolding, opportunities for reflection, explicit connections between data and scientific concepts, and assessment procedures aligned with the intended learning outcomes. Otherwise, students may concentrate mainly on assembling circuits or writing code without developing a deeper understanding of the scientific principles underlying the activity. Future ATL studies should therefore examine not only whether students can use or build Arduino-supported devices, but also how different instructional designs influence conceptual understanding, scientific process skills, epistemic knowledge, problem-solving, collaboration, motivation, and attitudes toward STEM fields.

The findings also reveal that the majority of ATL publications have focused on university or college students, whereas studies involving secondary school learners appear to be comparatively limited. This situation represents an important research gap from the perspective of science education. Because Arduino enables students to observe, measure, model, and control real-world phenomena through relatively accessible materials, it may support inquiry-oriented and design-based learning at earlier educational levels when activities are appropriately adapted to students' developmental and curricular needs. Future studies should investigate how Arduino-based teaching laboratories can be implemented in secondary science education and teacher education, particularly in relation to students' scientific literacy, engineering design competence, computational thinking, and interest in STEM careers.

In conclusion, using Arduino in teaching laboratories can create many advantageous situations and seems useful in eliminating some concerns about laboratories (cost, personnel, time). The data set examined shows that studies in this field have an annual growth rate of 22.11% and receive an average of 9.94 citations per document. As can be seen from here, it would not be wrong to say that such studies will frequently find a place in literature in the future. It is recommended that researchers who will work in this field should focus on designing equipment/devices available on the market at a lower cost, developing designs that will appeal to students from secondary school onwards, and examining the effects of these equipment/devices on teaching/learning processes.

5. LIMITATIONS

This study has several limitations that should be considered when interpreting its findings. First, the dataset was constructed based on a search conducted on November 4, 2025. Therefore, publications indexed after this date were not included in the analysis, and the findings reflect the state of the ATL literature available in the selected databases at the time of data collection.

Second, the search was limited to the Web of Science Core Collection and Scopus databases. Although these databases provide broad coverage of internationally indexed scholarly publications, relevant studies indexed in other databases or available through alternative academic sources may not have been captured.

Third, only research articles were included in the dataset. Consequently, other forms of scholarly and practical output, such as theses, dissertations, project reports, and conference proceedings, were excluded. These sources may contain additional evidence on the design, implementation, and educational use of Arduino-based teaching laboratories.

Finally, the study included only publications written in English. This criterion was applied to maintain linguistic consistency in the bibliometric and content analyses; however, it may have resulted in the exclusion of relevant studies published in other languages.

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