Technology integration in geometry teaching and learning: A systematic review (2010–2022)

Gladys Sunzuma

Bindura University of Science Education, Zimbabwe

Technology advancement provides an opportunity for helping both teachers and students to solve and improve mathematics teaching and learning performances. This systematic review aims to add to the discussion through a comprehensive overview of the integration of digital technologies into the teaching and learning of geometry at the secondary school level. A systematic literature review was conducted following the preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines, with a focus on publication trends, types of technologies used, types of contributions, learning domains and research methods. Twenty-nine articles published between 2010 and 2022 were searched from the ERIC database. The findings showed that the majority of the articles were published in 2015 and the technologies that were used were GeoGebra, augmented reality, computer animation package, video-based cooperative, graphing calculator, micromedia flash, Powtoon animation, learning management system, interactive whiteboard, digital simulations-applets, iPads and tablet. Most of the reviewed articles focused on the effectiveness of the technologies in geometry teaching and learning. The findings indicated that the majority of the reviewed articles used quantitative research methods followed by qualitative methods studies. It is suggested that other studies be conducted with other databases and focus on challenges of integrating technology into the teaching and learning of geometry.

Keywords: geometry, teaching, learning, technology, systematic review

1   Introduction

Mathematics consists of several components such as statistics, algebra and geometry among others. Geometry is a vital component in mathematics that includes the nature and relation between points, lines, shapes and space. Geometry is the mathematics knowledge that involves the nature of shape and space, measurement, magnitude as well as the relations of dots, lines, corners and surfaces (Abd Rahim et al., 2018). Geometry is an exceptionally rich area of knowledge, not merely for its great diversity and assortment, but in addition for its practical applications such as visual presentations, computer animation, virtual reality, and medicine (in the area of medical imaging, which led to substantial new results in fields such as geometric tomography), robotics, geometric modelling (including design, modification and the manufacture of cars and aeroplanes, in the construction of buildings, etc.) and

computer-aided design (CAD) (Viseu et al., 2022). According to Jones (2000), several modern developments in mathematics are largely geometric, for instance, geometric algebra (a representational and computational system for geometry that is entirely distinct from algebraic geometry), mathematical visualisation (the art of transforming the symbolic into geometry) and work on dynamical systems (a discipline closely intertwined with the main areas of mathematics). Due to its multiplicity of applications, there is a need for schools to promote geometry learning (Septia et al., 2018). Some of the reasons for including geometry in the mathematics curriculum and teaching in schools are helping students to think visually, helps in solving problems in other mathematics-related fields, helps students who experience abstraction problems and that the world is built by form and space (Petrus et al., 2017). In many countries globally, the objective of including geometry in the school curricula is to enable students to develop skills of problem-solving, visualisation, intuition, critical thinking, perspective, conjecturing, logical argumentation, deductive reasoning as well as the ability to produce proof (Jones & Tzekaki, 2016; Kuzniak, 2018; Horsman, 2019). In addition, the purpose of teaching geometry in schools is that students can use visualization; have spatial abilities as well as geometry modelling skills to solve problems (NCTM, 2000).

However, it was noted that the desired objectives associated with teaching geometry could not be accomplished and the conceptual understanding of geometry concepts could not be developed (Gülburnu, 2022). Regardless of the importance and popularity of geometry, researchers (Sutiarso et al., 2018; Nursyahidah, 2016) noted many difficulties associated with its teaching and learning and most students experience difficulties in learning geometry. Furthermore, research has established that geometry is one of the components of mathematics that is abstract and complex that both teachers and students find difficult to teach and learn (Gambari et al, 2014). Amongst the causes of the student's difficulties with geometry are misconceptions of geometry (Sutiarso et al., 2018) as well as the abstract and conventional approach of teaching that makes students learn by heart without understanding the concepts (Bergstrom & Zhang, 2016; Abdul Hanid et al., 2022). Such approaches have contributed to poor achievement in geometry.

Mathematics educators have been constantly searching for innovative approaches to teach mathematics for understanding including improving students' achievement and performance (Mensah & Nabie, 2021). An innovative approach to mathematics teaching that motivates learning and promotes higher achievement as

well as improves the performance of students is the integration of digital technologies in the teaching and learning process (Mensah & Nabie, 2021; Tay & Mensah-Wonkyi, 2018). Two major purposes of using digital technologies in mathematics teaching are supporting the organisation of the teacher's work such as formative and summative assessment of students and producing learning materials as well as support for new approaches to doing and representing mathematics (Clark-Wilson et al., 2020). According to Ayan and Isiksal Bostan (2016), the integration of digital technologies in mathematics teaching activities enables students to be actively involved and be in a position to solve complex problems. According to Klančar et al. (2019) using digital technologies in the teaching and learning process enables the designing of rich learning environments through the use of varied digital materials and digital support tools such as simulations, animations and applets. Such technologies support different methods of teaching, for instance, experimentation, simulation, modelling, and research including solving routine mathematical problems and non-routine problems (Klančar et al., 2019). Digital technologies augment the learning of mathematics by facilitating practical, problem-solving and collaborative methods of teaching and learning (Žakelj & Klančar, 2022). Given such benefits of integrating digital technologies into the teaching and learning of mathematics, this study is a systematic review of integrating technology into the teaching and learning of geometry.

2 Technology in geometry teaching and learning

The teaching and learning of geometry require students to be able to imagine, construct and understand the construction of shapes to relate them with associated facts (Praveen & Kwan Eu, 2013). Hence, digital technologies will help students in imagining, and making observations and facts (Praveen & Kwan Eu, 2013). Numerous digital technologies are available for the teaching and learning of geometry, for instance, Geometers Sketchpad, calculators, interactive whiteboards, and GeoGebra (Praveen & Kwan Eu, 2013). GeoGebra is a dynamic geometric software that amalgamates statistics, calculus, algebra, geometry, arithmetic, and spreadsheet elements into a solitary easy-to-use package that enables the learning and teaching of mathematics at various stages (Abebayehu & Hsiu-Ling, 2021).

Research has revealed that geometry concepts taught using computer-based technology result in improved student achievement as compared to the conventional approaches that rely on the use of textbooks (Christou et al., 2006; Abdul Hanid,

2022). The integration of technology in geometrical learning is crucial as it enables students to understand the geometry concepts' problem solving process, for instance, the use of various problem-solving approaches including reducing misconceptions to understand geometry concepts (Hwang et al., 2009). A study by Gutiérrez (1996) revealed students' ability to solve geometry problems using software that helped them to manipulate 3D Geometry object essentially for the visualisation and mental image. Students will be attentive and actively involved in geometry concepts taught through the use of technology (Hollebrands & Okumuş, 2018). In addition, digital technologies provide students with an opportunity to use the varied technology resources for the geometry content and solve any problem (Lee & Hollebrands, 2006).

Regarding the current systematic literature review about integrating digital technologies into the teaching and learning of mathematics, studies have been conducted. Mohamed et al. (2022), for instance, provides a systematic review of artificial intelligence in mathematics education. Zhong and Xia (2020) provide a stimulating learning experience with robotics in the learning of mathematics. Ahmad and Junaini (2020) focused on augmented reality in the teaching and learning of mathematics. A systematic review was also conducted by Abebayehu and Hsiu-Ling (2021) on the use of GeoGebra in the teaching and learning of mathematics. Even though these studies focused on digital technology integration into the teaching and learning of mathematics, they focused on mathematics in general. The current study focuses on the integration of digital technologies into particular mathematics topics geometry at secondary school level. To direct this systematic literature review, the current study addressed the following research questions:

1. What is the trend of articles on the integration of technologies into geometry teaching and learning from 2010 to 2022?
2. What are the leading technologies that have been integrated into the teaching and learning of geometry?
3. What are the types of contributions made by the articles in terms of implementation, development and effectiveness in geometry teaching and learning?
4. What are the learning domains in the teaching and learning of geometry?
5. What are the research methods used to study technology integration in geometry teaching and learning?

3   Methodology

A systematic search was conducted using the PRISMA specification that enables transparent and comprehensive reporting of systematic reviews (Page et al., 2021). Articles published in indexed journals are generally more systematically scrutinized such that they have a greater impact on the area of study (Duman et al., 2015). In this study, articles were searched from Education Resources Information Center (ERIC) because it is a chief source of high quality indexed academic journals (Akçayır & Akçayır, 2018). The search function was used and input the keywords "Geometry" or "Secondary level" or "Teaching and Learning" or "Technology" and "Information Communication Technology (ICT)."

The screening criteria excluded book chapters, books, conference proceedings, systematic review articles, or books. The study focused on English-language journal articles to avoid complex or uncertain translations. Journal articles published between the years 2010 and 2022 focusing on secondary school level geometry teaching and learning and technology integration were included. From the screening process, 873 articles were identified. To guarantee that all 873 articles fit the study's selection criteria and objectives, each article's title, abstract, methodology, results, and discussion were scrutinized. Ten articles were removed as they were duplicates. 812 articles were rejected because of the following reasons; they did not explain how technologies were integrated into the teaching and learning of geometry at the secondary school level, not written in English and were books and conferences. Another 32 articles were rejected because they focused on the teachers' use of technology only without the teaching and learning component. Finally, 29 articles were included in the final stage of the review process as shown in Figure 1. Thematic analysis was carried out to classify the themes related to the research trends and patterns in the study. Useful data was extracted from the 29 articles that were used to answer the research questions. The 29 articles used in this study were marked with an asterisk in the list of references.
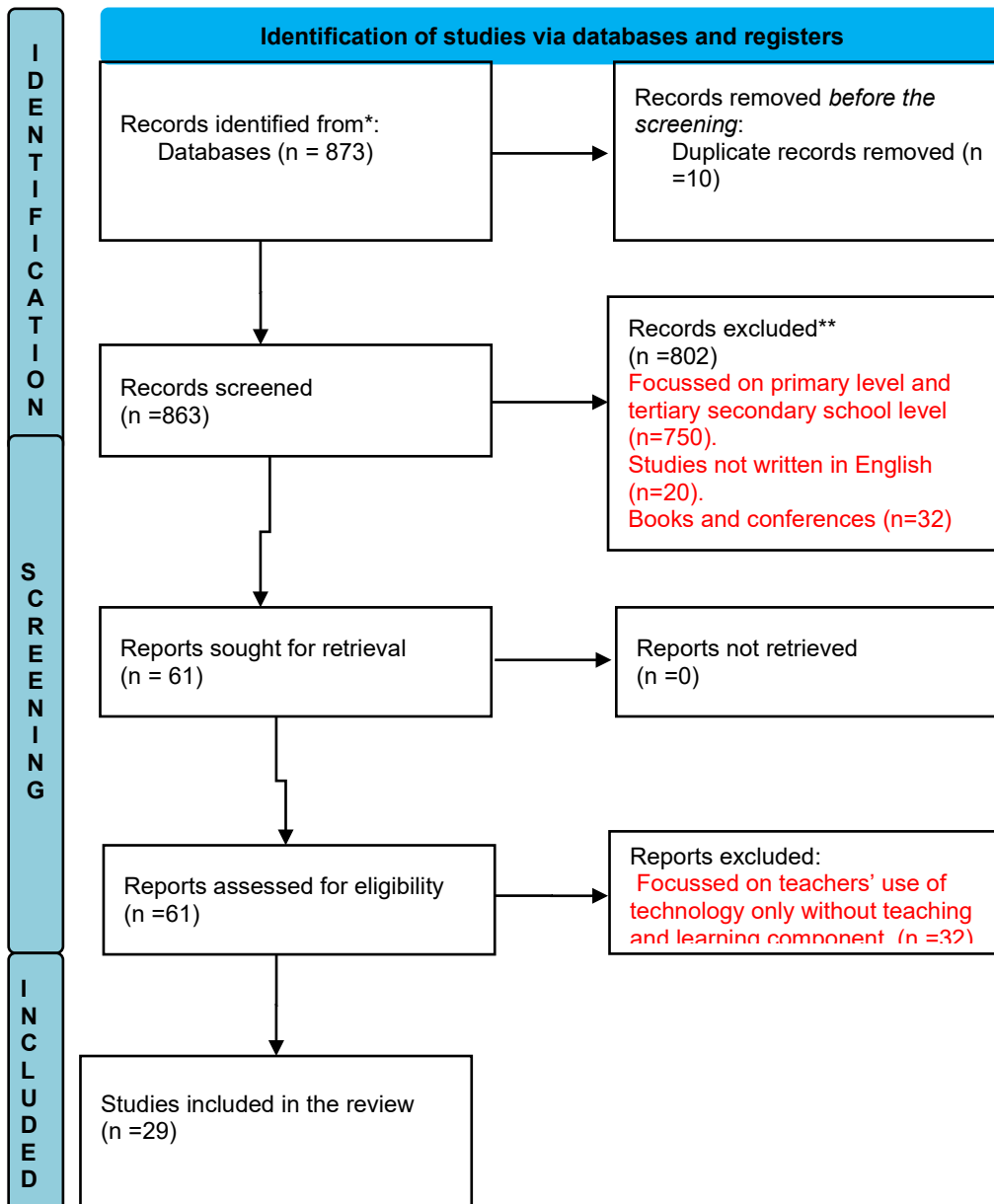
Figure 1. Systematic literature review procedure used in the study following concepts in Page, et al. (2021).

4   Results and Discussion

A search performed on the ERIC database resulted in 873 journal articles. Only 29 articles met the inclusion criteria. The findings of the systematic review are presented under the following themes: trends of article publication; type of technologies; type of contribution (development, implementation, and effectiveness), learning domain and research approaches used to carry out the studies.

4.1 Trends in article publication

The trend of the 29 published articles integrating different technologies into the teaching and learning of geometry from 2010 to 2022 is shown in Figure 2. To comprehend the development of the research, the 29 articles were classified based on the year of publication. There were no articles published in 2012 and 2017 (Figure 3). There is a gradual increase in articles from 2013 to 2015 with the highest number of seven articles recorded in 2015. The number of published articles remained relatively consistent from 2021 to 2022. The general trend shows that some researchers focus on the integration of technology into the teaching and learning of geometry. Such findings from the systematic review show that even though the articles were very few in terms of number some progress has been made in the integration of technology into the teaching and learning of geometry. Even though the trend is moving upwards and downwards there is evidence that the issue of technology integration in geometry teaching and learning is progressively becoming an area of focus that is getting numerous researchers' attention.
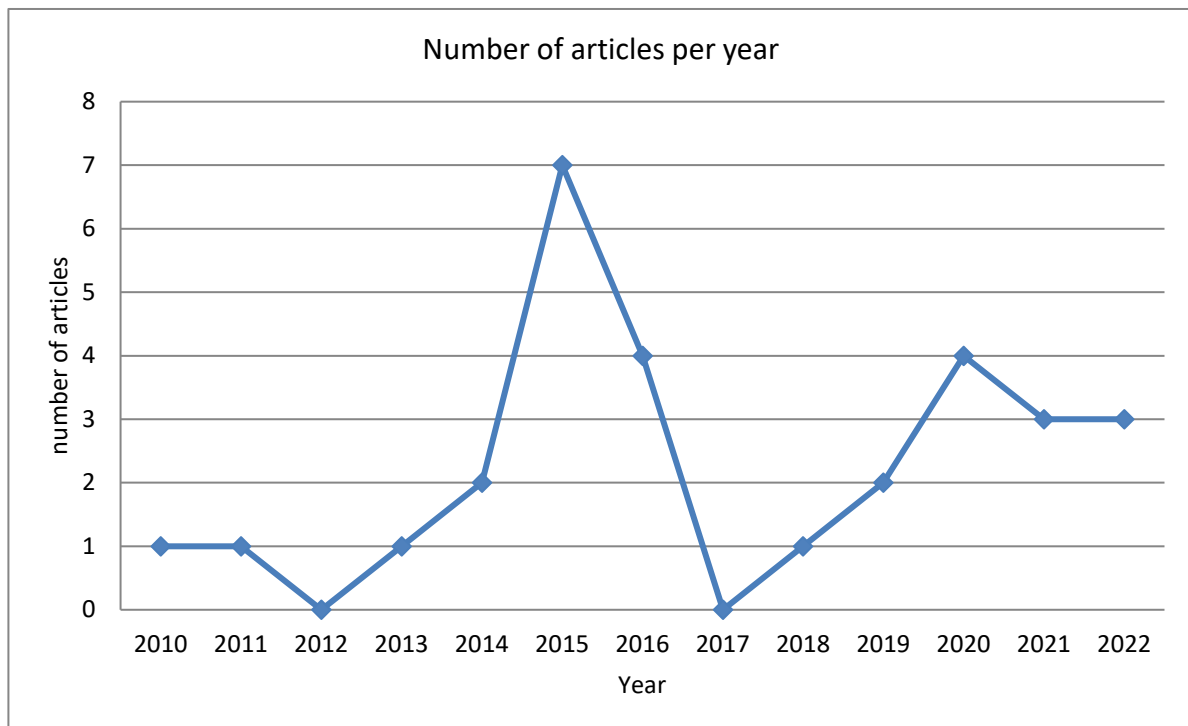

Figure 2. Number of articles per year.

4.2 Types of technologies used

Different types of technologies were used in the teaching and learning of geometry as shown in Figure 3. The majority of the studies used dynamic geometry software with GeoGebra having a total of 10 articles, Cabri had two articles, multiuser dynamic geometry, dynamic geometry general, and dynamic geometry of sketchpad each having one article. The findings of the current review are in line with Abebayehu and Hsiu-Ling (2021) who found out that GeoGebra is widely used in the teaching and learning of geometry. Geometry is one of the most frequent mathematics topics that integrate GeoGebra because of its potential to visualize abstract and difficult concepts through many representations. Representations help students to understand and make associations between geometry concepts. Visualization is not merely pertinent for illustrative purposes but is as well acknowledged as an essential component of problem solving, reasoning and even proofs (Abebayehu & Hsiu-Ling, 2021).

      Augmented Reality had the second largest number of four articles. Although augmented reality has the second largest number of articles, a study by Ahmad and Junaini (2020) showed its wide use in the teaching and learning of geometry. Augmented reality in geometry teaching and learning provides students with an interactive learning environment, increased understanding and retention as well as enhanced visualization (Ahmad & Junaini, 2020). Computer animation package, video-based cooperative, graphing calculator, micromedia flash, Powtoon animation, learning management system, interactive whiteboard, digital simulations-applets, iPads and tablet device each had only one article. The limited use of such digital technologies could be due to the lack of adequate and ample training for teachers as observed by Dockendorff and Solar (2018) who reported that a lot of teachers are inadequately prepared to incorporate digital technology into the mathematics curriculum.
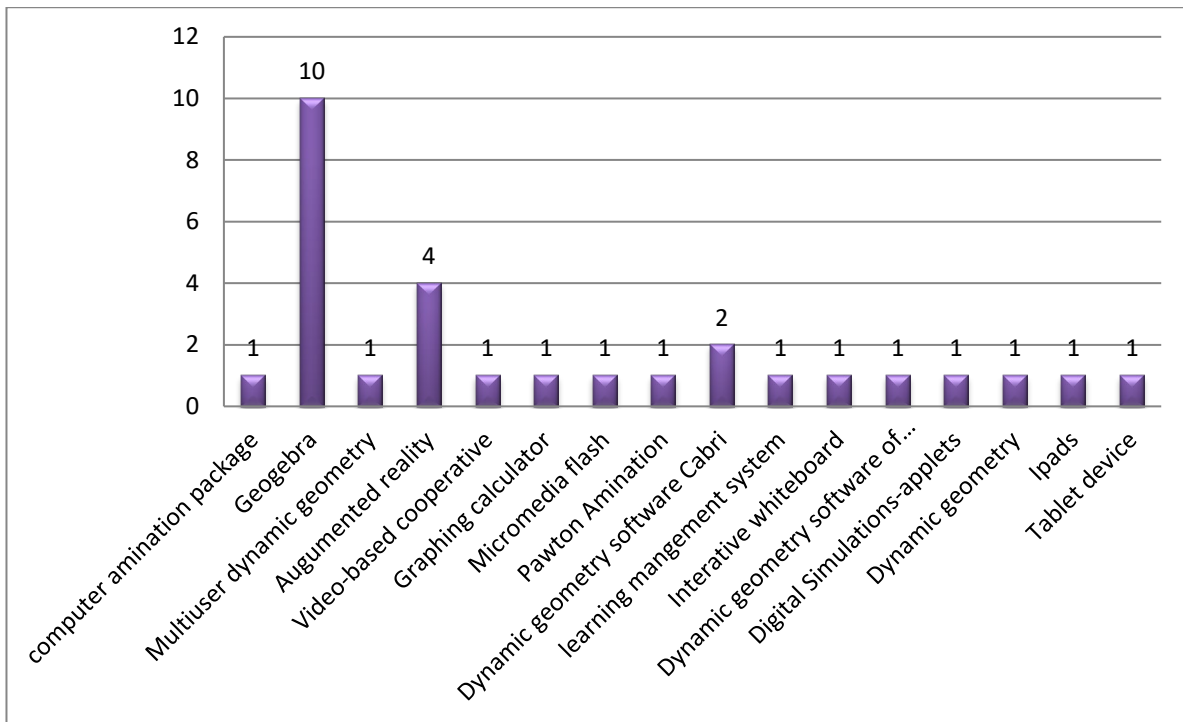
Figure 3. Types of technologies used.

4.3 Types of contributions (Implementation, development, and effectiveness)

Figure 4 shows the distribution of the types of contributions made by the articles to the teaching and learning of geometry in terms of implementation, development and effectiveness of technological tools for geometry learning. Twenty-one articles (73%) focused on the effectiveness of technological tools in the teaching and learning of geometry (Gambari et al. 2014; Doğan & İçel, 2011; Ibili et al. 2020; Praveen & Kwan Eu 2013; Gambari et al. 2016; Diaz-Nunja et al. 2018; Kandemir & Demirbag, 2019; et al. 2019; Yani & Rosma, 2020; Mailizar., & Johar, 2021; Brito et al. 2021; Shaame et al. 2020; Perry & Steck, 2015; Gómez-Chacón et al. 2016; Lin et al. 2014; Samur Turk & Akyüz, 2016; Abdul Hanid et al. 2022; Viseu et al. 2022; Lin et al. 2015; Duroisin et al. 2015). The greatest number of articles focused on the effectiveness of the technological tools as shown in Figure 4. Five articles (17%) focused on the implementation of technological tools in the teaching and learning of geometry (Ng & Sinclair, 2015; Lin et al. 2015; Prasad, 2016; Komatsu & Jones, 2020; Gülburnu, 2022). Only three articles (10%) focused on development. Akmalia et al. (2021) developed powtoon animation. Sherman and Cayton (2015) developed a framework for teaching geometry using technology. Baccaglini-Frank and Mariotti (2010) developed a dragging model for generating conjectures in dynamic geometry. The finding of this

review disagrees with earlier findings by Ahmad and Junaini (2020) where the findings showed that the major contribution of the articles reviewed was the development of apps. In view of the fact that most of the articles in the current review focused on effectiveness, additional research on technology integration into the teaching and learning of geometry other than effectiveness should be conducted even more.
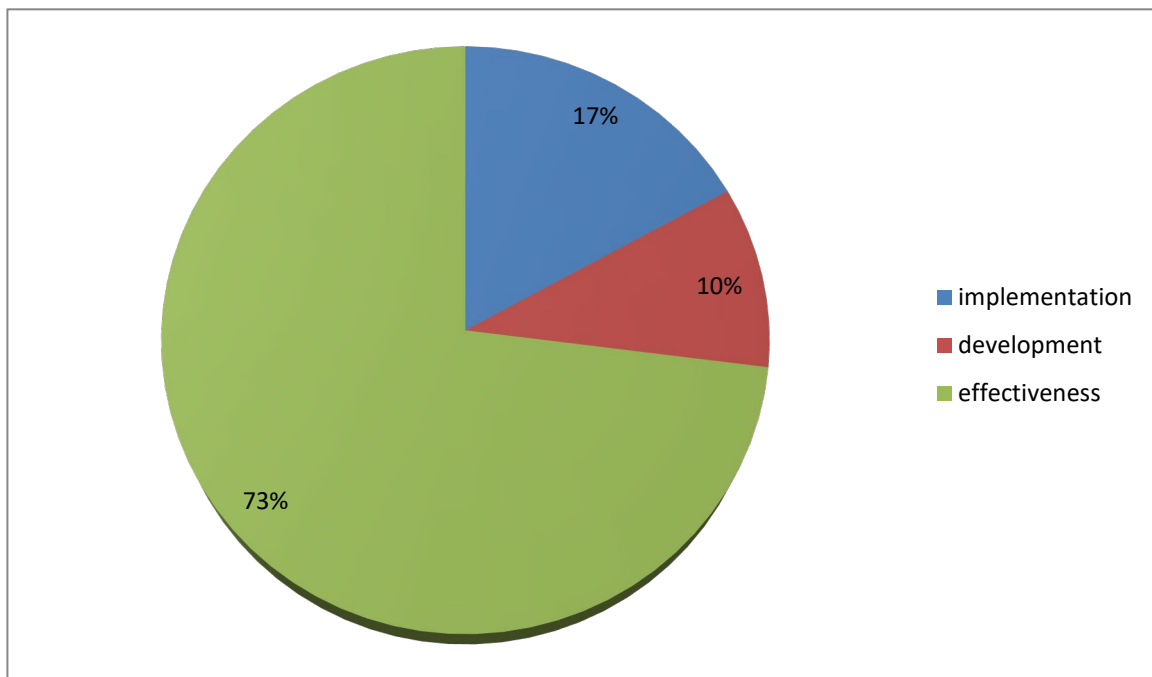

Figure 4. Types of contributions.

4.4 Learning domains

Technology integration into the teaching and learning of geometry had been classified based on Bloom's Revised Taxonomy of learning domains which includes the cognitive domain, the affective domain, and the psychomotor domain (Krathwohl, 2002). The cognitive learning domain which includes the component of obtaining knowledge from learning as well as the development of intellectual capabilities through low to higher-order learning such as problem solving and learning performance had ten articles (Gambari et al. 2014; Doğan & İçel, 2011; Lin et al. 2015; Praveen & Kwan Eu, 2013; Gambari et al. 2016; Kandemir & Demirbag, 2019; Adelabu et al. 2019; Kaushal Kumar & Chun-Yen, 2015; Shaame et al. 2020; Samur Turk & Akyüz, 2016). The articles revealed positive effects on student learning and achievement. They found an increased achievement in geometry after using various technologies. The study by Gómez-Chacón et al. (2016) shows that the use of dy-

namic geometry affords students greater intellectual independence in geometrical work, whilst Ibili et al. (2020) found out found that geometry teaching supported by Augmented Reality increased the students' 3D thinking skills. A study by Fukawa-Connelly and Silverman (2015) focused on the development of mathematical argumentation in an unmoderated, asynchronous multi-user dynamic geometry environment. The study showed that the students made progressively more in-depth and mathematical descriptions of the data, developed more conceptual warrants, as well as progressively behaved as if giving reasons was normative in the discussion.

The affective learning domain involves students' feelings about learning, for example, motivation and learning perceptions. Seven articles had issues to do with the affective domain. The integration of technology into the teaching and learning of geometry improves students' motivation as mentioned in one study. The study by Doğan and İçel (2011) has shown that the use of GeoGebra improves students' motivation with a positive impact. Five studies (Samur Turk & Akyüz, 2016; Gómez-Chacón et al. 2016; Gülburnu, 2022; Duroisin et al. 2015; Lin et al. 2015) found the benefits of various technologies in developing students' positive attitudes towards geometry learning. The study by Perry and Steck (2015) assessed the effect of integrating iPads in geometry teaching on student engagement, self-efficacy, and meta-cognitive self-regulation. The finding showed that the students who used the iPad experienced higher levels of off-task behaviours and similar levels of self-efficacy and meta-cognitive self-regulation as compared to the group that did not use the iPad.

The psychomotor learning domain involves the manipulation or motor skill area of learning such as spatial skills. The integration of technologies into the teaching and learning of geometry enhances the spatial ability and visualization skills. The study by Yani and Rosma (2020) showed an improvement in students' spatial ability and visualization skills after the use of the macromedia flash. Abdul Hanid et al. (2022) stated that Augmented Reality enhances students' visualization skills. Meanwhile, technology has made geometry learning more interactive. Three studies explained this benefit. Gómez-Chacón et al. (2016) stated that dynamic geometry software affords interaction with the context that impacts learning opportunities in geometric proofs; whilst Gülburnu (2022) was of the idea that Cabri 3D encourages interaction through facilitating drawings and measurements. Duroisin et al. (2015) stated that the use of the interactive whiteboard encourages interactions between the students and has a positive effect on the efficiency of the learning sequence itself.

A study by Gülburnu (2022) showed that Cabri 3D encourages the association of geometric knowledge about solids volume measurement with daily life by contributing to conceptual and permanent learning. GeoGebra offers students an opportunity to experiment and explore that result in improved results (Viseu et al. 2022).

4.5 Research Approaches used in the studies

Different research methods were employed in the 29 articles. The research findings show that only three research approaches which are quantitative, qualitative and mixed methods were used in the 29 articles as shown in Figure 5. The analysis revealed that the majority of the studies reviewed (62%, n=18), (Gambari et al. 2014; Doğan & İçel, 2011; Ibili et al. 2020; Praveen & Kwan Eu 2013; Gambari et al. 2016; Diaz-Nunja et al. 2018; Kandemir & Demirbag, 2019; Adelabu et al. 2019; Yani & Rosma, 2020; Mailizar., & Johar, 2021; Akmalia et al. 2021; Brito et al. 2021; Shaame et al. 2020; Perry & Steck, 2015; Gómez-Chacón et al. 2016; Lin et al. 2014; Samur Turk & Akyüz, 2016; Abdul Hanid et al. 2022) used quantitative research methods. The quantitative methods were mainly empirical studies. According to Yang et al. (2019), an empirical study is carried out to examine the cause-and-effect relationship between independent and dependent variables under conditions of apt control hence it is regarded as the most scientific method among all the experimental research. The quantitative approach was mainly chosen as it put more emphasis on the objective measurement and analysis of numerical or statistical, data collected through tests, surveys and questionnaires.

Seven studies (24%) of the reviewed studies used qualitative research methods (Ng & Sinclair, 2015; Fukawa-Connelly & Silverman, 2015; Gülburnu, 2022; Sherman & Cayton, 2015; Prasad, 2016; Baccaglini-Fran &, Mariotti, 2010; Komatsu & Jones, 2020). Qualitative research methods involve collecting and analyzing non-numerical data with the purpose of a better understanding of concepts, views, or experiences. Case studies are employed to examine a phenomenon in-depth as well as to understand particular situations and provide an in-depth analysis (Olsson, 2018). For example, Gülburnu (2022) employed a case study that enabled the researcher to investigate students' views on geometry teaching through the use of the three-dimensional dynamic geometry software Cabri 3D.

Although mixed methods incorporate the benefits of both quantitative and qualitative methods, the current systematic review showed that only four studies (14%) used the mixed method research (Viseu et al. 2022; Kandemir & Demirbag,

2019; Duroisin et al. 2015; Lin et al. 2015). Mixed methods are of use in understanding inconsistencies between quantitative and qualitative findings and they enhance the problem by comparing the findings. For example, in a study by Viseu et al. (2022), the quantitative method focused fundamentally on the characteristics of the student's answers with regard to their level of correctness, whilst the qualitative method focused as well on the students' answers but the intention to analyse the reasons beyond such answers. Mixed method research fosters intellectual interaction and flexibility since researchers would expand the distribution of data on technology integration into the teaching and learning of geometry.
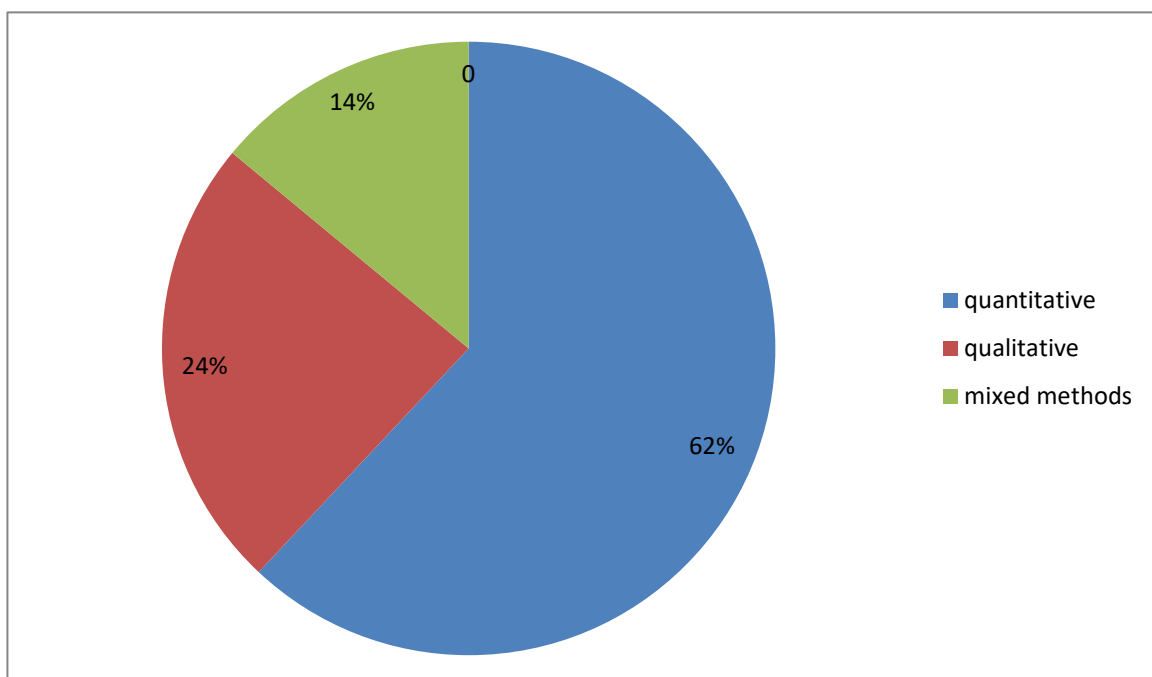

Figure 5. Research approaches used.

5   Conclusion and suggestions

The teaching and learning of geometry are challenging because most of the concepts are abstract. One effective method of improving geometry learning is through technology integration into the teaching and learning process. Students can investigate, solve, and explain geometrical concepts in different forms in a technology-rich environment. The current review assists to understand a systematic and comprehensive examination over the last twelve years of research in technology integration into the teaching and learning of geometry at the secondary school level. In addition, an updated analysis was provided that reveals learning and technological requirements for

further studies to be conducted in the future. Restricted by the scope of the current review findings were classified into themes such as publication trends, types of technologies used, types of contributions, learning domains and research methods. Technology integration into the teaching and learning of geometry helps to ease the process of learning.

The systematic review revealed that GeoGebra is widely used in the teaching and learning of geometry followed by augmented reality. This review also found that the most observed contribution of the articles is the effectiveness of technology integration into the teaching and learning process. It is important to be acquainted with the extent of the effectiveness of technology integration into the teaching and learning of geometry to enable its wide application in the future if results in positive effectiveness. In learning domains, the cognitive domain focused on students' learning achievement and 3D thinking skills. The affective domain was based on assessing student engagement, self-efficacy, meta-cognitive, motivation as well as perceptions. The psychomotor domain focused on students' visualization skills, spatial ability and interactive learning in geometry. The review reveals a clear outline of the often-used research methods employed in the articles incorporated in this study. For example, the quantitative research method was the most commonly used approach in articles on technology integration in the teaching and learning of geometry, whilst mixed methods had the least number of articles.

6   Limitation and Implications for Future Studies

The search terms used in the methodology are a limitation of this study. Only the articles published in ERIC database were included in this study. Therefore, further studies could be conducted using other databases. In addition, there is a need to carry out more research on the negative side effects of using technology in the teaching and learning of geometry.

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